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Assessing the Emerging Biorefinery Sector in Canada

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Abstract

The biorefinery is a key concept used in the strategies and visions of many industrial countries. The potential for Canadian biorefineries based on lignocellulosic forest and agricultural residues is examined. The sector is described in terms of research interests, emerging companies, and established corporate interests. It is found that the Canadian biorefining sector currently has an emphasis on specific bioproduct generation, and the process elements required for a true sugar-based process are in the research phase. A Canadian national strategy should focus on increasing forest industry participation, and increasing collaboration with the provinces, particularly in western Canada.

Index Entries: Biorefinery; bioproducts; national strategy; lignocellulosic biomass; feedstock.

Introduction

Biotechnology is an enabling technology that can utilize the properties, processes, or products of living organisms for industrial use. A key application of biotechnology is the development of biorefineries, which substitute renewable biomass feedstocks for fossil fuels in the production of energy, fuels, and products *(1).* The biorefinery concept has, in the past, been used to describe more complete waste utilization within existing food- or wood-processing plants. In this article, an expanded version of the concept is considered, which incorporates the more efficient use of chemicals and materials at all stages in the supply chain, including growth and harvest, production and conversion, and final disposition of products *(2).*

Biorefineries are an important global initiative that offers many potential environmental, economic, and security-related benefits to our society. For instance, fuels made from materials such as agricultural and forestry

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residues are characterized by reduced carbon dioxide emissions when compared to petroleum use and, thus, can play a role in meeting the challenges of climate change *(3)*. The processing facilities required to convert biomass into value-added products create direct and indirect jobs; provide regional economic development; and can increase farm and forestry incomes, particularly in rural areas *(4,5)*. Substituting sustainable biomass for fossil resources can also be viewed as a tool for increasing security of supply for a variety of products, including chemicals, fuel, and energy *(6)*. This may reduce Western reliance on foreign-owned oil supplies, which are subject to political uncertainty and conflict. This argument is particularly compelling because current reserves of fossil oil are being consumed at an increasing rate, while the discovery of new reserves is in decline *(7)*.

Canada is chosen as an illustrative example of the development of the biorefinery sector because of its role as a predominant supplier of biomass. Canadian forests supply more than 200 million m^3 of biomass annually through commercial operations and, as such, are the second largest supplier of woody lignocellulosic biomass in the world, behind the United States *(8,9)*. The relatively high availability of Canadian biomass, as harvested and in residue form, makes this country a highly suitable location for the development of a biorefinery sector. The environment itself will place some restrictions on the amount of residue that can ultimately be retrieved from forest operations. The issues of biodiversity conservation and soil and water protection will limit the removals of residue *(10)*.

In this article, we provide an overview of the sugar-based biorefinery and its associated products and emphasize the importance of feedstocks and product selection to biorefinery design. We also consider industrial strategies for implementing biotechnology for their suitability as approaches to the commercialization of lignocellulose-based biorefineries. We also consider the Canadian bioproducts industry in the context of these strategies and compare it to international examples of successful biorefineries. The objective of this article is to provide insights into successful pathways for commercializing biorefinery technology, and to apply these findings to the Canadian situation.

Importance of Feedstocks for Biorefinery Design

The biorefining platform chosen will be determined in part by the characteristics of the biomass available for processing. The majority of terrestrial biomass available for biorefining is typically derived from agricultural plants and from wood grown in forests, as well as from waste residues generated in the processing or use of these resources. Today, the primary barrier to utilizing this biomass is generally recognized to be the lack of low-cost processing options capable of converting these polymers into recoverable base chemical components *(11)*.

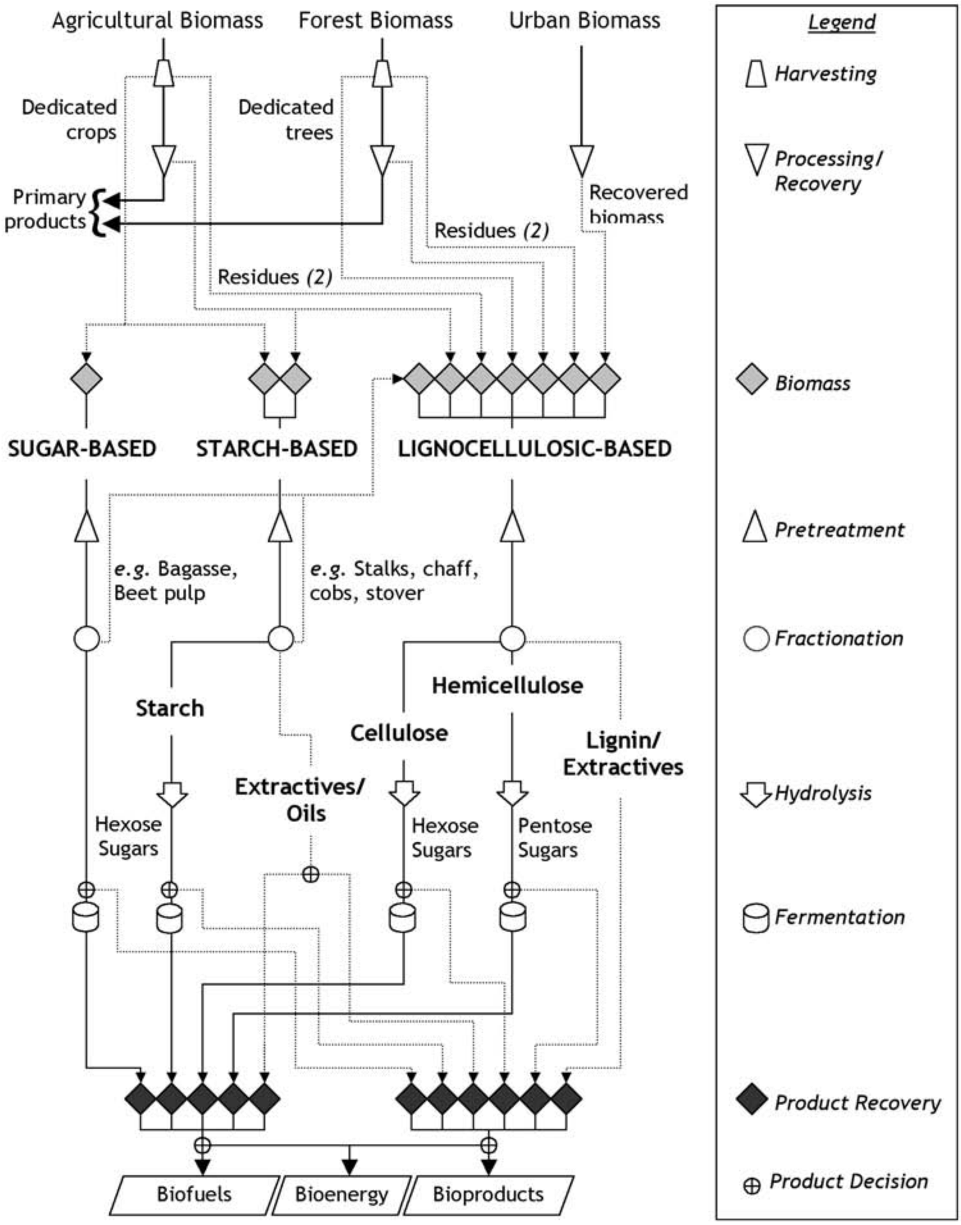

Fig. 1. Biorefinery pathways based on multiple product platforms, including carbohydrates, oil, lignin, and fiber.

Agricultural biomass considered for the biorefinery includes herbaceous plants that are the source of sugars, starches, or vegetable oils. These plants may be used as feedstock for biorefineries based on the carbohydrate and oil platforms, which are designed to isolate carbohydrates (including glucose from starch) or vegetable oil for further processing. The sugar-based and starch-based processes illustrated in Fig. 1 combine the process elements of pretreatment, fractionation, hydrolysis, and separation to create a number of end products. “Native” sugars found in sugarcane and sugar beet or vegetable oils can be easily derived from agricultural plants and refined in facilities that require the lowest level of capital input. Starch requires additional processing in the form of a hydrolysis step, but this can be achieved utilizing a single family of enzymes, the amylases, which makes bioconversion relatively simple.

Structural components, including fibers, are composed of lignocellulosic materials and found in all agricultural plants and in forest biomass *(12,13)*. Implementing a biorefining system utilizing these feedstocks requires the hydrolysis of five sugars (glucose, galactose, mannose, xylose, arabinose), compared with the single sugar (glucose) associated with starch *(14,15)*. Because of the increased complexity of the chemical structure, lignocellulosic-based bioconversion is much more difficult and therefore more expensive. As illustrated in Fig. 1, the number of potential biomass sources rises with the progression from sugar to starch to lignocellulosic feedstocks. In addition to carbohydrates, lignin and fiber become alternative products from the biorefinery. The complexity associated with the bioconversion process also rises, however, creating a trade-off between what is technically feasible and what is economically desirable. Several new facilities, each utilizing the lignocellulosic-based process, are currently in existence or are under development, indicating that this process is approaching commercialization. These facilities include the Etek Etanolteknik pilot facility in Sweden, the Abengoa demonstration plant in Spain, and the Iogen demonstration plant in Canada.

As the ability of biorefineries to handle multiple biomass streams is increased, the security of supply is improved. Utilizing increasingly recalcitrant biomass streams has a corresponding rise in the cost of processing, however, which has subsequent implications for the range of products that may be produced.

Relating End Products to Biorefinery Design and Choice of Feedstock

The application of biotechnology in the biorefinery differs from pharmaceutical and medical applications because of the relatively large scale of production, and the correlating importance of feedstock availability to the process *(11)*. Biorefinery design is therefore heavily influenced by both the biomass source and the selection of desired end products. The biorefinery concept gives manufacturers an option of coproducing high-value, low-volume products for niche markets together with lower-value commodity products, such as fuels or energy *(16,17)*. Correspondingly large amounts of feedstock are required if biorefining is to be successfully used in the generation of these products. For this reason, developing the lignocellulosic processing stream is of critical importance, because it provides a greater number of options to source biomass for the facility.

Many bioproducts that may be produced in a sugar-based biorefinery are not feedstock specific but, rather, can be derived from virtually all sugar, starch, or lignocellulosic feedstocks. For instance, polyols can be derived from xylose and arabinose and used in a variety of products, including antifreeze, plastic bottles, brake fluid, synthetic fibers, resins, auto bodies, and sweeteners *(18)*. Lactic acid is used as a food additive, and polylactic acid (PLA) polymers are used in biodegradable plastic bags *(19)*. Glucose can be accessed microbially and chemically to produce whole family trees of industrially relevant products, including such products as lactic acid, ethanol, acetic acid, and levulinic acid *(20)*. Bioethanol can be produced through the fermentation of both six- and five-carbon sugars and can be used in a gasoline blend, as a neat fuel, or as a precursor for hydrogen in fuel-cell vehicles. A specific example of an innovative glucose product is 3G (1,3-propanediol), which can be used to develop a polymer called 3GT, which has excellent stretch recovery, resiliency, toughness, and dye capability *(18)*.

A significant output from the biorefinery is energy that can be utilized in-house or sold to a distributed energy grid. Four technologies currently dominate research and development efforts in bioenergy generation: cofiring, direct combustion, pyrolysis, and biomass gasification *(21)*. The sale of bioenergy as a product has the dual benefits of increasing economic revenues for the biorefinery, and increasing the security and resilience of the domestic energy supply by providing additional, decentralized sources of power to the grid.

Commercialization of Biorefineries

A successful biorefinery sector must be driven by the participation of industrial partners. According to a study by Díaz et al. *(22)*, the development of biotechnology companies follows one of the following three corporate approaches.

1. The creation of new, dedicated biotechnology firms (or start-ups), sometimes organized around the figure of an "entrepreneur-scientist."
2. The creation of new companies (or spin-offs) dedicated to biotechnology by established firms, based on preexisting industrial assets.
3. The diversification of preexisting industrial interests to incorporate biotechnology.

Established companies may diversify their interests in order to enter the biorefining sector. A good Canadian example of this is found in Tembec Ltd. of Quebec, which has created a division called Tembec Silvichemicals Group to process mill waste streams into value-added products, including lignosulfonates, bioethanol, and resins. In the United States, Archer Daniels Midland (ADM) is another example of the diversification approach, with its prototype biorefinery in Decatur, IL. Both Tembec and ADM have built the capacity within their operations that is required to operate a biorefining operation. Each company has access to excess biomass in the form of waste or residues from existing operations, and both have established markets for their existing products that could be exploited for new biorefinery outputs.

The spin-off approach, which is another method of diversifying corporate interests, has been used successfully with the Cargill-Dow Polymer LLC subsidiary in the United States. Cargill-Dow polymer LLC is a joint creation of Cargill Inc. and the Dow Chemical Company. Cargill-Dow LLC has developed a process to derive PLA from corn starch. PLA is a bioplastic that can replace many traditional, petroleum-derived polymers in industrial and consumer packaging. Cargill-Dow LLC has begun commercial production at a 140,000 t/yr operation in Blair, NE *(18)*, and anticipates opening future plants about every 2 yr. The combination of an agricultural or biomass-based company with a major chemical producer creates the necessary natural and human capital for successful biorefining.

Iogen Inc. of Ottawa is representative of the start-up approach to commercialization, having begun operations more than 20 yr ago. Its strategy has been unique in that it has focused on value-added products from its operation to sustain the development of lower-value commodity products such as biofuels. Today, it has established itself as an enzyme supplier and is one of only a few companies that are on the verge of commercializing bioethanol production from lignocellulosic feedstocks *(18,23)*. The biomass feedstock under consideration by Iogen includes agricultural residues, namely wheat straw, as well as grass grown as an energy crop. Throughout much of its corporate history, Iogen has benefited from the Canadian government's goal to increase bioethanol production capacity, a goal that has become more critical after Canada ratified the Kyoto Protocol in 2003. Over time, Iogen has built working partnerships with several major corporate interests in order to connect with the distributors of fuel products and, ultimately, the markets for these products. Petro-Canada has partnered with Iogen to build a demonstration plant for its process and is currently utilizing bioethanol from the Iogen process as an antiknock agent in gasoline. Royal Dutch Shell has also supported the development of the Iogen process.

National Strategies

Meeting national strategies has been described as one of four primary mechanisms for successfully commercializing biotechnology, based on a review of companies operating in a variety of European and North American countries *(22)*. One priority, responses to perceived changes in climate, will influence the resource sectors most closely linked to the biorefinery concept, including energy, agriculture, and forestry. Climate change is the driver behind many of the policies that influence the actions taken by these sectors, including the Kyoto Protocol, which has been ratified by Canada and many European countries, and the Clean Skies Initiative, which has been implemented in the United States. By utilizing these policies to support development of the biorefinery, governments have the potential to create new opportunities for employment and government revenues while responding to climate change. As an example, bioethanol generation in the United States has created an estimated 200,000 jobs and $500 million in annual tax receipts *(4)*, which has led to the investment of more than $985 million (US$) over the past 3 yr toward biorefinery research.

Bioproducts generated through a biorefinery process may also be utilized as tools for increasing energy and economic security. There is a pressing need to reduce dependence on foreign energy supplies, because these supplies may be threatened by conflict, as evidenced by the second Gulf War in the Middle East. A secure, renewable energy supply is also required to support long-term economic development.

Canadian governments, both federally and provincially, lack an integrated political vision or strategy for implementing the biorefinery that addresses all of these goals. This is not to say that there is no understanding of the potential of this technology in Canadian administrations. Governments are promoting the progress of the biorefinery through the mechanism of product-specific policy and industry-government partnerships. A positive example of product-specific policy is the federal Ethanol Expansion Program (EEP), which is investing $78 million Canadian (CDN) in added ethanol capacity across the country *(24).* Other key Canadian federal policies supporting biofuel development include the Future Fuels Initiative; the Transportation Energy Technologies Program; and the newly created Climate Change Technology Development and Innovation Program, which allocates $19 million CDN over 5 yr to promote emissions reduction technology. Biofuel use is also supported through the FleetWise and Fleet$mart programs *(25).*

Canadian governments have shown considerable support for an industry-led approach to development of the bioproducts sector. There are significant Canadian efforts toward developing and promoting this sector, both at the national level and within specific provinces, including British Columbia, Alberta, Saskatchewan, Ontario, Quebec, and the Maritimes. A drawback to the existence of multiple efforts in jurisdictions across the country is that provincial initiatives are not necessarily coordinated with each other, although duplication of efforts is reduced by mechanisms such as the Federal-Provincial-Territorial Working Group Under Ministers of Energy and the Environment. Provincial policies are more likely to be related to national programs such as the EEP, in part owing to the existence of matching-funds programs that require coordination between Ottawa and the provinces. Strengthened coordination may be necessary between provincial strategies and federal visions for the biorefining sector.

Methods

To determine the effectiveness of the Canadian approach to nurturing the biorefining sector, the participants in the Canadian development of bioproducts, biofuels, and bioenergy were examined. A comprehensive database of these participants was created by examining lists generated by the national and provincial initiatives that we have described, as well as through consultation with various members of government at the federal and provincial level. These participants were categorized according to the feedstocks that they used: agricultural, forestry, fisheries, or urban waste–derived feedstocks. Where applicable, the elements of the sugar-based biorefinery platform that they were investigating were recorded. It should be noted that many participants were involved in single-stream product recovery, rather than investment in a platform that could provide multiple products. Each participant was identified and categorized by its position in the sector. Categories applied included governments and nongovernment organizations involved in sector development, public and private research groups, emerging companies (including start-ups and spin-offs), and established commercial interests.

By applying this methodology, 187 participants in the Canadian bioproducts industry were identified. Of these organizations, 20 were involved in sector development, either in the form of the provincial initiatives already described, or as consultants who work specifically on bioproducts. Eighteen research-oriented groups were identified, including universities and other private or public research laboratories. A further 46 organizations were established companies representing a variety of sectors, including agriculture, chemical production, and forestry. Only 6 organizations were recognized as spin-offs of existing corporate interests, and a further 97 start-up companies were identified, for a grand total of 103 emerging industrial participants. This list should be considered representative of a selection of the interested participants in Canadian bioproducts.

Results and Discussion

Canadian Biomass Feedstock Interests and Availability

The feedstock available for biorefining has a strong influence on the selection and operation of process elements for the facility. Figure 2 illustrates the number of participants who expressed interest in biomass from agricultural crops, forests, fisheries, or urban residues. In the left-hand pie chart, all participants in the Canadian bioproducts industry are categorized. In the right-hand pie chart, the interests of research-oriented participants are shown. It can be seen from the left-hand pie chart that the most important biomass type considered by the Canadian bioproducts sector is agricultural in origin. This is primarily owing to the number of

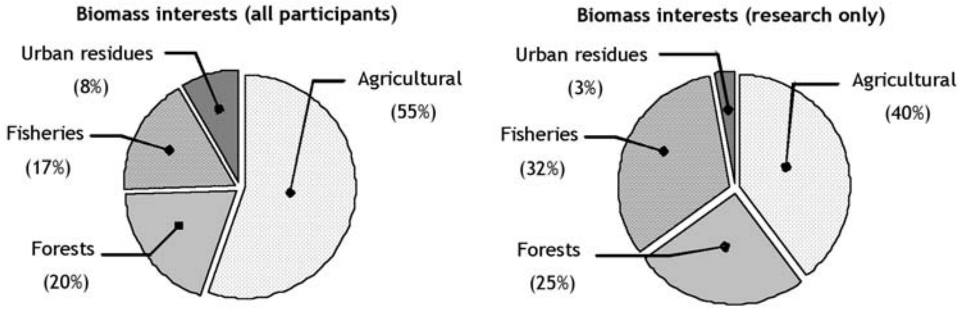

Fig. 2. Biomass interests for Canadian bioproducts sector (total and research).

feedstock-specific products associated with agricultural crops, including starches and oils, as well as the existence of competitive commercial processes to refine these products.

Because the majority of commercial bioproducts operations related to terrestrial biomass are working on starch or oilseed processing, it makes sense that the majority of attention is given to these materials. As the process improves, however, it will gain the ability to handle lignocellulosic material, which may take the form of residues. By analyzing both international and national data sets, it can be deduced that about 37 million t of cereal and oilseed crops are produced in Canada, generating about 5.3 million t of agricultural residues in Canada annually, approx 80% of which is located in the western provinces of Manitoba, Alberta, and Saskatchewan *(26–30)*. A further 4.1 million t of forest residues, generated from harvesting and manufacturing operations, may be available for further processing. More than 50% of this material is generated in the four western provinces *(9,28,29,31–33)*. Although forest biomass represents almost half of the available biomass for biorefining in Canada today, only 20% of the participants in bioproduct development currently express an interest in utilizing this material. This indicates an opportunity for increased participation for the forest industry.

It may be speculated that a progression will take place, as facilities that process agricultural feedstock for sugars and starches add the capability of converting the lignocellulosic components of their biomass. When proven commercially, the process will then be adapted to process forest biomass. This speculation is supported by observing the interests of the research community in bioproducts. It was noted that agricultural biomass remains the primary feedstock of interest, with 40% of researchers investigating this material. Proportionally, a greater percentage of researchers are interested in forest biomass (25%) and fisheries biomass (32%) when compared to the current structure of the overall sector. Interestingly, only 3% of researchers are concentrating on urban waste, which indicates that interest in this source of biomass for bioproducts may be on the wane. These findings indicate that research is slowly leading a progression in the carbohydrate platform from the starch-based bioproducts derived from dedicated agricultural crops toward a process that may handle lignocellulosic-based feedstocks. In addition, the oil and fiber platforms will undergo their own evolution and provide products that are complementary to the carbohydrate platform.

Development of Canadian Bioproducts

In Fig. 3, the Canadian industry is characterized in a histogram that indicates the number of sector participants working in the areas of biomass supply, biorefinery platform development, as well as bioproducts research and manufacture. These interests are further characterized by the number of established and emerging companies, as well as the number of research organizations. Finally, some of the regional differences across Canada are highlighted by isolating the four western canadian provinces.

It can be seen from Fig. 3 that the number of companies that might act as potential biomass suppliers to the biorefinery remains relatively low. The scarcity of suppliers of feedstock represents a significant challenge for the Canadian biorefining industry. By far, the most intensive focus of the sector today is the fractionation of product streams. This interest is matched by corporate investment in gasification or pyrolysis systems, which are largely being used today for bioenergy production. For most of the fundamental elements of the sugar-based bioconversion process, research is ongoing with little industrial activity at this point. Note that for the biorefining sector, research and corporate activities are represented proportionally within western Canada.

As shown in Fig. 3, the primary interests of the sector fall in the development of new, value-added products. Industrial interest from both emerging and established companies was primarily directed toward biochemicals, nutraceuticals, biocomposites, and vegetable or bio-oils. Of these product categories, only the latter is highly feedstock specific, requiring the input of oilseed plant biomass. The three other products may be generated through a sugar-based biorefining platform. Industrial interest in the area of biofuels, which combines both biodiesel and bioethanol, is also significant. It was found that interest in bioenergy is relatively low and is being pursued largely by emerging corporate entities. Product categories that are currently receiving the majority of research focus include biochemicals, nutraceuticals, biodiesel and bioethanol, protein and enzyme development, and biofertilizers. For many of these bioproducts, biorefineries should be the preferred mechanism for production because of the need to integrate lower-value commodity production with other, higher-value outputs. Figure 3 also illustrates the relatively small proportion of development that is occurring in the western provinces, which is the source of much of the biomass. A federal strategy for the biorefining sector must take steps to balance this inequity.

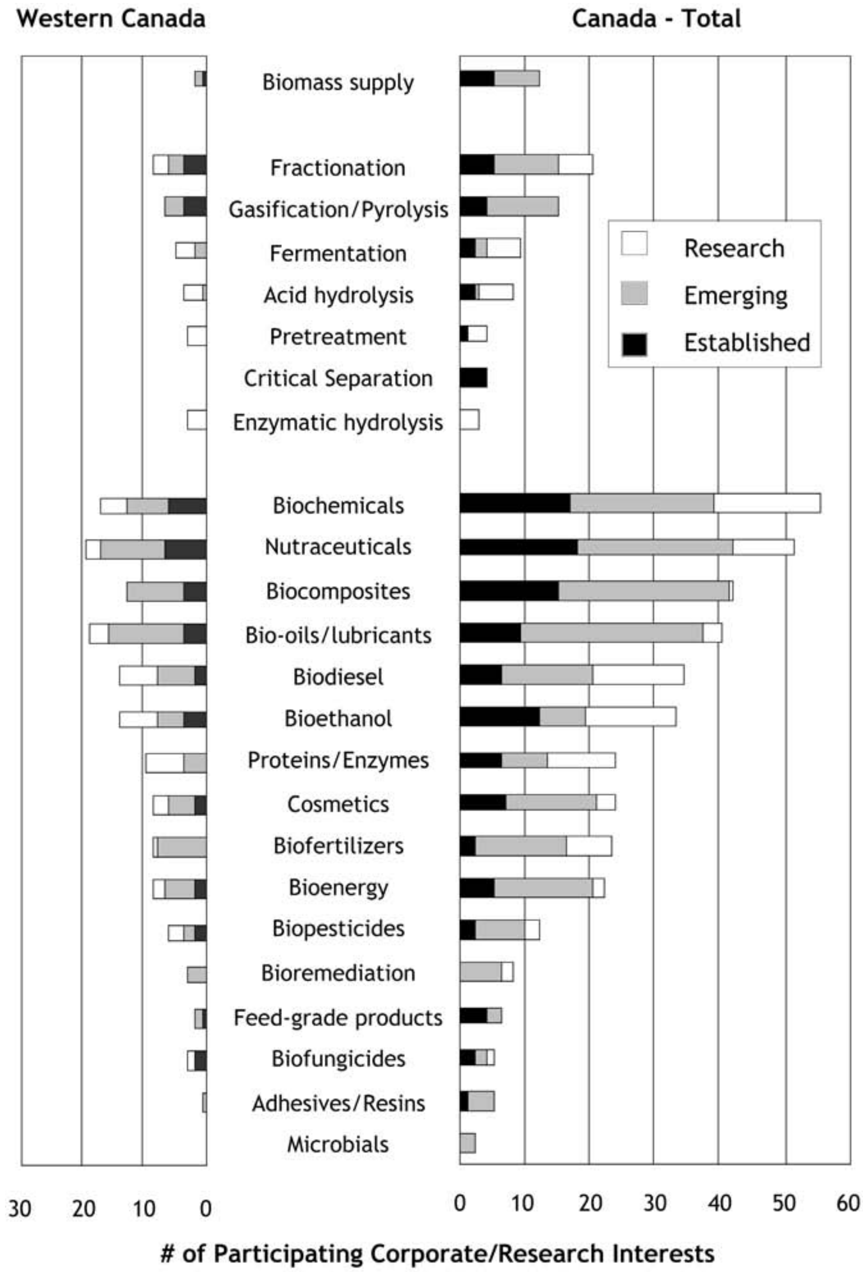

Fig. 3. Participating corporate and research interests in bioproducts development, Canada and western Canada.

Recommendations for a Canadian National Strategy

Canada could benefit from a more integrated national strategy that views the biorefinery as a tool for addressing issues of security, economy, and environment. A comparison with the United States may prove helpful in devising such a strategy. In the United States, two agencies have become the primary implementing bodies for policies related to biorefineries. The Department of Agriculture has a mandate to increase rural employment, diversify agricultural economies, and stimulate rural development by harnessing crops and crop residues. The Department of Energy has a mandate to diversify the energy supply, expand the availability of renewable energy resources, and develop new technologies to exploit renewables in all forms.

The American vision for developing the biorefinery for the agricultural and forestry sectors was released late in 2002. It provides a detailed road map for the implementation of bioenergy, biofuels, and bioproducts. The U.S. approach promotes public-private partnerships with major development goals targeted in the categories of feedstock production, biomass processing, and bioconversion, particularly of lignocellulosics. It also covers product uses, distribution, and markets. From yr 4 until yr 10, a period of testing and demonstration of biorefinery is anticipated. The planned result is widespread implementation and commercialization of biorefineries in about 10 yr *(21,34)*. Of course, early adoption of the biorefinery concept has begun in the United States, with facilities being operated by ADM in Decatur, IL, as well as Cargill-Dow's operation.

In Canada, full implementation of the biorefinery concept has not happened beyond the pilot scale, perhaps owing to the lack of clear national directives in biorefinery development. Vision documents such as the Saskatchewan Hibernia (Ethanol) Strategy do describe the key players that must be involved in launching the concept. In the public sector, all levels of government—First Nations, municipal, provincial, and federal—must be involved in supporting a biorefinery approach. At the local level, governments must work to make industry welcome. These governments should be proactive in identifying partners and making strategic connections. At the provincial level, it is necessary to make connections with neighboring jurisdictions, as well as with the federal government. It is important to recognize the powerful role that provinces play in developing their own unique strategies, and the federal role in coordinating these strategies.

Conclusion

The technology for the bioconversion of lignocellulosics is rapidly approaching commercialization and an opportunity exists to expand biorefining ventures in Canada. Canadian forest biomass represents about half of the available feedstock for biorefining but is not yet widely represented in biorefining initiatives. The majority of available biomass, forest and agricultural, is located in the four western provinces, but the relatively low portion of product development that is currently occurring in the western part of the country does not correspond to the amount of biomass that is available.

An opportunity exists for the federal Canadian government, together with its provincial counterparts, to implement policy that supports lignocellulosic-based biorefining efforts. In particular, national policy should be designed to complement provincial approaches, and to support western Canadian biorefining initiatives. There are many positive reasons to create this type of policy. Biorefineries based on lignocellulosics will be able to access a much wider variety of feedstocks, including forest biomass. Successfully doing so will increase security of supply and improve the ability of biorefineries to support a transition to a carbohydrate-based economy. The dependence of bioproducts on specific feedstocks becomes less significant as the complexity of the process increases; thus, biorefineries that rely on lignocellulosic material can utilize a more diverse selection of biomass.

In developing policy to support biorefineries, the Canadian government would do well to consider the primary business templates that are utilized by different biotechnology sectors. Various approaches have been applied successfully to biorefineries. Technology to support biorefining platforms has been incubated in both public and private-sector research institutions and in small, start-up companies and then adopted by larger companies through diversification of their product base or through creation of a new corporate entity. Thus, the pattern of start-up to spin-off or diversifying industrial interests may be seen as a progression rather than a differentiation. A Canadian strategy must support the development of the biorefining sector through each stage of its progression by coordinating provincial and federal efforts, and concentrating on linking biomass suppliers with technology providers.

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