



ADVANCED BIOFUELS: THE EVOLUTION OF INTERNATIONAL RESEARCH NETWORKS¹

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Abstract: Alternative fuels for transportation are gaining momentum in the global market. Ethanol has been the most used biofuel as an additive and as a substitute for gasoline in a number of countries. Current technology to produce ethanol based on sugar and starch crops creates price imbalances in the food market and cannot supply a sustainable industry of ethanol in the long term. Second generation technologies based on cellulose-based feedstocks use non-edible crops and have a positive energy balance. Notwithstanding, they are not yet economic at the industrial level, requiring investment in Research and Development (R&D) to help overcome technological barriers. Many countries recognise the value of collaboration to increase benefits and reduce costs of research, and some of them have in place policy instruments to promote this practice. Given the policy relevance, multidisciplinary characteristics of biofuels, and increasing incentives towards international cooperation, the monitoring of the evolution and patterns of international collaboration in R&D is in place. We map the evolution of the global scientific activity of research on cellulosic ethanol. We carry out a bibliometric analysis by building a publication dataset drawn from the ISI Thompson Science Citation Index database covering the period between 1970 and 2006. We identify the most productive institutions and countries, their historical evolution and interaction patterns.

Keywords: cellulosic ethanol; biofuels; international collaboration; energy; Research and Development; R&D.

INTRODUCTION AND BACKGROUND

Biofuels for transportation are gaining momentum in the global policy scenario. Main factors driving growing production of biofuels include geopolitical instability in oil producing countries, increased energy

demand in China and India, and environmental concerns over the consequences of intense fossil fuel consumption (Bettelheim, 2006; U.S.DOE, 2007). Ethanol has been the biofuel most used as an octane enhancer and as a substitute of gasoline in a number

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of countries. Current ethanol production uses conventional food crops that also supply the global feed and food markets. The growing demand of biofuels raises concerns over the long term impact over food prices, and the sustainability of intense use of land, water, among other environmental implications (Ragauskas et al., 2006; Royal Society, 2008; Science, 2007).

There is general recognition that biofuels using conventional food crops and first generation technologies are not the sustainable solution to supply the long term demands of global energy (Science, 2007; Solomon et al., 2007), and some countries have designed specific policies that provide incentives towards developing research on second generation technologies using cellulose-based materials (DOE, 2007; EU-EC, 2007; U.S.BRDI, 2007). The European Union 7th Research Framework devotes one of its themes to research on biomass and sustainable biofuels, a continuation of the project 'New Improvements for Ligno-cellulosic Ethanol' (NILE) carried out by the 6th Framework Program (EUREC, 2008). In the USA, research on cellulose-based ethanol has been supported by the 'Biomass Research and Development Initiative' (BRDI), a multiagency effort in collaboration with academia and industry that coordinates research in bioenergy (U.S.BRDI, 2007).

Already explored for many years, the technology to produce cellulosic ethanol presents technological and economic challenges. There is general agreement that in order to achieve sustainable efficiency throughout the whole supply chain, public and private Research and Development (R&D) must build capacity in fundamental areas of knowledge (Royal Society, 2008; Wyman, 2003). To achieve the production of cellulosic ethanol that is competitive at

the industrial scale, research must overcome a number of challenges:

- 1 maximising the energy crop yield per hectare with minimal environmental impact;
- 2 developing sustainable energy crops;
- 3 improving efficiency in the process of breaking down ligno-cellulose materials into sugars;
- 4 developing enzymes and microbes that facilitate the degradation of lignocellulose and the fermentation to ethanol;
- 5 developing systems to integrate the supply chain;
- 6 developing efficient biorefineries and
- 7 creating advanced techniques to assess the sustainability of the biofuels industry.

Those demands in research require expertise in many different areas of knowledge, leading the scientific community to engage in different patterns of collaboration (Interacademy Council, 2007; Royal Society, 2008; U.S.BRDI, 2007).

The process of technological change for many energy technologies is long, requiring a portfolio of instruments to maximise the cost-benefit ratio of investments in Research and Development (R&D). By expediting the process of learning, international collaboration can decrease risks of early stage research, may increase the exchange of knowledge and reduce operational costs by facilitating the harmonisation of standards (Justus and Philibert, 2005). Most OECD countries recognise the value of collaboration in research activities. International collaboration is an integral part of European Science and Technology policy. Under the European Union 7th Research Framework Program, around 60% of funding has been

devoted to cooperation among universities, industry and research centres, at the national and at the international level. The goal is to strengthen research capacity and knowledge exchange to promote sustainable and competitive economic growth. The initiative focuses on multidisciplinary areas that require expertise from the various fields of science and technology. Some areas benefiting from such programs include agriculture, food, energy, transportation, environmental sciences and biotechnology, among others (EU-EC, 2007).

International collaboration in science and technology has also been part of the USA foreign policy since 1999, when the President's Committee of Advisors on Science and Technology (PCAST) has underlined in the report 'Powerful Partnerships' the critical role of international cooperation in energy innovation to strengthen the country's national interest (PCAST, 1999).

Given the policy relevance, multidisciplinary characteristics of biofuels, and increasing incentives towards international cooperation, the monitoring of the evolution and patterns of international collaboration in R&D is in place. Our research goal is to map the evolution of the global scientific activity of research on cellulosic ethanol. We carry out a bibliometric analysis by building a publication dataset drawn from the Thompson ISI Web of Knowledge Science Citation Index database covering the period between 1970 and 2006. We identify the most productive institutions and countries, their historical evolution and interaction patterns. We expect to find a growing pattern of international scientific collaboration. The remainder of this paper describes the methodology to be used, and presents the results, identifying the major institutions and countries active in the research.

METHODOLOGY

In order to build the dataset we draw on records from the Science Citation Index database, covering the period between 1970 and 2006. We set a search strategy targeted to gather publications involving cellulosic ethanol topics, looking for records including the following concepts: ethanol, cellulose, hemicellulose and biomass. We use truncated terms for cellulose and hemicellulose concepts. The search is structured using ethanol as the main term and the rest as secondary terms according to the following scheme:

(Ethanol) AND (cellulos OR hemicellulos* OR biomass)*

We download the SCI dataset into a text-mining software in order to analyse and group the data by year, country and affiliation.

RESULTS

The search brings up a dataset with 3203 publications. Figure 1 reveals a clear upward trend along the period covered. However, we note a major increase in the beginning of the 1990s. While just 4% of research was published before 1990, 47% and 49% of this papers were published during the 1990–1999 and 2000–2006 periods, respectively.

Consistent with the increased pattern of international collaboration in Science and Engineering (S&E) research (NSB, 2008), there is a positive trend in international collaboration among countries doing research in cellulosic ethanol. Figure 2 shows that after 1999, the level of collaboration is more intense when compared to previous years.

Figure 3 shows the contrasting behaviour among the USA, France and China on international collaboration during the last 13 years. While France follows a clear pattern of interaction with international players, China

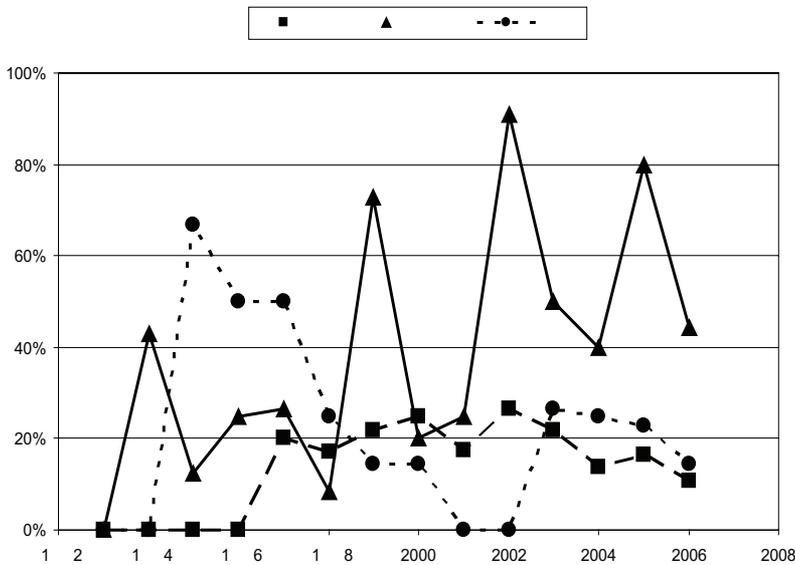


Figure 3 Annual Participation in International Collaboration

Source: Own Authors from SCL.

80% of articles published between 1996 and 2006 in forestry were originated in institutions from developed countries, 75% of publications in WSS during the 1996–2005 period came from the rich world (Catalán et al., 2008; Cozzens and Catalán, 2007;). For both fields, the US remains the most prolific country, with shares of publication higher than the ones found for cellulosic ethanol. Over 27 in forestry and 29% of articles in WSS were written by researchers from US institutions. Canada, the third in publication in cellulosic ethanol, has been the second most prolific country in research in forestry, with 8% of papers published in the field between 1996 and 2006.

Table 1 provides the 20 most prolific countries in cellulosic ethanol research. Most of the countries are either important energy producers/consumers (e.g. USA, Germany, France, UK, China and India) or rich in forestry resources (e.g. USA, Canada, Brazil, Sweden and Spain). China, India and Brazil, emerging economies active

in R&D in cellulose-based ethanol, are also prolific in the field of forestry (Catalán et al., 2008).

In Figure 4, we present the number of publications for the USA, Japan, Canada, the top three countries and China along the 1990–2006 period. The graph shows a growing pattern of publication for all countries. However, the US performance stands out in light of its significant take off in the mid-1990s, 2002 and 2005. The first one may be interpreted as a lagging result of the enactment of the Clean Air Act Amendments of 1990 mandating the use of oxygenated gasoline in non-attainment areas, spurring demand for ethanol. More aggressive federal funding came after 2000 with the Biomass R&D Act of 2000 (Yacobucci, 2007). China is another case to be highlighted. Since the beginning of the 21st century, China’s number of publications has steadily increased becoming by 2006 the most important publishing country after the US. Brazil is another developing

Table I Top 20 countries

Country	NB of PUB	Share (%)
USA	477	14.89
Japan	218	6.81
Canada	165	5.15
Brazil	152	4.75
France	152	4.75
Spain	145	4.53
China	144	4.50
UK	133	4.15
India	131	4.09
Sweden	131	4.09
Germany	98	3.06
Italy	82	2.56
Netherlands	76	2.37
South Korea	75	2.34
Denmark	63	1.97
Greece	58	1.81
Turkey	49	1.53
Australia	47	1.47
Portugal	44	1.37
Switzerland	43	1.34

Source: Own Authors from SCL.

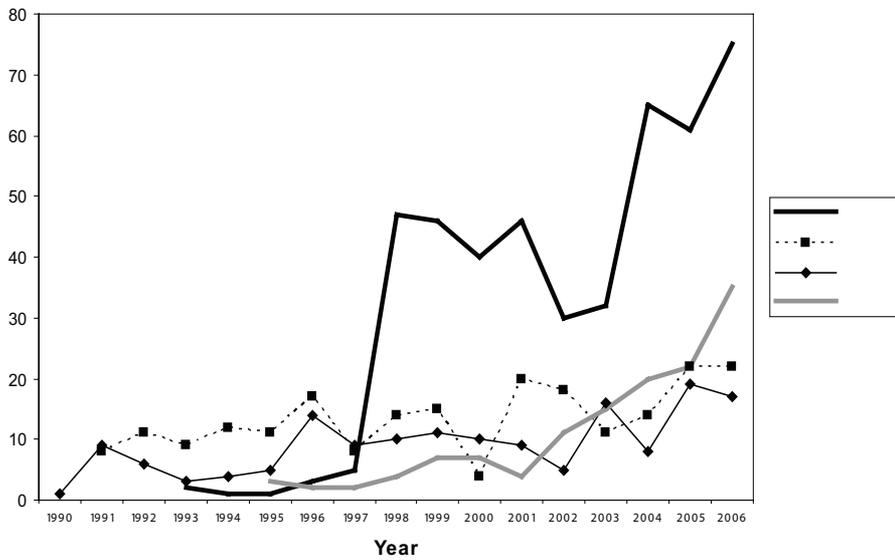


Figure 4 Top 3 countries and China

Source: Own Authors from SCL.

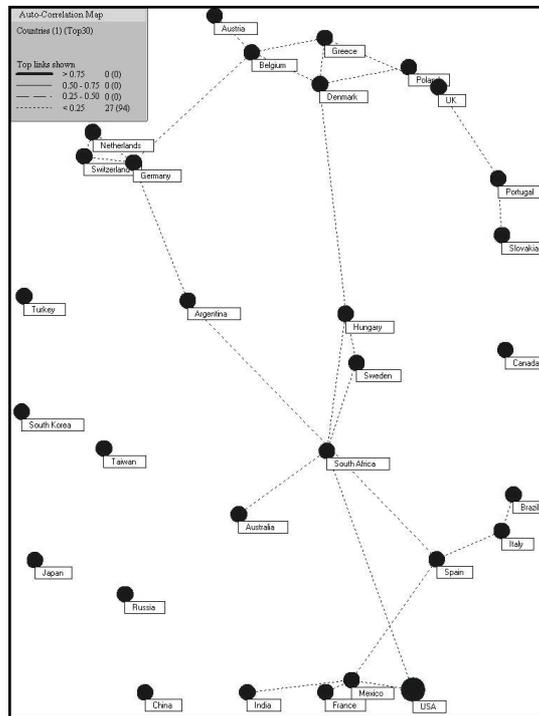


Figure 5 Map Top 30 countries

Source: Own Author from SCI

country pursuing research on cellulosic ethanol from sugarcane bagasse, a subproduct of ethanol produced using first generation technology.

Figure 5 presents a country interaction map, where countries are represented by nodes. The node's size indicates the publication productivity of each country: the larger the node, the greater the publication productivity of the country. The links among nodes indicate the strength of the interaction, or the intensity in the collaboration (measured by co-authorship) between authors coming from two different countries. Each link is associated with a numerical value equal to the quotient between the number of publications co-authored by authors coming from the two countries in reference and the sum of the total number

of publications of each country. Further, the spatial distribution among nodes reveals the scientific bond between countries. The closer two nodes are from each other, the stronger the interaction between the countries represented by the nodes. The country map represents interactions having a minimum strength value. For example, research collaboration between the USA and Brazil, the two largest producers of ethanol, is not strong enough to be taken into account by the country map.

The map reveals different patterns of interaction. European countries show a clear network pattern of collaboration (see Figure 5). Meanwhile the USA, Canada and some of the Asian countries do not present such networking behaviour tending to be involved either on weaker networks (e.g. USA)

Table 2 Top 20 Institutions

Institution	Number of publications
Lund University, Sweden	74
National Renewable energy Laboratory, USA	67
USDA, USA	66
Technological University of Denmark, Denmark	47
Dartmouth College, USA	46
University of Sao Paulo, Brazil	43
University of Florida, USA	42
Purdue University, USA	41
University of British Columbia, Canada	36
University of Vigo, Spain	35
Chinese Academy of Science, China	30
Delft University of Technology, The Netherlands	29
Russian Academy of Science, Russia	28
Chemical Engineering College, Lorena, Brazil	27
University of Patras, Greece	26
University of Ulster, UK	24
Inst Nat Res Agr, France	22
Virginia Tech, USA	21
Michigan State University, USA	20
University of Toronto, Canada	20
Chalmers University of Technology, Sweden	19
University of Genoa, Italy	19
University of Wisconsin, USA	18
Indian Institute of Technology, India	17
Kyoto University, Japan	17
Oak Ridge National Laboratory, USA	17
Riso National Laboratory, Denmark	17
Zhejiang University, China	17
National Technological University Athens, Greece	16
University of Tokyo, Japan	15

Source: Own Authors from SCI.

or act under more individualistic approaches (e.g. Canada, Japan and China). The pattern of collaboration for the US is not specific to the field of cellulosic ethanol. Previous analyses on forestry and WSS identify a similar US research collaborative pattern (Catalán et al., 2008; Cozzens and Catalán, 2007).

Affiliation

Lund University of Sweden is the most prolific organisation worldwide. Among the Top30 Publication Producer Institutions 9 are Americans, namely the Department of Agriculture (USDA), the National Renewable

Energy Laboratory (NREL) and a pool of universities led by Dartmouth College, University of Florida and Purdue University among others (see Table 2). Only two institutions from developing countries are on the list: the University of Sao Paulo, Brazil and the Zhejiang University, China. We exclude the Chinese Academy of Science since such label includes more than one Chinese institution. The pattern of collaboration among institutions supports some previous analysis by country, and confirms that while the interaction pattern among American institutions is intense, it is less so with foreign organisations (see Figure 6). With the exception

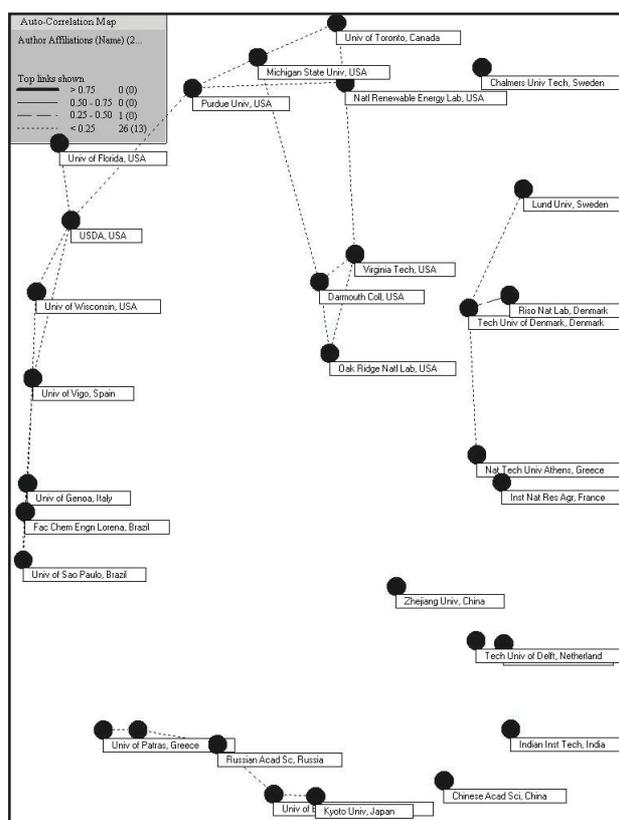


Figure 6 Map Top 30 institutions

Source: Own Authors from SCI.

of Scandinavian organizations which seem to be involved in setting up strong research links with other institutions, the pattern of collaboration among Europeans is not so strong when compared to the pattern of collaboration among American institutions. The collaboration between American and Brazilian institutions was strong enough and taken into account by the map.

CONCLUSION

As we hypothesised, there is a growing trend of research collaboration in cellulosic ethanol at the international level. However, patterns vary by country. While US players have adopted a more inward approach

and seem to cooperate more with other American actors, European countries such as France cooperate aggressively with international players in research. As presented, the pattern of collaboration is similar to other research fields, such as forestry and WSS. China has been an important player in the global R&D network. However more research is needed to understand change in Chinese patterns of collaboration.

The analysis allows one to make the following points. Firstly, the scientific productivity measured as number of publications has significantly increased during the last 15 years. Although our analysis does not provide any causal evidence, some possible factors contributing to this trend may include

public policies promoting cellulosic ethanol research and mandating the production of alternative transport fuels in a number of countries. Secondly, developed nations are the ones driving research in the area with the exception of Brazil and China. Furthermore, countries have followed different approaches regarding working methods: whereas European countries seem to be involved in strong research networks, nations such as the USA, Canada and Japan tend to interact less with other countries. Finally, in the case of the US, there is a strong pattern of research collaboration among American institutions, with intense interaction among universities and government research laboratories.

Given the policy relevance and increasing funding towards research in this area, we believe that bibliometric studies serve as a useful tool to map research, identify complementarities, and guide potential collaboration. Future research combining bibliometric studies with information on policies and research funding in major countries might be an interesting area of investigation to evaluate public policies aimed to promote R&D in cellulosic ethanol.

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BIOGRAPHY

Pablo Catalan is a Doctoral Candidate pursuing a degree in Public Policy with a major in Science, Technology and Innovation, and a minor in Management of Technology. Before coming to Georgia Tech, Pablo worked at the Directorate of Strategic Studies of the University of Concepcion (UdeC) in Chile, and was part of the Organizing Committee of the Global Biotechnology Forum held in Concepcion in March 2004 organized by the United Nations Industrial Development Organization (UNIDO) and the National Chilean Government. At the Technology Policy Assessment Center (TPAC) at Georgia Tech, he has been involved in an NSF-funded project to identify innovative dynamics in the water supply and sanitation at global level by means of case studies in Mozambique, South Africa, Costa Rica, and Mexico; and a project funded by Chile's National Commission of Science and Technology to determine patterns ruling technology diffusion in the Chilean Forestry Industry.

Elena Berger is a Doctoral Candidate pursuing a degree in Public Policy with a major in Science, Technology and Innovation and a minor in energy policy. She has been working for the Technology Policy Assessment Center (TPAC) at Georgia Tech on a project exploring the dynamics of international research collaboration. Her dissertation research compares the innovation in the ethanol sector between the US and Brazil. She applies the concept of functions of innovation systems to map the innovation process of ethanol during the last thirty years. Before joining Georgia Tech, she has worked as business consultant in the US. Elena has an MSc in International Affairs and Certificates of International Business and European Studies from Georgia Tech as well as a BA in Chemical Engineering from the University of Sao Paulo, Brazil.

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NOTE

- ¹ A previous version of this paper is published in World Association for Sustainable Development Conference Proceedings 2008, Editor Allam Ahmed, Brighton, UK, August 2008.

