Cellulosic Ethanol: The Evolution of Patterns of Collaboration in Research and Development (R&D)

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Abstract: Alternative fuels for transportation are gaining momentum in the global market. Current technology to produce ethanol based on sugar and starch crops is not sustainable 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 at commercial stage, requiring more research and development (R&D) to help overcome technological barriers. Many countries recognize the value of collaboration to increase benefits and reduce costs of research, and some have in place policy instruments to promote this practice. Given the policy relevance, the monitoring of the evolution and patterns of international collaboration in R&D is in place. 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

1 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 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 United States, research on cellulose-based ethanol has been supported by the "Biomass Research and Development Initiative" (BRDI), a multi-agency 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 R&D must build capacity in fundamental areas of knowledge (Wyman, 2003, Royal Sociey, 2008). To achieve the production of cellulosic ethanol that is competitive at the industrial scale, research must overcome a number of challenges: (1) maximizing 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 Sociey, 2008, U.S.BRDI, 2007).

The process of technological change for many energy technologies is long, requiring a portfolio of instruments to maximize the cost-benefit ratio of investments in research and development. 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 harmonization of standards (Justus and Philibert, 2005). Most OECD countries recognize 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 centers, 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 United States 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.

2 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 analyze and group the data by year, country, and affiliation.

3 Results

The search brings up a dataset with 3,203 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 percent of

research was published before 1990, 47 and 49 percent of the papers were published during the 1990-99 and 2000-06 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 behavior among the U.S., France, and China on international collaboration during the last thirteen years. While France follows a clear pattern of interaction with international players, China starts in a more international pattern to become, as the U.S., more inward centered.

3.1 Country

Developed nations make 70 percent of publications in cellulosic ethanol. The US is the main producer of publications, accounting for 15 percent of publications between 1970 and 2006, followed by Japan and

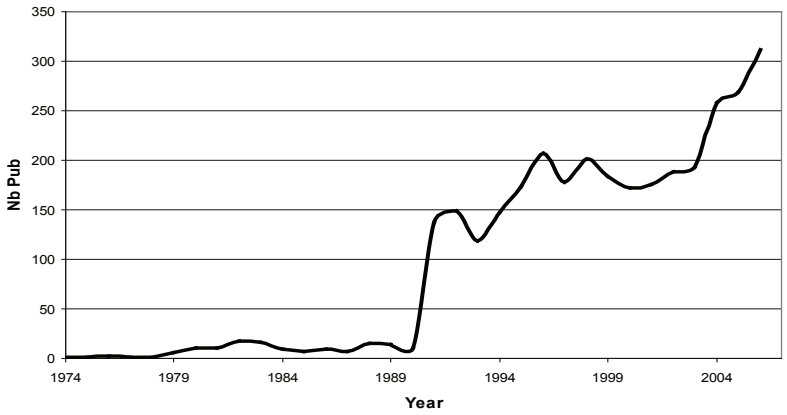

Figure 1 Number of Publications per year

Source: Own Authors from SCI

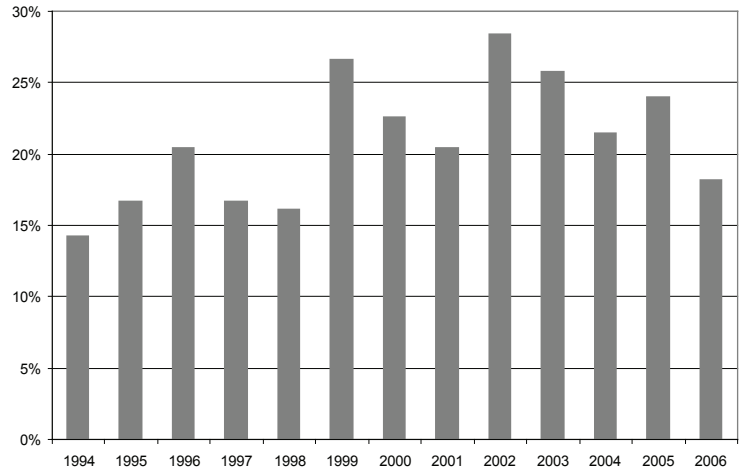

Figure 2 Publications of 6 most prolific countries with authors from multiple countries (a measure of international collaboration) as a share of total publications on cellulosic ethanol.

Source: Own Authors from SCI

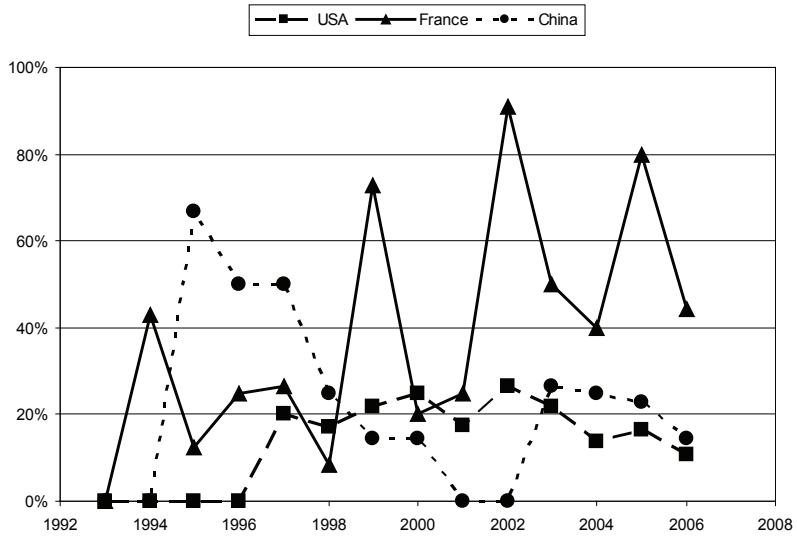

Figure 3 % Annual Participation in International Collaboration

Source: Own Authors from SCI

Canada with 7 and 5 percent respectively. However, the American dominance in the field is low compared to the overall S&E research output, from which the U.S. represented 29 percent of articles in 2005 (NSB, 2008).

We compare research output in cellulose-based ethanol with the fields of forestry and water supply sanitation (WSS). While over 80 percent of articles published between 1996 and 2006 in forestry were originated in institutions from developed countries, 75 percent of publications in WSS during the 1996-2005 period came from the rich world (Cozzens and Catalán, 2007, Catalán et al 2008). 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 percent of articles in WSS were written by researchers from U.S. institutions. Canada, the third in publication in cellulosic ethanol, has been the second most prolific country in research in forestry, with 8 percent of papers published in the field between 1996 and 2006.

Table 1 provides the twenty 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. US, 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 U.S., Japan, Canada, the top three countries, and China along the 1990-06 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 Research and Development 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 country pursuing research on cellulosic ethanol from sugarcane bagasse, a sub-product 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

Table 1 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 SCI

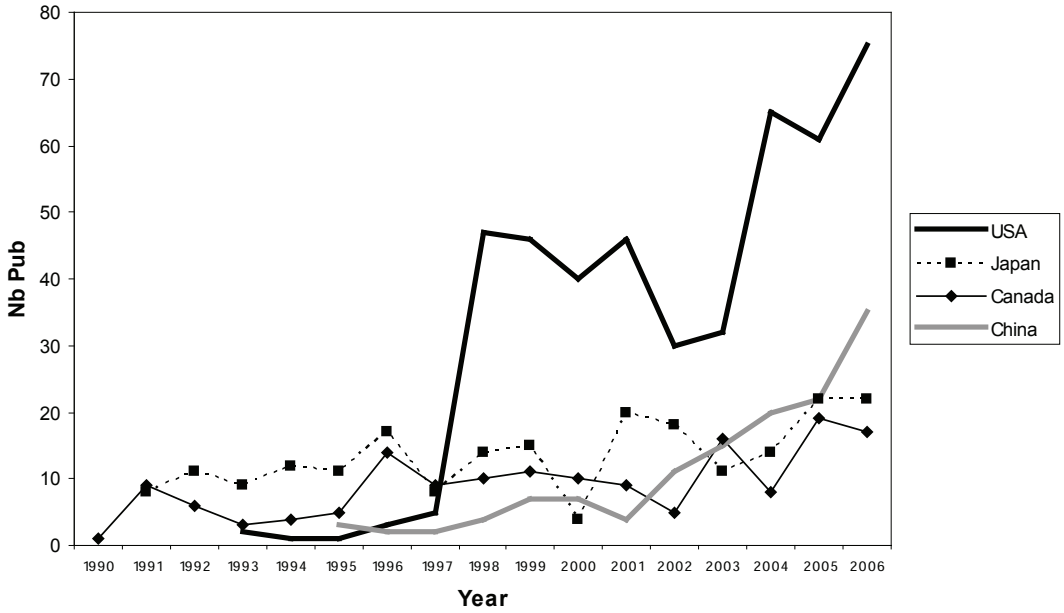

Figure 4 Top 3 countries and China
Source: Own Authors from SCI

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 U.S. 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 US, Canada, and some of the Asian countries do not present such networking behavior tending to be involved either on weaker networks (e.g. USA) or act under more individualistic approaches (e.g. Canada, Japan, and China). The pattern of collaboration for the U.S. 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).

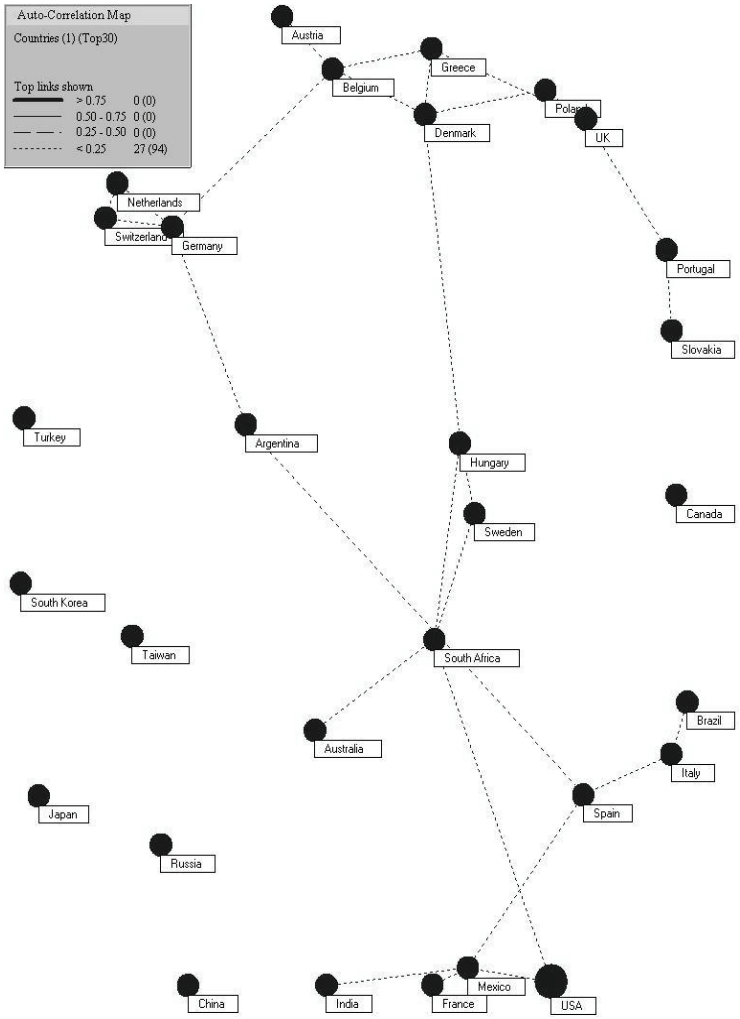

Figure 5 Map Top30 Countries

Source: Own Author from SCI

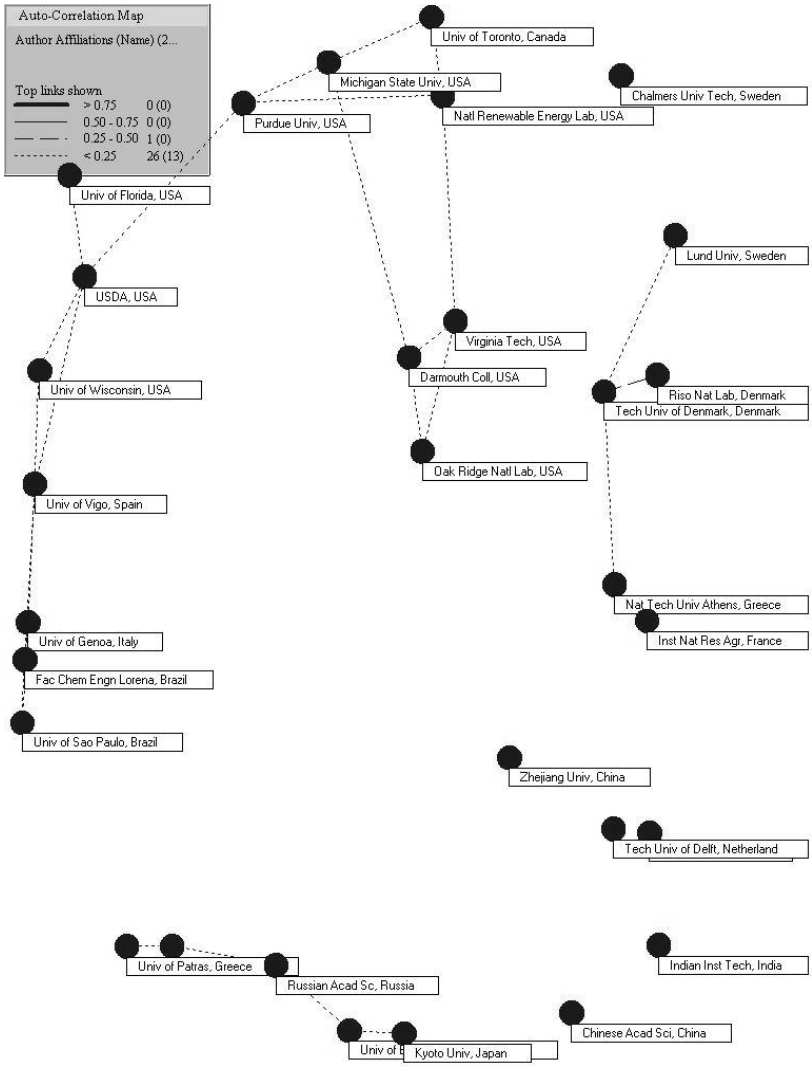

Figure 6 Map Top30 Institutions

Source: Own Authors from SCI

3.2 Affiliation

Lund University of Sweden is the most prolific organization 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 organizations (see Figure 6). With the exception 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.

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

4 Conclusion

As we hypothesized, there is a growing trend of research collaboration in cellulosic ethanol at the international level. However, patterns vary by country. While U.S. 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. First, the scientific productivity measured as number of publications has significantly increased during the last 15 years. Although our analysis doesn't 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. Second, 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 coun-

tries seem to be involved in strong research networks, nations such as the US, Canada and Japan tend to interact less with other countries. Third, 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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