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Patterns of innovation and organizational demography in emerging sustainable fields: an analysis of the chemical sector

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Abstract

This paper examines the eco-innovation dynamics in the chemical sector by analyzing Sustainable Chemistry (SC) technologies and the organizations that generated those technologies. First, we build an original dataset of patents and investigate trends emerging from patent statistics. Second, by using a clustering algorithm for the analysis of citation networks, we identify the main clusters of innovations that are driving the evolution of the field and analyze the demography of involved organizations. We found that SC is emerging slowly, and remains importantly concentrated in the US and in Europe. Public organizations, in particular US organizations, have played an important role in the development of the field. Relatively established and large chemical companies are the most active organizations and their continuity is more evident in the less recent clusters. However, there is some evidence, for the most recent years, of a greater importance of new and more specialized firms, often active in the clusters relating to biochemistry. Overall, our analysis suggests that the development of SC has stimulated the emergence of new organizations only in a partial way and in some specific sub-fields. This, as well as the relatively slow development of SC, may undermine the potential of SC to generate a radically new, and more sustainable, way of doing chemistry.

Keywords: Innovation dynamics; Industrial dynamics; Eco-innovation; Chemical sector; Sustainable Chemistry; Citation Network Analysis

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1. Introduction

In the last few years, eco-innovation has attracted considerable interest as it is considered one of the most important ways to face environmental pollution and resource depletion. Eco-innovation has been defined as the ability of firms to develop new methods, products and/or processes which benefit the environment and contribute to environmental sustainability (Rennings 2000). Eco-innovation also plays an important role in the definition of firms' innovative strategy, as developing more sustainable technologies is increasingly viewed not only as a way of complying with environmental regulation, but also as a source of competitiveness (the so-called green business) and a mean to improve public image of firms. However, eco-innovation often requires large investments and firms may be reluctant to engage in such investments because of the high uncertainty surrounding the technological and commercial potential of these emerging technologies.

In this context, the chemical industry has a leading role to play. This is indeed an important sector in many countries, in terms of both economic growth and employment, and its products, from oil to medicines, are widely spread. However, the chemical industry is also one of the biggest sources of pollution, environmental risk and hazard. It employs enormous amounts of polluting and nonrenewable feedstocks (i.e., petroleum), and produces toxic wastes; its products are often not degradable and it is responsible of many severe industrial accidents (e.g., Bhopal, Three Mile Island, etc.) that have contributed to create a bad reputation of the industry.

In spite of the importance of the chemical sector for environmental sustainability, little quantitative evidence has been provided for examining the eco-innovation dynamics in this sector[2]. The aim of this paper is to contribute to fill that gap by analyzing Sustainable Chemistry (SC) technologies and the organizations that generated those technologies. As a first step, we will try to answer a number of basic questions: 1) how can we identify and quantify SC? 2) What are the most important countries and organizations involved in the development of SC? 3) What are the main clusters of innovations that are driving the evolution of the field? Answers to those questions are relevant to assess the potential of SC to generate a more sustainable way of doing chemistry and to affect future industrial leadership in the sector, as well as to shed lights on the technological areas where organizations are focusing their innovative efforts.

As a second step, we analyze the networks of organizations that have contributed to the development of SC and ask ourselves whether or not there has been a change in the demographical characteristics of such organizations. With organizational demography we intend the organization type (public vs private organizations), the size, the age and the nationality. This question is relevant since the emergence of new organizations may involve the generation of radically new technological knowledge, which, in turn, may be of critical importance for the development of radically new eco-innovations. On the contrary, incumbents may hesitate to invest in radically new technologies because they focus their innovative strategy on mainstream consumers and established markets (Christensen 1997). During the long history of the chemical sector, major innovations have witnessed the emergence of new players, which have created new,

[2] To our knowledge, the only exception is the study by Nameroff et al. (2004), which nevertheless has a focus on the Green Chemistry approach.

larger or smaller, markets and have established networks with existing organizations (Cesaroni et al. 2004). However, by exploiting economies of scale and scope, large and established chemical companies have showed great continuity in their production and innovative activity (Oltra and Saint-Jean 2007).

In order to answer the mentioned questions, firstly we reviewed the specialized literature related to SC and interviewed a number of experts. On this basis, we identified SC technologies and built an original dataset of USPTO patents granted between 1971 and 2011 for those technologies. One of the reasons behind the lack of quantitative studies relating to SC relies in the difficulties posed by the selection of the relevant dataset of patents. Those difficulties are due to both the high heterogeneity of the chemical sector and the nature of emerging field of SC. Therefore, we put particular emphasis on the construction and validation of the patent dataset. The dataset has been created by combining keyword search with technological class search, and has been defined with the assistance of experts in the field. Secondly, we analyzed the main trends emerging from patent statistics, highlighting how SC evolved over time and spread among different technological areas, countries and organizations. Finally, we constructed a network of citations among SC patents and applied to it a clustering algorithm. That allowed us mapping the most important clusters of innovations of SC, and thus discussing both the areas where organizations are concentrating their research efforts and the characteristics of such organizations. The rest of the paper is organized as follow. Section 2 is an overview of the chemical sector and of the main SC technologies. Section 3 illustrates the data and methods. In section 4, we present and discuss the results of our empirical analysis. Section 5 concludes.

2. Background

2.1 The chemical sector

The chemical sector is an old, large and heterogeneous sector. Indeed, its origins date back to XIX century, with the emergence of British and German dyestuff manufacturers, and it is today one of the largest manufacturing industries in the US, in Europe and in Japan. As we will see below, the chemical industry has acquired a growing importance in many emerging countries as well, in particular China and India. The chemical sector is also highly heterogeneous. It is composed of at least four different subsectors (Gavrilescu and Chisti 2005): 1) basic chemicals, which include polymers, bulk petrochemicals and intermediates, and basic industrials; 2) life sciences products like pharmaceuticals, diagnostics products, and products of modern biotechnology; 3) specialty/fine chemicals, which comprise electronic chemicals, industrial gases, adhesives, coatings, industrial cleaning chemicals, catalysts; 4) consumer products including soaps, detergents, and cosmetics. Basic chemicals are low value-added products that are manufactured in massive quantities and are used to produce more sophisticated and differentiated products like life sciences products and specialty chemicals.

The chemical sector is a science-based and R&D intensive sector. Chemical innovation has always relied on the application of scientific knowledge to the discovering of new products and processes, e.g., the scientific understanding of the chemical structure of raw materials is used to synthetize new materials with better properties. For this reason, universities and public research centers have always played an important role in fuelling chemical innovation. As to private firms, the chemical sector has a long and important tradition of in-house R&D, which typically takes place in the laboratories of large, established, multinational firms. All the major technological innovations in the 1920s and 1930s – such as polystyrene, perspex, PVC, polyethylene, synthetic rubbers, nylon and other artificial fibres – were developed in the laboratories of large chemical companies, most of which still exist today (e.g., DuPont, Bayer, BASF, Hoechst) and are leading multinational companies (Cesaroni et al. 2004). Moreover, due to the high fixed costs of plants' setting and product development, the chemical sector is capital-intensive. As a consequence, it has high barriers to entry and exit.

In terms of market shares, in the last decade there have been important changes involving the fast high growth of Asian countries, especially China, and the decline of European and NAFTA countries. Fig 1 shows the global market shares in 2001 and in 2011. In 2001, European and NAFTA countries were the overall leaders in terms of world chemicals sales, but the regions have gradually lost ground to China and other Asian countries (except Japan). In terms of demand, it is important to note that from 50% to 70% of all chemical products are intermediate goods used by a variety of sectors ranging from manufacturing, service, agriculture and construction. Therefore, the chemical sector is the upstream sector providing intermediates for several downstream users, and industrial clients represent an essential share of the market. This means that, on the one hand, to innovate successfully, firms have to develop extensive linkages with the downstream market segments to become knowledgeable about their needs, and, on other hand, that successful innovations in upstream sectors may have positive effects in downstream industries (Cesaroni et al. 2004). In that sense, the chemical sector is an important source of knowledge spillovers and technology diffusion.

The prevailing industry structure in the chemical sector is made by a few large players with several smaller, specialized companies (Cesaroni et al. 2004). Large players are established firms, which benefit from economies of scale and scope and have showed a great continuity (Oltra and Saint-Jean 2007). Many of these firms have been founded in the XIX century, have been leaders in their own domestic markets up to the 1980s, and now act as global oligopolies in specific subsectors. Those large multinational companies are connected to smaller SEFs (specialized engineering firms), which are specialized in the engineering of the new plants (process technology), as well as to SMEs in the fine and specialty chemicals. SMEs typically act as buyers and/or suppliers of larger multinational companies.

Finally, in terms of basic firms' strategies, we can distinguish a cost leadership strategy, characterized by price competition in the sector of basic chemicals, and a specialization strategy, characterized by great product differentiation and higher profit margins, in the other subsectors (Cesaroni et al. 2004). Cost leadership strategies require process innovations in order to reduce production costs, while specialization strategies focus on product innovations, in order to better respond to customers' needs and to set higher prices. In this context, SC may represent both a way to reduce costs through the development of energy-save technologies and a way to differentiate products in order to meet the consumers' demand of more sustainable products.

In this study we are especially interested in the demographical characteristics of organizations involved in the development of SC: the organization type (firms, universities, and public agencies), their size, age, and nationality. In particular, we are interested in assessing whether the development of SC is associated with the emergence of new organizations. This is because the emergence of radically new technological knowledge is often associated with the emergence of new players, with new and specific capabilities. On the contrary, incumbents may be reluctant to invest in radically new technologies because they focus their strategy on current mainstream consumers and established products (Christensen 1997). The long history of the chemical industry also supports the relevance of such question. As documented in Cesaroni et al. (2004), the chemical industry has witnessed three main technological discontinuities: the dyestuff model, the development of polymer chemistry and the chemical engineering (i.e., the unit operations). Each of those discontinuities has been associated with the emergence of new players: the German dyestuff manufacturers, the petroleum companies for the development of polymer chemistry, and the SEFs in the case of the unit operation. These new players have created new, larger or smaller, markets and have established networks with existing organizations.

2.2 Sustainable Chemistry

The severe impact of chemicals on human and environmental health, as well as the expected increase of energy demand and depletion of fossil resources, has increased the interest for developing a more sustainable chemistry. Such an interest has materialized in a number of government initiatives that have taken the form of environmental regulation and government programs. In the US, the Pollution Prevention Act (1990) formalized the need to adopt pollution prevention policies, rather than command and control policies, and opened financial means to the Environmental Protection Agency (EPA) for launching new programs aimed at developing more sustainable chemical technologies. The EPA started the Green Chemistry Program officially in 1993 and this program continues to promote green chemistry with research grants and education. In Europe, the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation, which entered into force in 2007, strengths the former legislative framework on chemicals of the EU, in particular by asking industry for assessing and managing the risks posed by chemicals and for providing appropriate safety information to users. Two industry groups, Cefic and EuropaBio, along with the EC have established the European Technology Platform for Sustainable Chemistry (SusChem) to encourage R&D in Europe (OECD 2011). Similar initiatives have been taken in many other countries, including Japan and Canada. Moreover, a number of governments provide financial support (grants and tax preferences) for R&D expenditures relating to SC, implement green public purchasing policies, and offer incentives for the adoption of green chemistry products (see OECD 2011).

Universities, often supported by government initiatives, have made an important contribution to the development of a more sustainable chemistry. Scholars have established specialized networks for the purposes of information dissemination and education (e.g., the Green Chemistry Network, the Japanese Green and Sustainable Chemistry Network), specialized research centers (e.g., the Green Chemistry Institute) and scientific journals like the *The Green Chemistry*

Journal[3] and *ChemSusChem,* a sister journal of *Angewandte Chemie*. Many renowned journals have dedicated special issues on SC advancements, as well. More in general, scientific research on SC has increased exponentially in the last few years, with an important contribution given by the Green Chemistry community (Epicoco et al. 2014). Moreover, SC has been incorporated into the curriculum of standard chemistry courses, and specialist undergraduate and postgraduate courses are offered at a number of universities.

As to private firms, little evidence has been provided and it is mainly anecdotal evidence (Sanderson 2011, OECD 2011). As unique exception, Nameroff et al. (2004) try to quantify the extent of adoption of green chemistry by using US patent data. The authors found that green chemistry technologies are emerging slowly and that many industrial sectors are not rapidly moving toward more sustainable practices and processes. However, this study mainly focuses on the Green Chemistry approach promoted by the US EPA (it does not take into account, for example, the developments relating to biomass) and on a relatively restricted period of time (patents granted between 1983 and 2001). In the present work, the objective is to take into account all the main technological developments relating to the broader field that, for simplicity, we have called Sustainable Chemistry, in order to analyze innovation and organizational dynamics.

2.3 SC technologies

In order to identify SC technologies, we reviewed the scientific literature[4] and interviewed a number of chemists[5]. On this basis, we identified the following 4 areas of SC research. It is important to note that this is not, and neither can be, an exhaustive presentation of all SC developments. However, we hope it is a good representation of the most important advances in the field.

2.3.1 Alternative feedstocks

Petroleum-based feedstocks are the current basis of the chemical industry with 90% of all organic chemicals derived from oil, while 90% of the world's energy needs are met by non-renewable resources (OECD 2011). This explains the enormous interest in developing alternative feedstocks, using annually renewable raw materials instead of fossil resources like oil, coal and natural gas. These alternative feedstocks not only allow conservation of nonrenewable petroleum resources, but also have low or no net CO2 emissions (contrary to fossil resources). The chemical sector has already witnessed two important changes in the basic feedstocks used by the industry: the shift from wood to coal and from coal to petroleum. Both these changes have had a fundamental technological and economic impact.

[3] In 2009, its tenth year of publication, the *Green Chemistry Journal* was ranked #15 out of 140 chemistry journals according to highest impact factor (OECD 2011)

[4] We relied especially on OECD (2011), Anastas et al. (2010), Beach et al. (2009)

[5] We interviewed researchers from the Laboratoire de Chimie des Polymères Organiques (LCPO), University of Bordeaux I and participated to two focus groups organized at the University of Reims within the ANR research program "Une Approche Economique de l'intégration des dimensions socio-économiques et techniques dans les Programmes de Recherche en Chimie Doublement Verte".

The main alternative solutions currently explored relate to agricultural products, i.e., the biomass derived from plants. Carbohydrates, natural oils and soy are examples of biomass that, together with agricultural waste and non-food-related bioproducts (which are often made up of lignocellulosic materials), are already used in a variety of applications, ranging from biofuels to biopolymers. For example, advanced biofuels have been developed by converting food crops (such as corn or sugarcane) to ethanol through fermentation (OECD 2011). Biopolymers are new polymer materials based on biomass that are currently used for producing recyclable and/or biodegradable commercial plastics (e.g., PLA). Biomass and agricultural waste need to be processed in new dedicated plants, the so-called biorefineries, in order to obtain the desired chemicals (e.g., ethanol). Therefore, the development of efficient biorefineries is considered of crucial importance for the development of more sustainable feedstocks. CO_2 and other gases like hydrogen and methane are also being studied as alternative solutions to traditional feedstocks.

2.3.2 Alternative solvents

Solvents are the media in which chemical reactions are carried out and represent the bulk of reactions' waste. They are heavily used in industrial processes for the isolation, separation and purification of materials, but they are typically toxic, flammable and corrosive. Moreover, their volatility contributes to air pollution (Volatile Organic Compounds emissions), increases the risk of worker exposure and is responsible for industrial accidents. Therefore, developing alternative solvents is an important area of SC research. The main advances relate to developing new reaction processes that do not use solvents at all (the so-called solvent-free reactions), designing more biodegradable and/or recyclable solvents, and inventing new environmentally benign solvents. Among the environmentally benign solvents, attention has been devoted to supercritical fluids, in particular supercritical CO_2 (this has been used for example in the decaffeination of coffee bean), ionic liquids (organic salts that are liquid at room temperature), and water.

2.3.3 Alternative catalysis

SC also calls into question the traditional way of performing chemical reactions (catalysis). Alternative catalysis techniques are focusing in particular on the development of biocatalysis, which uses natural catalysts, such as protein enzymes, to perform chemical transformations. For example, enzymes have completely displaced conventional catalysts as a low-cost option in the manufacture of several generic pharmaceuticals (Poliakoff 2007). In addition to being green catalytic processes that are performed at ambient temperature and pressure, often in water as solvent, the catalysts themselves (enzymes) are biocompatible, have low ecotoxicity and are produced from natural, renewable raw materials.

Besides being used as natural catalysts, enzymes are also manipulated by using genetic engineering and molecular biology techniques to obtain modified enzymes with enhanced properties compared to their natural counterparts. Similar techniques are providing microorganisms, transgenic crops and animals with new and enhanced capabilities for producing chemicals. This area of investigation closely interacts with biotechnologies and engineering advances. It has been estimated that, of the enzymes used commercially, about 60% are products of modern biotechnology (Gavrilescu and Chisti 2005). SC efforts are also directed towards both the design of more selective catalysts to reduce the number of stages in a given process (e.g., ibuprofen and Zoloft) and the development of reusable or recyclable catalysts.

2.3.4 Alternative industrial processes and reactors (chemical engineering)

The development of alternative industrial processes and reactors is another important area of SC research. The goal is to design eco-efficient processes that minimize waste and are simultaneously energy efficient. In this perspective, process intensification is of crucial importance since, in this way, the ratio between reactors size and production capacity can be reduced, and equipment can be miniaturized, the so-called microreactors. Microreactors, in which reaction components are manipulated in channels as small as 10 µm in diameter, enable to enhance yield and selectivity of reactions. Switching from batch reactions to continuous processing is also considered important, as continuous processing is safer and often gives a higher-purity product. Alternative techniques like microwave-, sono-, or photo- assisted chemistry have been developed and applied as well in order save energy, reduce reactions times, simplify experimental conditions and increase the effectiveness of catalysts.

3. Data and methods

One of the reasons behind the lack of quantitative studies relating to eco-innovation in the chemical sector relies in the difficulties posed by the selection of the relevant dataset of patents. Those difficulties are due to both the high heterogeneity of the chemical sector and the nature of emerging field of SC. Indeed, being SC an emerging field, it is still not clear what are the most important technologies, in the community of practitioners there are different visions on "how to do things" and a variety of alternatives are explored. In this paper, we try to overcome such difficulties by putting particular emphasis on selecting and validating the patent search strategy. Since SC spreads among different technological classes and there is not a single set of technological classes that clearly refers to SC, the dataset has been created by combining keyword search and technological class search.

More in particular, we first selected a list of keywords for each of the SC technologies detailed in section 2, and included a number of generic terms as well (e.g., alternative feedstocks, biodegradable products etc.). In writing up such list, we also relied on previous patent research filters, namely Nameroff et al. (2004) and OECD (2011). We then discussed the keyword list with chemists working in different chemical fields, asking them to integrate or modify the keywords list. We searched for the final keyword list on titles, abstracts and claims of patents granted from 1971 to 2011 by the USPTO. In order to minimize the number of irrelevant patents contained in our dataset, the keyword search has been limited to patents belonging to the chemical field[6]. Following OECD (2011), we added as well a number of technological sub-classes that can be clearly associated with SC. Finally, a sample of the dataset has been analyzed by an expert and the dataset has been further refined. We obtained a final dataset of 27355 patents, which, we believe,

[6] Following Nameroff et al. (2004), total chemical patents have been computed by including the IPC C, B01 and B04.

represent a good, although not perfect, indicator of the technological knowledge relating to sustainability research in chemistry.

To analyze SC technological knowledge, we used a clustering algorithm for the analysis of citation networks. Analysis is performed on backward citation data associated with the 27355 patents contained in our dataset. In particular, we created a network of citations among SC patents, so that SC patents correspond to the vertices of the network and are connected with each other by a number of arcs, which symbolize citational links among patents. Each patent represents a discrete piece of technological knowledge that has passed the scrutiny of trained specialists and has been granted on the basis of relatively objective standards. Since it is a legal duty for the assignee of a patent to disclose the existing knowledge, each cited patent represents a previously existing piece of knowledge that has been incorporated and further developed by the citing patent. Citations among patents, by making explicit the epistemic links among the pieces of knowledge from which a field emerges and grows, can be used to trace the dynamics of technological knowledge underlying the field (Mina et al. 2007).

To that purpose, we applied the Island algorithm, which is implemented by the software *Pajek,* to our SC network. The algorithm enables us to identify and explore the main clusters of innovations that populate the domain of SC, thus providing an indication of the technologies where organizations are concentrating their research efforts. More in particular, the Island algorithm identifies in the whole network of patents, all non-overlapping sub-networks (subsets of vertices) that are more closely connected within each other than with external vertices (i.e., patents that do not belong to the same sub-network). However, the Island algorithm is not based on simple citations; rather it uses traversal weights on arcs calculated following the Hummon and Doreian (1989) main path analysis. Those traversal weights measure the importance of paths linking the oldest vertices in a citation network (i.e., entry vertices) to the most recent ones (i.e., entry vertices)[7] and are used to calculate longitudinal connectivity among vertices in a network[8]. Using traversal weights, we can define a cluster (or an Island) as a connected sub-network of size in the interval k-K (k is the minimum size of the sub-network and K is the maximal size of the sub-network[9]), with stronger internal connectivity relatively to its neighborhood (Batagelj 2003). As demonstrated in Batagelj et al. (2006), each sub-network identified by the Island algorithm has the same topic; therefore Islands can be considered as thematic clusters and can be here used to identify the main clusters of innovations that contributed to the development of SC. Moreover, we applied to each cluster a number of algorithms that allow visualizing the time evolution of the cluster and the relative importance of vertices (as revealed by traversal weights). This will permit

[7] Entry vertices are those vertices that are not cited within the data set, while exit vertices are vertices that are not citing within the data set. Traversal weights on arcs are calculated in the following way. In an acyclic network there is at least one entry vertex and at least one exit vertex. Let us denote with I and O the set of all entries and all exits, respectively. The SPC method assigns to each arc as its weight the number of the different I–O paths passing through the arc. This number is then divided by the total number of paths between entry and exit vertices in the network. This proportion is the traversal weight of an arc (de Nooy et al. 2005).
[8] See for example Mina et al. (2007) and Barberá-Tomás et al. (2011).
[9] We discard clusters of size smaller than k as ’noninteresting’, since they are too small, while the clusters of size larger then K are too large, they contain several themes (Batagelj 2003).

us to identify the patents, and the corresponding organizations, that have been most influential in enabling the development of each cluster.

Patent documents are a fundamental source of data, since each patent contains information such as the year of publication, the organization that developed the invention (the name of the patent assignee), its location (the address of the patent assignee), the technological field (IPC) and citations to previous patents. We used such information firstly to assess trends relating to the evolution and distribution of SC innovative activity, and secondly to identify the main clusters of innovations and organizations involved in the development of SC. On this basis, we will try to detect whether or not there has been a change in the characteristics of involved organizations.

This methodological approach has of course limitations. The first set of limitations relate to the patent dataset. Despite our efforts to validate the patent search strategy, our dataset may contain a number of irrelevant patents (patents that do not relate to SC) and may have missed some relevant patents. To the best of our knowledge, there is not a way to completely avoid this type of errors. However, the incorporation of practitioners in construct measurement, as has been done in this study, may mitigate the importance of such errors (Nelson et al. 2014). In addition, in the absence of a unified global patent dataset, this study has used the USPTO, the most representative dataset. Although that has, to some extent, biased the results of our analysis towards US organizations, patenting in the US market is still important for foreign countries in order to protect areas of competitive advantage, and US patenting activity by foreign organizations remains a good measure of the technological capabilities of foreign countries (Pavitt, 1985).

The second set of limitations relate to patents as measure of innovation. It is very well known that the extent of innovative activity is not fully revealed by patenting activity because many patents never reach the market. Most importantly for our analysis, patents are often used for strategic objectives, and patent strategies differ both over time and across organizations, even within the same industry or technological area (Hall and Ziedonis, 2001). Therefore organizations may have different propensity to patents, depending on their strategies for protecting intellectual property. Despite of that, patent data remain the best standardized proxy by which we can account for the overall technological evolution. Besides, the propensity to patent in the chemical sector is relatively high compared to other sectors, thus patents can be considered as relatively good measure of innovation.

Finally, further limitations may come from the use of patent citations as measure of connectivity among patents. Indeed, patent citations may not perfectly reflect the knowledge bases that organizations rely on. For example, Alcacer and Gittelman (2006) found that the magnitude of citations added by USPTO patent examiners is high, and they raise concern about the unknown noise that such citations, which typically are not separately reported, can add to the data. In response to such concern, Barberá-Tomás et al. (2011) have tested patent citations methods and, in particular, the network citation methods used in the present analysis, showing their validity in studying technological evolution. That seems to suggest that, at least for what concerns the analysis of technological evolution, the bias introduced by examiners' citations is not bad per se.

4. Results and discussion

In this section, we first show the main trends emerging from the analysis of patent statistics, highlighting how SC knowledge evolved over time and spread among different technological areas, countries and organizations (section 4.1). We then present the network analysis results, illustrating and discussing the main clusters of innovations and organizations that are driving the evolution of SC (section 4.2).

4.1 Evolution and distribution of SC innovative activity

Fig 2 displays the evolution over time of SC patents. We observe that the innovative activity in the field has progressively increased since the end the 1980s, and, after a slight decline between 2003 and 2008, it has witnessed an exponential growth. This suggests that only in the very recent years organizations have considerably intensified their innovative efforts in the field of SC. Fig. 3 provides the time evolution of SC patents as share of total chemical patents[10]. It highlights a slower growth of SC patents, but the same sharp increase in the last few (available) years. However, although the share of SC patents has doubled in the last 10 (available) years, from 3.06% in 1991 to 6.16% in 2011, SC patents still represent a relatively low share of total chemical patents.

Table 1 contains the distribution of SC patents among the top 10 technological classes. These results show that most of the innovative activity in the SC field relates to three wide technological areas: biochemistry (C12), organic chemistry (C07), and organic macromolecular compounds (C08). The result relating to organic chemistry is not surprising. Indeed, organic chemistry deals with the study of organic compounds and materials (i.e., matter that contains carbon atoms). As such, the range of application of organic chemistry is enormous and organic compounds form the basis of, or are important constituents of, many products, including petrochemicals, plastics, food, drugs and paints.

More interesting is the result relating to biochemistry. Biochemistry (also called biological chemistry) deals with the study of chemical processes within and relating to living organisms. As mentioned in section 2.2, this field has made important advances in the development of alternative enzyme-based catalysts (i.e., biocatalysts), as well as in the design and application of modified enzymes and microorganisms. The third highest ranked technological class deals with the development of organic macromolecular compounds, i.e. various types of polymers. Because of their broad range of properties, both synthetic and natural polymers play an essential role in everyday life. Synthetic polymers are derived from petroleum and range from familiar synthetic plastics (e.g., polystyrene), to synthetic fibers and rubbers. Natural polymers (biopolymers) occur in nature and include cellulose, proteins, wool, DNA, and biopolymers produced from biomass (e.g., PLA). Among the other prominent technological classes, we can find the development of physical and chemical processes (B01), as well as a variety of chemical products ranging from medical products (A61) to petroleum (C10) and paint products (C09).

We also detected the distribution of SC patents among technological subclasses (Table 2) and got the confirmation that research relating to biochemistry (C12) is focusing in an important

[10] Total chemical patents have been computed by including the IPC C, B01 and B04.

way on the development of both new microorganisms/enzymes by using genetic engineering techniques (C12N) and alternative catalysis techniques using enzymes (C12P). For research relating to organic chemistry (C07), two fields are particular important: acyclic or carbocyclic compounds (C07C) and heterocyclic compounds (C07D). Those are the most important bulk chemicals (the so-called building-blocks) and are massively used to synthetize most of the finer chemical products, including petrochemicals, plastics, food, drug and paints.

Table 3 shows the distribution of SC patents among the top 20 countries. The patent activity in the SC field seems to be highly concentrated in the US, which own more than 57% of SC patents. However, this result is, to some extent, overestimated due to the bias of the USPTO dataset toward US organizations (see section 3). If we look at the other top countries, we observe that, not surprisingly, Japan and Germany come soon after the US, with a percentage of 10.51% and 9.23% out of all SC patents, respectively. The total share of European countries ranked among the top 20 countries amounts to 20.89%. This makes European countries important players in SC research. Emerging or latecomer countries – Korea, India, Taiwan and China – own a negligible share of SC patents. This is also confirmed by the country distribution of patents granted in the most recent years. As showed in Table 3, even if the share of patents owned by emerging countries has increased in the last 10 (available) years, their role remains relatively minor. Therefore, even if Asian countries, especially China, have now overtaken US and Europe in terms of market share and growth rate in the whole chemical industry, SC technologies are still importantly concentrated in the US, in Europe and, to a lesser extent, in Japan. Data relating to total chemical patents show similar patterns (see Eurostat statistics).

Fig 4 contains the time evolution of patents granted to public organizations as share of total SC patents. We observe that such a share has been rapidly increasing until 2006, experiencing then a slight decline. This decline is not due to a reduced activity of public organizations, but rather to a higher increase of firms' patent activity. This confirms that, in the very recent years, private companies have considerably intensified their innovative efforts in the SC field. In general, the share of patents owned by public organizations remains very important: in 2006, its peak, it was 23.22% of total SC patents (it was 2.5% in 1971), and the average value over the whole period is 14.83%. This confirms the important role played by universities, research centers and government agencies in the development of SC (Nameroff et al. 2004).

Table 4 shows the geographical distribution of patents granted to public organizations. We can see that most of the public organizations are based in the US. Even if this result is to some extent biased by the limitations of our dataset discussed above, still European universities seem to be less active than their international counterparts, in particular German organizations, which only own 1.90% of total patents granted to public organization. Indeed, the share of European public organizations out of total patents granted to public organizations amounts to 14.13%, while as reported above, the total share of European countries out of all SC patents is 20.89%. In Table 5, patents owned by public organizations are shown as share of national SC patents. Here we observe that emerging countries present the highest shares. Therefore, in these countries public organizations are the most important players.

Finally, Table 6 presents the top 30 patent assignees in the field of SC. Among the most active organizations we find some of the largest and established chemical companies, including the US DuPont, the German BASF and Bayer, the US Union Carbide (since 2001, a wholly owned subsidiary of Dow Chemical) and the German Henkel. Quite surprisingly, the second highest ranked assignee is the US government. This signals the importance of the involvement of the US government in the field of SC. Among the other public and research organizations we find *IFP Energies Nouvelles* (the old French *Institut du Petrol*), some of the most important US universities (University of California, MIT, Michigan State University), and, quite surprisingly, the Council of Scientific and Industrial Research, the India's largest R&D organization. By looking at the remaining organizations, we observe some of the most important US oil and gas corporations, including Exxon, Mobil Oil (which in 1999 merged with Exxon to form ExxonMobil), UOP, Chevron, Texaco (which in 2001 merged into Chevron), Phillips Petroleum (which in 2002 merged with Conoco to form ConocoPhillips), and the Anglo-Dutch Shell. We also find conglomerate corporations like the US 3M and General Electric, consumer goods companies (Proctor & Gamble), agricultural biotechnology corporations (Monsanto), and life science companies (Hoechst)[11]. Thus, even if the innovative activity in the SC field seems to be spread among a relatively high number of organizations (the top assignee only owns 1.67% out of total SC patents), the most important patenting organizations result to be large and established chemical companies from the US and Germany, together with the US government and some of the major US oil corporations.

4.2 Clusters of innovations and organizations

Table 7 provides summary statistics on the SC network of patents. The network contains 27355 vertices, which correspond to the total number of SC patents, and 31588 arcs, which correspond to citations among SC patents. The relatively low average degree (2.31%) seems to be due to the high number of isolated vertices[12] (11624). This suggests that innovation efforts in the field of SC are still relatively low connected. If we eliminate isolated vertices, we obtain a network with average degree equal to 4.02%. We observe from Table 7 that the network displays a large component that connects 10818 patents (40% of total patents) and a high number of smaller components, whose size declines rapidly. This suggests the presence of a variety of competing and/or complementary areas of technological research.

These areas can be detected by using the Island algorithm, which, as mentioned in section 3, identifies the main clusters of innovations in the entire research space of SC. We therefore detected all Technological Islands of size between 2 and 250 in our dataset, and found 2331 clusters, which include 8622 patents of the dataset. Table 8 provides information on the Technological Islands with size equal or greater than 20 vertices. We observe two large Islands (including 249 and 246 patents, respectively) and a few Islands with more than 100 patents. Then, the Islands' size declines very rapidly. The Islands' size frequency distribution is presented in a log-

[11] It was a German chemicals then life-sciences company that became Aventis Deutschland after its merger with the French Rhône-Poulenc in 1999. With the new company's 2004 merger with Sanofi-Synthélabo, it became a subsidiary of the resulting Sanofi-Aventis pharmaceuticals group.

[12] Isolated vertices represent patents that are not citing other patents in the dataset and that are not cited by other patents in the dataset.

log scale in Fig 5, confirming the presence of a few large Islands and a great number of small or very small Islands.

We extracted the Islands reported in Table 8 and, with the assistance of an expert, analyzed the topic of the patents involved, as well as the characteristics of the organizations that have been granted of these patents. The first Island relates to the development of biodegradable materials to make environmentally degradable articles**.** These materials are based on natural polymers extracted from biomass (biopolymers) and can be used to replace conventional materials like plastics, which are hardly degradable. In addition, petroleum based plastics are not renewable and are responsible of CO2 emissions, whereas biomass based plastics are renewable and potentially carbon neutral. Applications of these materials include replacement of plastic materials in packaging, coating, textiles, and in many consumer goods. Patents in this Island focus especially on methods for synthetising or blending polylactide (PLA), which is one of the most important bioplastics.

In order to better visualize and analyze the dynamics of this Island, we applied a number of algorithms that allow depicting the time evolution of the Island, together with its most influential patents and organizations (see section 3). The resulting graph is contained in Fig 6. If we start from the bottom of that figure and move along the vertical axis, that graph shows all major paths of growth of knowledge and identifies the most important ones. The size of vertices and the thickness of arcs correspond to the relative importance of patents and citational links, respectively (as revealed by traversal weights on arcs; see section 3). That allows us to easily identify the patents, and the corresponding organizations, that have been most influential in enabling the development of the technological cluster.

In the graph, we can see that the patent that laid the foundation of the cluster was granted to Union Carbide, an important US chemical company founded in 1917 and, since 2011, a wholly owned subsidiary of Dow Chemical. The patent was granted in 1975 and discloses a new biodegradable polymer to make degradable plastics. The subsequent developments, from the 1970s to the 1980s, were disclosed by two main organizations: Coloroll and the US government. Coloroll was a UK wallpaper company founded in the 1970s, which in the 1980s became dominant in the home furnishings business and collapsed in 1990 through excessive debt. In the 1990s and 2000s, we observe a wider variety of organizations, including larger and more established companies (the US Cargill and Warner-Lambert), smaller and younger firms active in the field of bioplastics and biodegradable packaging (the German BIOTEC and the US E. Khashoggi Industries), and public organization (Michigan University). Thus, the network of organizations that have been most influential in the development of this cluster is mainly composed by relatively large and established companies, together with public organizations. However, in the most recent years, there seems to be evidence for a more important role played by more specialized and younger firms.

The second Island deals with methods for processing waste (waste treatment process and recycling) and includes wastewater treatment, bioremediation of contaminated soils, solid organic waste treatment. The treatment for waste is performed with biological methods (e.g., microbial anaerobic or aerobic processing) based on the action of bacteria that break down the compounds into simpler chemicals. Fig 7 provides the time evolution of this cluster. Here we observe a higher degree of organizational continuity, in particular with patents granted to Air Products and Chemicals, an international corporation founded in 1940 whose principal business is selling gases and chemicals for industrial uses. However, we can also note a network of organizations similar to the one of Island N°1, including other relatively large and established firms (Union Carbide, Celanese Corporation, Siemens), public organizations (US government, Polytechnic University, Institute of Gas Technologies, Iowa State University) and smaller, younger firms active in the biotech sector (Bioprocess Engineering, Gist-brocades).

The third Island deals with processes and apparatuses for fluidized catalytic cracking (FCC), which is the process by which hydrocarbons (from petroleum) are broken down into simpler chemicals used for producing fuel or as building blocks for making plastics. Patents in this cluster focus on different aspects of extraction and separation processes. As we can observe from Fig 8, this Island is characterized by a high degree of organizational continuity: most of the patents are owned by two important and established companies active in the petroleum sector, namely Mobil Oil and UOP. Neither public organizations nor smaller and specialized firms played a role in the development of this cluster.

By analyzing the other relevant Islands, we found a variety of topics. The Islands' topics are summarized in Table 8[13], which also displays the average publication year of each cluster, providing an indication of the average "age" of the different clusters. Islands' topics include relatively established fields like the development of extraction and separation methods from petroleum (Island N°15 and 22), of asbestos-free materials for vehicles and industrial machinery (Island N°12), and of environmentally-friendly adhesives and coatings (Island N°11). The most recent clusters relate to biopolymers and bioplatics (Island N°1), and different biochemistry applications, ranging from chemical and biochemical microreactors (Island N°8) to various biodegradable compounds (Island N°14, 19, 20, 21).

Finally, we analyzed the demography of organizations in each clusters. We found that public organizations, especially US organizations, played an important role in the development of many clusters, particularly in the most recent ones. Established and large chemical companies show an important presence, and their continuity is more evident in the most established fields, especially those linked to petroleum developments. In many clusters we observed as well a number of important firms active the electronics, automotive and paper industry. However, since the 1990s, and especially in the most recent clusters, there seems to be evidence for a greater importance of new and more specialized firms, often active in the field of biochemistry.

[13] Islands N° 13 and 17 deals with pharmaceuticals products, but we did not observe any explicit environmental claim.

5. Conclusion

By building an original dataset of patents and using a clustering algorithm, this paper has provided, for the first time, a quantitative analysis of the eco-innovation dynamics in the chemical sector. After having overviewed the main Sustainable Chemistry (SC) technologies, we have defined, with the assistance of experts, a dataset of 27355 patents granted by the USPTO from 1971 to 2011. We have analyzed trends emerging from patent statistics and citation network analysis.

Patent statistics show a progressive increase of SC patents since the end of the 1980s and an exponential growth since 2008. This suggests that only in the very recent years private companies seem to have considerably intensified their innovative efforts in the field of SC. Moreover, SC patents still represent a relatively low share of total chemical patents. Our results also highlight that SC innovative activity is importantly concentrated in the field of biochemistry, which has made advances in the development of alternative enzyme-based reactions (biocatalysis), as well as in the design of "modified" enzymes and microorganisms.

Even if Asian countries, especially China, have now overtaken US and Europe in terms of market share and growth rate in the whole chemical industry, SC technologies (and chemical innovation in general) remain mainly concentrated in the US, in Europe and, to a lesser extent, in Japan. Therefore, while production and consumption of chemicals are moving rapidly toward emerging countries, innovation and eco-innovation apparently still lag behind in these countries. Public organizations own a considerable and increasing share of SC patents. This confirms the important role played by universities, research centers and government agencies in the development of SC (Nameroff et al. 2004). However, European universities are less active than their international counterparts. This may impact on the ability of the European chemical industry to exploit the opportunities contained in SC. The innovative activity in the SC field seems to be dispersed among a relatively high number of organizations. The top innovative organizations result to be large and established chemical companies from the US and Germany, together with some of the major US oil and gas corporations. These results also show a considerable involvement of the US government, which is one of the most active organizations.

Our citation network analysis identified the main clusters of innovations that are driving the evolution of SC, as well the networks of organizations that generated those clusters. We found a variety of competing/complementary clusters, which provide an indication of the technologies where organizations are concentrating their research efforts. The largest clusters deal with the development of biodegradable plastics produced from biomass, methods for processing waste by using biochemical techniques, and applications in the petroleum sector (methods of extraction and separation of petroleum). Other clusters relate to both more established fields, like the development of asbestos-free materials, and more recent developments, including different biochemistry applications. With respect to organizations that generated those clusters, we found that public organizations, especially US organizations, played an important role in the development of many clusters, particularly in the most recent ones. Established and large chemical companies show an important presence, and their continuity is more evident in the most established fields, especially those linked to petroleum applications. In many clusters we observed as well a number of important firms active the electronics, automotive and paper industry.

However, since the 1990s, and especially in the most recent clusters, there seems to be evidence for a greater importance of new and more specialized firms, often active in the field of biochemistry.

Overall, these analyses seem to indicate that the development of SC has involved the emergence of new organizations only in a partial way and in some specific sub-fields, while incumbent firms still remain the most active organizations. This, as well as the relatively slow development of SC, may undermine the potential of SC to generate a radically new, and more sustainable, way of doing chemistry. These conclusions, on the one hand, call for effective policies supporting eco-innovation, and, on the other hand, suggest that probably sustainability cannot be addressed only on the supply side, but rather requires important changes on the demand side (consumption patterns) as well.

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Tables and Figures

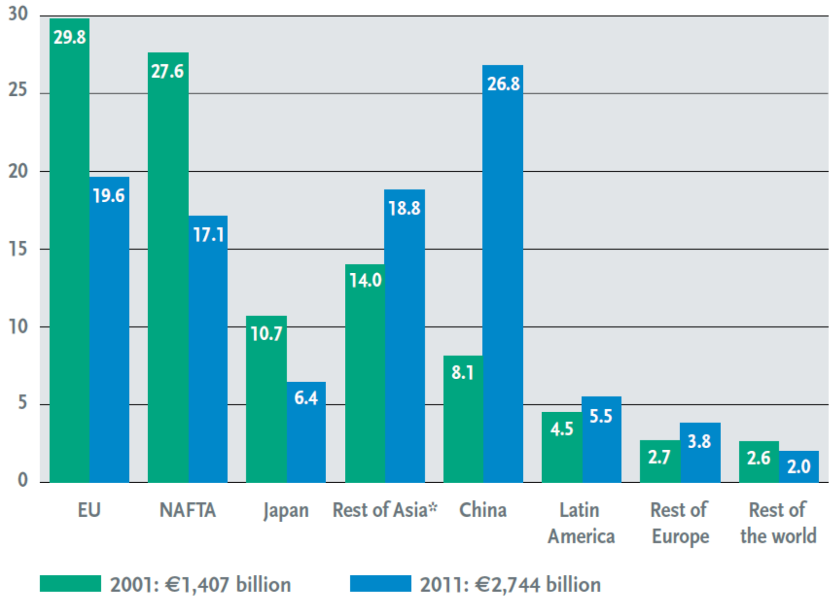

Fig 1. Market shares: world chemicals sales in 2001 and 2011
Source: Cefic (2012)

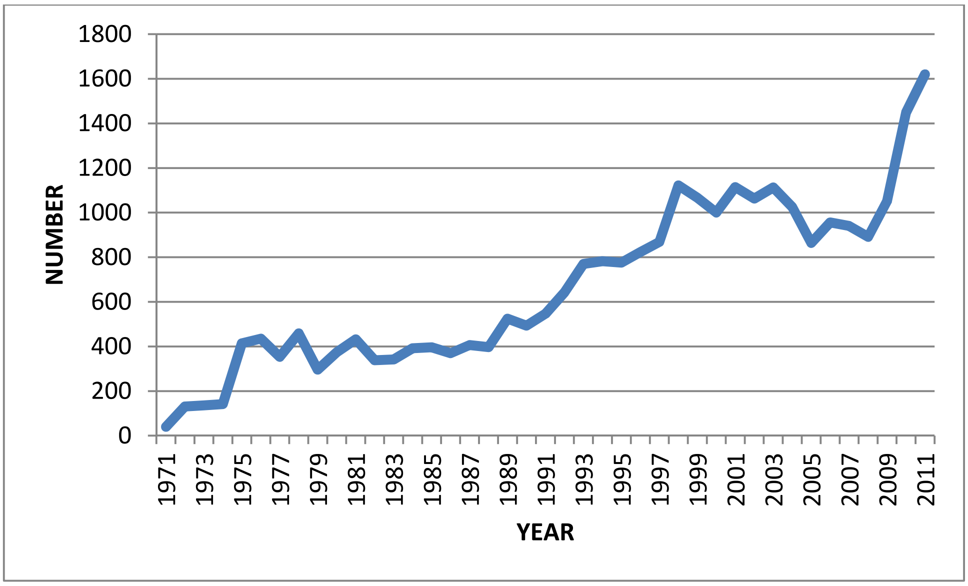

Fig 2. Evolution over time of SC patents (patents granted by the USPTO by publication year)

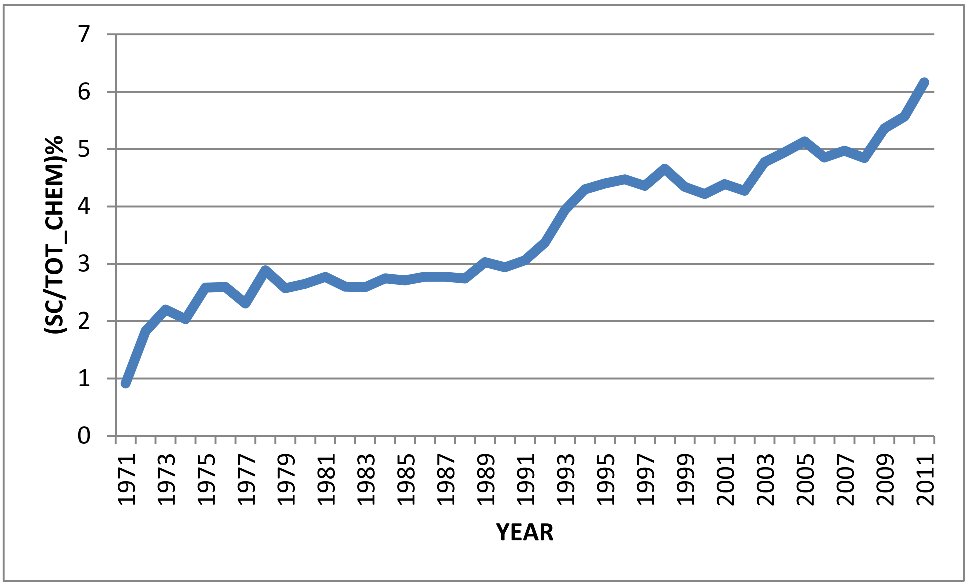

Fig 3. Evolution of over time of SC patents as share of total chemical patents (patents granted by the USPTO by publication year)

Table 1. Distribution of SC patents among technological classes[14]

Technological class	% of 27355
C12: BIOCHEMISTRY; BEER; SPIRITS; WINE; VINEGAR; MICROBIOLOGY; ENZYMOLOGY; MUTATION OR GENETIC ENGINEERING	45.80
C07: ORGANIC CHEMISTRY	45.15
C08: ORGANIC MACROMOLECULAR COMPOUNDS; THEIR PREPARATION OR CHEMICAL WORKING-UP; COMPOSITIONS BASED THEREON	39.07
B01: PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL	20.12
A61: MEDICAL OR VETERINARY SCIENCE; HYGIENE	14.01
C10: PETROLEUM, GAS OR COKE INDUSTRIES; TECHNICAL GASES CONTAINING CARBON MONOXIDE; FUELS; LUBRICANTS; PEAT	10.18
C09: DYES; PAINTS; POLISHES; NATURAL RESINS; ADHESIVES; COMPOSITIONS NOT OTHERWISE PROVIDED FOR; APPLICATIONS OF MATERIALS NOT OTHERWISE PROVIDED FOR	8.52
C11: ANIMAL OR VEGETABLE OILS, FATS, FATTY SUBSTANCES OR WAXES; FATTY ACIDS THEREFROM; DETERGENTS; CANDLES	6.82
C02: TREATMENT OF WATER, WASTE WATER, SEWAGE, OR SLUDGE	6.39
C01: INORGANIC CHEMISTRY	6.16

[14] Patent counts are whole counts: all technological classes cited by each patent in the dataset have been taken into account.

Table 2. Distribution of SC patents among technological subclasses[15]

Technological subclass	% of 27355
C12N: MICRO-ORGANISMS OR ENZYMES; COMPOSITIONS THEREOF; PROPAGATING, PRESERVING, OR AINTAINING MICRO-ORGANISMS; MUTATION OR GENETIC ENGINEERING; CULTURE MEDIA	22.56
C07C: ACYCLIC OR CARBOCYCLIC COMPOUNDS	18.04
C12P: FERMENTATION OR ENZYME-USING PROCESSES TO SYNTHESISE A DESIRED CHEMICAL COMPOUND OR COMPOSITION OR TO SEPARATE OPTICAL ISOMERS FROM A RACEMIC MIXTURE	13.88
A61K: PREPARATIONS FOR MEDICAL, DENTAL, OR TOILET PURPOSES	11.41
C07D: HETEROCYCLIC COMPOUNDS	11.20
C08G: MACROMOLECULAR COMPOUNDS OBTAINED OTHERWISE THAN BY REACTIONS ONLY INVOLVING CARBON-TO-CARBON UNSATURATED BONDS	10.44
B01D: SEPARATION	9.65
C08L: COMPOSITIONS OF MACROMOLECULAR COMPOUNDS	8.88
B01J: CHEMICAL OR PHYSICAL PROCESSES, E.G. CATALYSIS, COLLOID CHEMISTRY; THEIR RELEVANT APPARATUS	8.87
C08F: MACROMOLECULAR COMPOUNDS OBTAINED BY REACTIONS ONLY INVOLVING CARBON-TO-CARBON UNSATURATED BONDS	8.29

Table 3. Distribution of SC patents among countries[16]

Country	% of 27355 (1971-2011)	% of 13087 (2000-2011)
United States	57.42	55,26
Japan	10.51	11,58
Germany	9.23	9,17
France	3.28	3,49
United Kindom	2.54	2,35
Canada	2.07	2,05
Switzerland	1.35	1.63
Netherland	1.21	1.51
Korea	1.09	1.99
Italy	0.98	0.88
India	0.74	1.50
Sweden	0.61	0.62
Israel	0.57	0.70
Australia	0.50	0.57
Taiwan	0.49	0.88
Belgium	0.48	0.56
Denmark	0.47	0.56
Finland	0.45	0.63
China	0.37	0.69
Austria	0.30	0.24

[15] Patent counts are whole counts: all technological sub-classes cited by each patent in the dataset have been taken into account.
[16] Patent counts are whole counts: individual companies are credited with a patent, even if several companies are listed as co-assignees. The country statistics are calculated considering the address of each patent assignee.

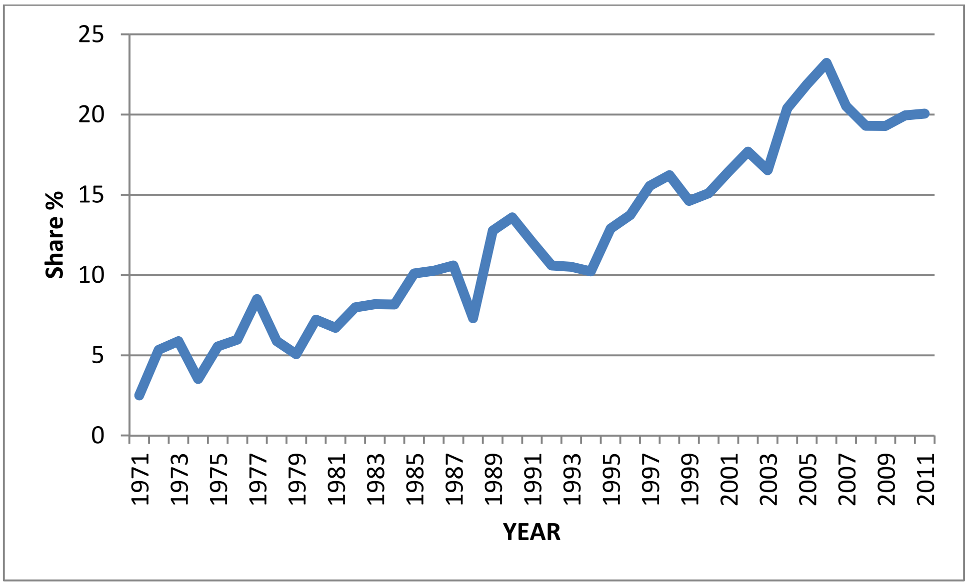

Fig 4. Evolution of over time of patents granted to public organizations as share of total SC patents

Table 4. Geographical distribution of patents granted to public organizations

Country	% of 4058
United States	73.56
France	8.01
Japan	6.58
Canada	4.02
India	3.89
United Kindom	2.41
Korea	2.05
Germany	1.90
Taiwan	1.70
Israel	1.48
China	1.43
Australia	1.16
Switzerland	0.94
Italy	0.71
Netherland	0.71
Spain	0.67
Singapore	0.47
Denmark	0.30
Finland	0.27
Belgium	0.22

Table 5. Geographical distribution of patents granted to public organizations as share of national patents

Country	% of national SC patents
India	78.22
Singapore	76.00
China	57.43
Taiwan	51.11
Spain	39.13
Israel	38.71
France	36.27
Australia	34.56
Canada	28.85
Korea	27.85
United States	19.01
United Kindom	14.10
Italy	10.78
Switzerland	10.30
Denmark	9.30
Japan	9.29
Finland	9.02
Netherland	8.79
Belgium	6.87
Germany	3.05

Table 6. Top patent assignees in the field of SC[17]

Organization' Name	Total Count	% of 27355
Du Pont de Nemours	458	1,67
USGOV	424	1,55
BASF	388	1,42
Bayer	301	1,10
3M	214	0,78
Exxon	214	0,78
Proctor & Gamble	206	0,75
Union Carbide	206	0,75
Mobil Oil	196	0,72
UOP	194	0,71
IFP Energies Nouvelles	175	0,64
Monsanto	171	0,63
Henkel	148	0,54
Hoechst	148	0,54
Chevron	145	0,53
General Electric	143	0,52
Council of Scientific and Industrial Research	141	0,52
University of California	136	0,50
Texaco	135	0,49
Mitsubishi	133	0,49
Degussa	131	0,48
Phillips Petroleum	130	0,48
Shell	129	0,47
Dow Chemical	119	0,44
Ciba Geigy	102	0,37
Massachusetts Institute of Technology	102	0,37
Michigan State University	100	0,37
ExxonMobil	99	0,36
Boehringer Ingelheim	92	0,34
Canon	87	0,32

[17] The procedure to draw up this list is based only on the name of the patent assignee listed on the patent, and did not attempt to take into account ownership relations between organizations (e.g. mother- and daughter-firms), or mergers, acquisitions and split-ups. As an exception to this rule, it was decided to create a category that unites all different US government organization, such as a ministry or the army (universities are not included here). This category is called "USGOV". Moreover, the name of patent assignees has been normalized by the author for taking into account the use of different names for the same company, e.g. IBM and International Business Machines Corporation.

Table 7. Summary statistics on the SC network

Statistics	Value
No. of vertices	27355
No. of links	31588
No. of isolates	11624
Average degree	2.31
Average degree without isolated patents	4.02
No. of weak components	42
No. of vertices in the main component	10818
No. of vertices in the following components	123
	107
	44
	43
	27
	27
	22
	19
	18
	18
	17
	….

Table 8. Technological Islands

Island No.	Island size	Average year of publication	Island topic
1	249	1998.93	Biopolymer to make environmentally degradable articles
2	246	1994.66	Methods for processing waste (waste treatment process and recycling)
3	142	1990.77	Processes and apparatuses for fluidized catalytic cracking (FCC)
4	123	1998.57	Materials that are free of lead and toxic metals (e.g., cadmium) with applications in semiconductors, electronics and electronic components
5	107	1996.30	Materials that are free of lead and toxic metals (e.g., cadmium) with applications in electronics, imaging, projection, telecommunication
6	102	1994.29	Environmentally improved processes for bleaching lignocellulosic materials (chlorine free bleaching processes) in paper industry
7	98	1995.20	Non-toxic gases, explosives, pyrotechnics
8	89	2002.44	Chemical and biochemical microreactors
9	71	1999.38	Biodegradable, environmentally-friendly fluids used in drilling operations for extraction of oil or gas, or as lubricants, surfactants and detergents for industrial machines
10	50	2001.22	Methods for molecular biological reactions, analysis and diagnostics
11	45	1991.67	Environmentally-friendly adhesives and coatings
12	44	1987.07	Asbestos-free materials (e.g., friction materials for vehicles and industrial machinery)
13	43	2001.21	Pharmaceutical compounds active as antiviral agents
14	41	2000.66	Biodegradable compounds used in tissue engineering
15	38	1989.66	Alternative extraction methods: supercritical fluids
16	31	1995.35	Improved methods for preparing Polyol fatty acid polyester for use in food, beverage, pharmaceutical, and cosmetic applications
17	27	1999.48	Pharmaceutical compounds
18	27	1996.04	Methods to reduce pollutants in the exhaust gases produced from the combustion of fuel (e.g., in vehicles) and to clean air from pollution (e.g., filters)
19	23	1999.13	Biologically active peptides with reduced toxicity for controlling pests
20	22	2005.23	Processes of reduced or no toxicity for forming metal nitride (MN)
21	21	1997.43	Non-toxic, non-flammable, safe compositions of biodegradable components for removing and stripping paint, varnishes and stains
22	20	1989.40	Environmentally improved methods for extraction and separation from petroleum
Total	1659		

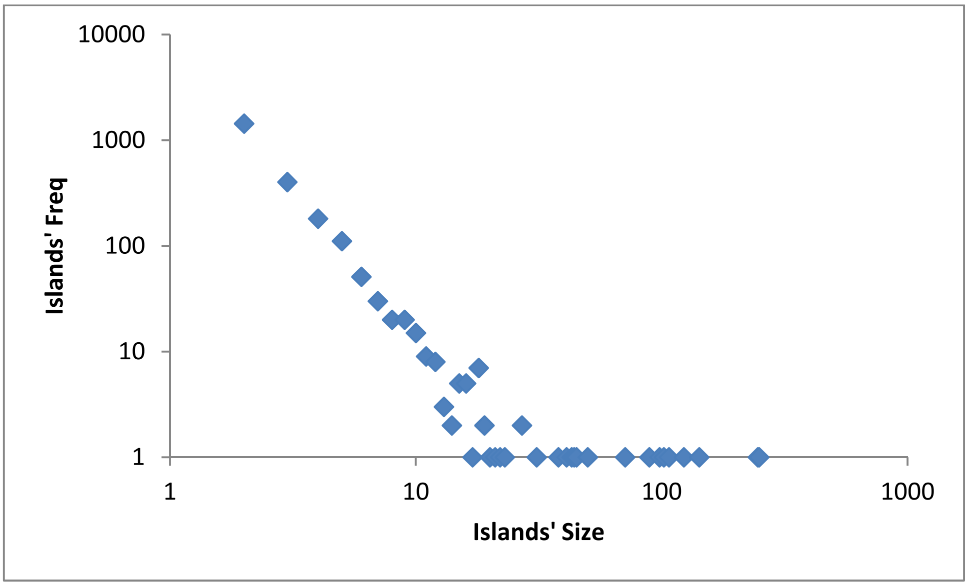

Fig 5. Island size frequency distribution (log-log scale)

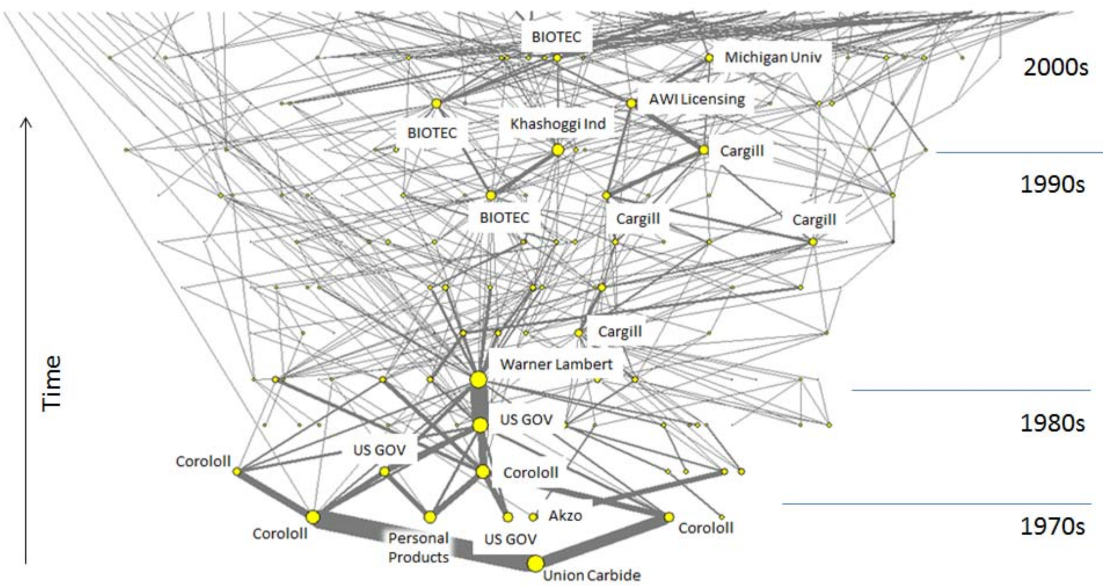

Fig 6. Island 1: Biopolymer to make environmentally degradable articles

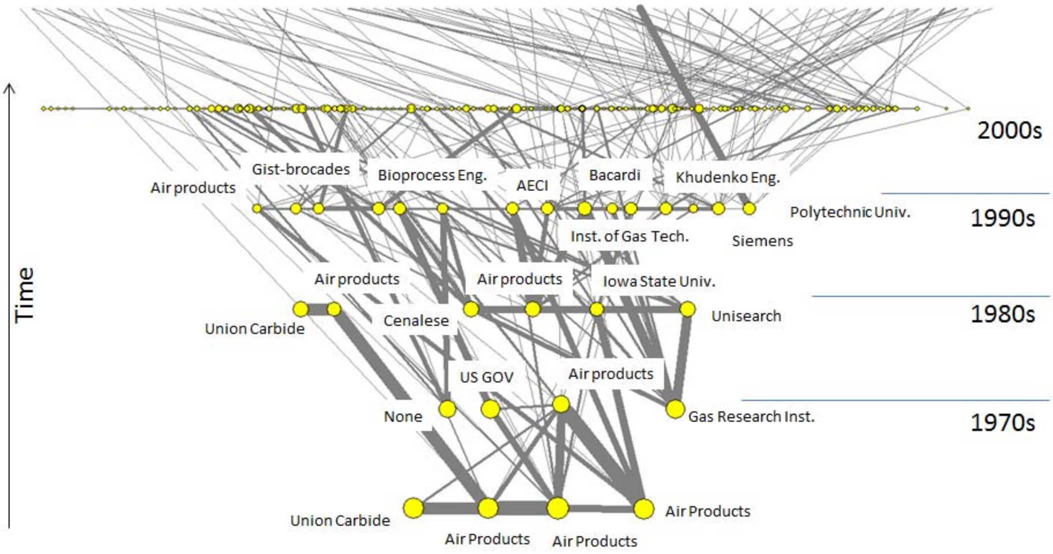

Fig 7. Island 2: Methods for processing waste (waste treatment process and recycling)

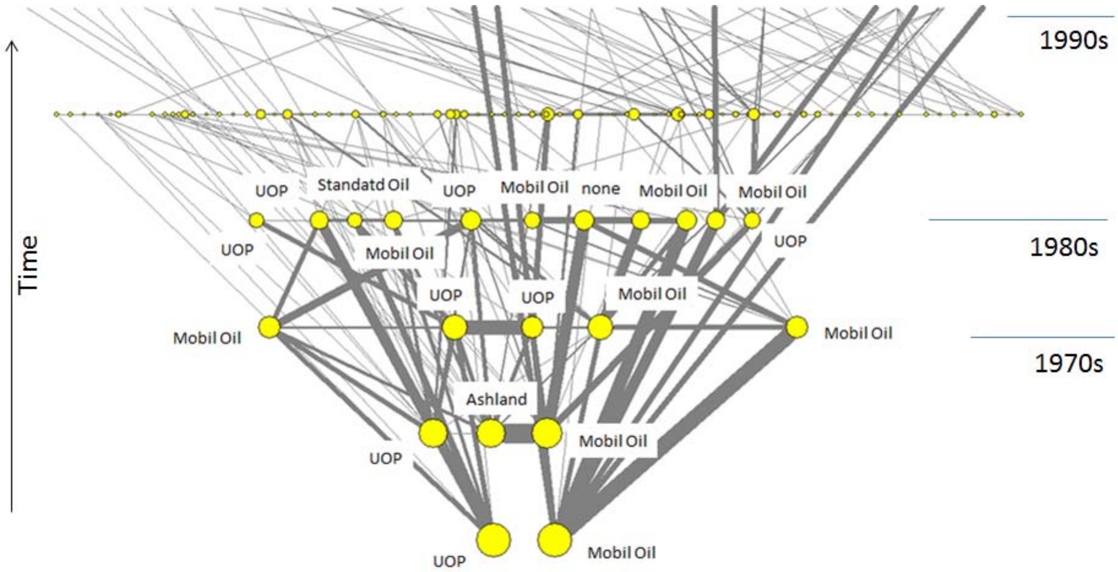

Fig 8. Island 3: Processes and apparatuses for fluidized catalytic cracking (FCC)