Technological Forecasting & Social Change 81 (2014) 388–402

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

FROM MY PERSPECTIVE

Knowledge dynamics and sources of eco-innovation: Mapping the Green Chemistry community

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ARTICLE INFO

Article history:
Received 25 April 2012
Received in revised form 6 October 2012
Accepted 15 March 2013
Available online 9 April 2013

Keywords:
Eco-innovation
Green chemistry
Scientific knowledge dynamics
Epistemic community
Citation network analysis

ABSTRACT

Over the last few decades, the interest for developing a more sustainable chemistry has increased worldwide and has triggered the proliferation of new knowledge. The present article aims at investigating the dynamics of scientific knowledge underlying this emergent field, the main countries and organizations involved, and the factors that have shaped the evolution of the field. In order to circumscribe such a still fluid area of research, we first show how an epistemic community around the concept of Green Chemistry (GC) has emerged and materialized. We then build an original dataset of scientific publications generated by this community and apply two algorithms for the analysis of citation networks. That allows us to identify and analyze the scientific knowledge that laid the foundations of the GC community and the main scientific trajectory that emerged along its whole evolution. The results highlight that the GC community, strongly supported by the US EPA, has grown exponentially since 2000 and has spread among a wide range of countries, including emerging countries. The results also suggest that policy and industry interests, as well as regulation, have played a significant role in shaping the emergence and evolution of GC.

1. Introduction

A grand challenge facing modern economy is to move towards more sustainable systems of production and consumption. Addressing this challenge will require to modify the relationship with natural resources, to rethink the ways of producing and using materials, and finally to call into question patterns of consumption. On the supply side, this transition toward more sustainable systems mainly depends on eco-innovation, i.e., the ability of firms to develop new methods, products and/or processes which benefit the environment and contribute to environmental sustainability [1].

Within this perspective, 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 is energy-intensive, it is responsible for producing, using and transporting many harmful substances, and chemical products are largely created using non-renewable, petroleum-based resources as feedstocks. The chemical industry also releases more hazardous waste to the environment than any other sector, and more in total than is released by the next nine sectors combined [2]. For those reasons, the sector is characterized by very stringent environmental regulation, which can take the form of product bans that impede the use of harmful chemical inputs in the production process itself, thus forcing chemical producers to look for alternative substances and changing the traditional production practices [3].

As a consequence of the impact on human and environmental health of traditional chemical products and processes, the interest for developing a more sustainable chemistry has increased worldwide over the last few decades and has triggered the proliferation of new knowledge, which has taken a multiplicity of appellations. Such a multiplicity is symptomatic

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0040-1625/$ – see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.techfore.2013.03.006

of the fuzziness of the field: being this an emerging field, its boundaries are not well defined, in the community of practitioners there are different visions on “how to do things” and a variety of directions of search are currently explored.

Scientific research, often supported by government initiatives, has made a fundamental contribution to the development of this new way of doing chemistry. This is mainly due to the science-based nature of the chemical industry, which typically benefits from the important and direct contribution of scientific advances for innovating [4]. In spite of that, no systematic quantitative evidence has been yet provided in order to examine the scientific knowledge underlying the “movement” towards a more sustainable chemistry. The novelty of the present article is to fill that gap in the literature by addressing the following questions. How can we delineate the boundaries of this emerging scientific field? What are the most relevant scientific advances that are driving the evolution of the field? What are the main countries and organizations involved? What are the factors that have shaped the emergence and evolution of the field? The answers to those questions are relevant for understanding both the technological trajectories that are moving towards a more sustainable chemistry and the sources of eco-innovation in the chemical industry.

In order to answer the mentioned questions, we first review the historical and specialized literature of the field, and interacted with the community of practitioners. On this basis, we show that despite the diversity of visions and approaches of practitioners, an epistemic community has emerged and materialized around the concept of Green Chemistry (GC). Second, we take the GC community as unit of our analysis, build an original dataset of scientific publications generated by this community and discuss the main trends emerging from its examination. In doing so, we highlight how GC knowledge evolved over time and spread among different scientific journals, disciplines and countries. Third, we further investigate GC knowledge by constructing a network of citations among GC publications and using two network analysis algorithms, namely the Hubs and Authorities algorithm and the Main Path algorithm. That allows us to identify and analyze the scientific knowledge that laid the foundations of the GC community and the main scientific trajectory that emerged along its whole evolution, as well as the countries and organizations involved in the generation of that knowledge. The analysis of the scientific knowledge selected by network analysis algorithms also allows us to discuss the factors that have shaped the emergence and evolution of the GC community.

The rest of the article is organized as follow. In Section 2, we outline the historical evolution of GC and its main research areas. We then present the GC community, which is defined and characterized as an epistemic community. Section 3 illustrates the data and methods. Section 4 shows the results of our empirical analysis and discusses the factors that have shaped the GC community, as revealed by the study of scientific publications selected by the network analysis algorithms. Section 5 concludes.

2. Background

2.1. The historical evolution of GC

Under societal and political pressures, the last few decades have witnessed the emergence of new knowledge aimed at developing a more sustainable chemical industry. In the 1980s, several environmentally conscious terms, like clean chemistry, environmental chemistry, green chemistry, benign chemistry and sustainable chemistry, entered the chemical arena, and still today scientists use a variety of terms to qualify sustainability research in chemistry, talking about bio-based chemistry, biomass chemistry, decarbonized chemistry, renewable carbon chemistry etc. Such a multiplicity of terms, whose boundaries are not precisely defined, is symptomatic of the fuzziness of the field and of the different visions underlying such an emergent area of research.

Despite that diversity of terms and visions, a Green Chemistry movement came out and materialized, strongly supported by a network of professionals from the academic, industry and policy spheres. That is also shown by the rapid growth, since 1998, of term “green chemistry” in scientific publications (see Fig. 1 in Appendix A) and in public debate. Linthorst [5] provides a historical analysis of the origins and development of GC, stressing a three-stage process of construction. The first period goes from the 1980s until end of 1993 and is characterized by the need for adopting pollution prevention, rather than a command and control policy, at the level of the US Environmental Protection Agency (EPA). This new approach was politically formalized in the Pollution Prevention Act of 1990, which outlined the shared interest of government and chemical industry to cooperate and opened financial means to EPA for launching new programs aimed at developing alternative synthetic designs.

The second period [1993–1998] is marked by a movement of progressive institutionalization of GC. A symposium was organized to allow networking and cooperation between industry, academia and government, but also between nations like Japan and Italy. During these years, the terminology started to change in favor of the term green chemistry (compared to benign chemistry for example). In 1998, Prof. Paul Anastas, who is also an EPA representative, and John Warner published the first handbook on GC [2], in which they expose the GC objectives, visions and challenges. Here, the authors define GC as the “design of chemical products and processes to reduce or eliminate the use and generation of hazardous substances” and illustrate the 12 principles of GC, a set of “design rules” to help chemists developing GC.[1] Linthorst [5] notes that this handbook clearly results from a politically supported network originating from the US. Political support of the concept of GC continued in the following years, taking the form of the US Presidential GC Challenge Awards (1995), the GC Institute (a non-profit organization funded in 1997 and aimed at the incorporation and dissemination of GC principles), the GC Network (1998), and the Green Chemistry Journal (1999), a scientific journal explicitly focused on GC research.

The third period [1999–2008] is characterized by a significant contribution of the Green Chemistry Journal (GCJ) in terms of output. In 2009, its tenth year of publication, the GCJ was ranked #15 out of 140 chemistry journals according to highest impact factor.[2] Networking activities, special issues, conferences and a continuous political support were all drivers for the growth of GC in this period. It is also important to note that, since the beginning, the EPA put particular emphasis on promoting networking and cooperation between academic

[1] The list of the 12 principles of GC is contained in Appendix A.

[2] ISI Web of Knowledge, Journal Citation Report.