Thoughts on the Short History of the Field*

by Pietro Tundo and Fabio Aricò

The adoption of green chemistry as one of the primary methods of pollution prevention is a fairly recent phenomenon. It is certainly reasonable to question why this fairly straightforward approach is only now taking hold. The answer is found in a combination of economic, regulatory, scientific, and even social factors, which coalesced in the 1990s to give rise to green chemistry. Since then, green chemistry has found implementation and commercialization on a wide scale.

Fabio Aricò (left) and Pietro Tundo.

Since the early 1960s, environmental statutes and regulations have proliferated at an exponential rate. With these regulations came costs, restrictions on the use of chemicals, and increased testing of chemical substances to determine their hazards. This provided powerful incentives for industry to find replacements, substitutes, or alternatives. The toxicity testing required by many of these statutes generated new knowledge and a new awareness about the types and degrees of hazard associated with many chemicals.

As this collective knowledge grew in scientific and industrial circles, there was corresponding growth in the public's demand for more information about chemicals that are present in their communities. For example, in the USA, this culminated in the 1980s with the passage of the Emergency Planning and Community Right-to-Know Act (EPCRA), which made public relevant data on chemicals being released to the air, water, and land by industry. As a consequence, industry has been confronted by tremendous pressure, not only to reduce the release of toxic chemicals to the environment, but also to reduce the use of hazardous chemicals overall. Thus, it is not surprising that since 1990, sustainable chemistry has been an official focus of the U.S. Environmental Protection Agency, involving a great deal of activity in research, symposia, and education.

The year 1993 was formative for the green chemistry movement as Paul T. Anastas and Carol A. Farris published the first book of the ACS symposium series: *Benign by Design, Alternative Synthetic Design for Pollution Prevention* (ISBN-10: 0841230536). The book was based on a symposium sponsored by the Division of Environmental Chemistry at the 206th National Meeting of the American Chemical Society in Chicago (22–27 August 1993). Most importantly, this book provided an opportunity for several chemists who were pioneers in the field to present their basic research and encourage other scientists to become involved in environmentally responsible chemistry.

In the same year in Italy, the Consorzio Interuniversitario "La Chimica per l'Ambiente" (Interuniversity Consortium Chemistry for the Environment), or INCA, was established with the aim of uniting academic groups concerned with chemistry and the environment. One of its main focus areas became pollution prevention through the development of cleaner reactions, products, and processes. INCA organized its first meeting in Venice, Processi Chimici Innovativi e Tutela dell'Ambiente (Innovative Chemical Processes and Environmental Protection), in February 1993.

However, it was only between 1996 and 1997 that the term green chemistry was first used. The definition "green chemistry" or "sustainable chemistry" has been the subject of a long debate. Both expressions have been used for the same or very similar meanings, but each has its supporters and detractors. The word "green" is brightly evocative, but may assume unintended connotations,[1] whereas "sustainable" can be paraphrased as "chemistry for a sustainable environment," and may be perceived as a less focused and less incisive description of the discipline. Other terms have been proposed, such as "chemistry for the environment," but this combination of words does not capture the economic and social implications of the concept of sustainability. Herein, the term green chemistry will be used for the purposes of this article.

* This article is not intended to be exhaustive, but merely provide a brief overview of the ongoing research and events in the field of green chemistry. In that regard, the authors apologize in advance for unintentionally omitting any additional projects that have helped shape the field of Green Chemistry.

Green chemistry is defined by IUPAC as follows: "The invention, design, and application of chemical products and processes to reduce or to eliminate the use and generation of hazardous substances" (*Pure and Applied Chemistry*, 2000, Vol. 72, No. 7, pp. 1207–1228).

This definition is not only straightforward, but it also marks a significant departure from the manner in which environmental issues have been considered or ignored in the up-front design of the molecules and molecular transformations that are at the heart of the chemical enterprise. Paul Anastas, then of the EPA, and John C. Warner developed 12 principles of green chemistry, which illustrate the definition in a practical sense. The principles cover such concepts as:

Invention and design imply that the impacts of chemical products and chemical processes are included in the design criteria. This definition inextricably links hazard considerations to performance criteria.

Use and generation signify that green chemistry must focus not only on those undesirable substances that might be inadvertently produced in a process, but also on all substances that are part of the process. In this sense, green chemistry recognizes that there are significant consequences associated with the use of hazardous substances, including regulatory, handling and transport, and liability issues, to name a few.

Hazardous means that green chemistry is a way of dealing with risk reduction and pollution prevention by addressing the intrinsic hazards of the substances rather than those circumstances and conditions of their use that might increase their risk.

A conference on Challenging Perspectives on Green Chemistry was held in Venice in 1997.

In August 1996, IUPAC began its involvement in the green chemistry field with the creation of the Working Party on Synthetic Pathways and Processes in Green Chemistry (Seoul, Korea 1996). A year later, in September 1997, the First International Conference on Challenging Perspectives on Green Chemistry was held in Venice. The meeting was sponsored by IUPAC and co-sponsored by ACS, EPA, and UNESCO. Since then, IUPAC has been actively involved in several projects related to green chemistry:

- International Conference on Organic Synthesis ICOS 13, Mini Symposium on Green Organic Synthesis, Warsaw, Poland, 2000
- Special Topic Issue and Symposium-in Print on Green Chemistry, *Pure and Applied Chemistry*, 2000, Vol. 72, No. 7
- a CHEMRAWN (Chemistry Research Applied to World Needs) conference in Boulder, Colorado, USA, June 2001, titled Toward Environmentally Benign Process and Products
- 38th IUPAC Congress, Brisbane, Australia, 2001, which had as one of its five themes, Environmental Chemistry and the Greening of Industry
- Workshop on Education in Green/Sustainable Chemistry, Venice, Italy, 2001
- ICOS 14 in Christchurch, New Zealand, July 2002, at which there was a Symposium on Green Chemistry

This year, IUPAC organized the CHEMRAWN-XVII and ICCDU-IX Conference on Greenhouse Gases—Mitigation and Utilization, held in Kingston, Ontario, Canada, from 8–12 July 2007.

In July 2001, IUPAC approved the establishment of the Subcommittee on Green Chemistry (under the Organic and Biomolecular Chemistry Division, Division III). The committee's primary focus is to establish and carry out educational green chemistry programs. Since its conception, the subcommittee has actively organized international workshops, symposia, and conferences in addition to preparing and disseminating numerous books (the Green Chemistry Series) on global topics related to green/sustainable chemistry, which are specifically aimed at university students. Current projects and activities include:

- Global Climate Change—translation and dissemination of a monograph for secondary schools (IUPAC project 2005-015-1-300)
- an online Green/Sustainable Chemistry Directory (IUPAC project 2002-029-1-300, jointly with INCA) <www.incaweb.org/transit/iupacgcdir/INDEX.htm>

- Green Chemistry in the Arab region (IUPAC project 2003-043-1-300).

Another important step in the development of green chemistry was the foundation in 1997 of the Green Chemistry Institute (GCI) in the USA. After more than a year of planning by individuals from industry, government, and academia, GCI was incorporated in 1997 as a not-for-profit corporation devoted to promoting and advancing green chemistry. In January 2001, GCI joined the American Chemical Society in an effort to address global issues at the intersection of chemistry and the environment.

From its earliest days, the Institute has sought to be the premier change agent that has the knowledge, expertise, and capabilities to catalyze the movement of the chemical enterprise toward sustainability through the application of green chemistry principles. To fulfil its mission, GCI supports research, works to integrate green chemistry into all levels of chemical education, aides companies with industrial implementation, hosts conferences, and coordinates efforts with an international network of green chemistry advocates. The GCI also provides national recognition for outstanding student contributions to furthering the goals of green chemistry.

GCI offers two well-known awards established in memory of Kenneth G. Hancock and Joseph Breen. Hancock, former director of the Division of Chemistry at the National Science Foundation, was one of the earliest proponents of green chemistry and "environmentally benign chemical synthesis and processing." The Hancock Memorial Award in Green Chemistry allows undergraduate and graduate students an opportunity to compete for a prestigious award in recognition of their studies and/or research in green chemistry.

GCI and ACS also established the Joseph Breen Memorial Fund through the ACS International Endowment Fund in 2000. Breen was a founder of the worldwide green chemistry movement and the first director of the Green Chemistry Institute. This fund commemorates his commitment and accomplishments, and each year awards one or more fellowships.

In the late 1990s and at the beginning of the new millennium, interest in green chemistry spread all over the world. In 1998, following an EPA proposal, the OECD (Organization for Economic Co-operation and Development) issued a directive to develop a program on sustainable chemistry. The USA and Japan were nominated co-leaders in the field of research and development, while Italy was appointed leader of education. In particular, INCA was chosen as coordinator of the Educational Acts on Green Chemistry for OECD.

A year later, in 1999 the Royal Society of Chemistry (UK) introduced a new journal entirely dedicated to sustainable chemistry: *Green Chemistry*. Around the same time, similar projects were initiated in many other countries. Following are just a few examples:

- foundation of the Green Chemistry Institute of Spain in February 2000
- creation of the Green and Sustainable Chemistry Network in Japan in 1988 (officially operating since 2000), which in 2007 co-organized the first Asian-Oceania Conference on Green and Sustainable Chemistry
- the foundation of the Centre of Green Chemistry of Monash University in Australia, operating since January 2000

In addition, the German government has begun to dedicate special attention to renewable chemistry. In 2002, in connection with the Johannesburg's "World Summit for Sustainable Development," the government launched an international conference to promote the use of renewable energy in industrial and global development processes. The conference was held in Bonn and gathered 3600 participants.

In order to address the increasing need for green chemistry education, the Carnegie Group (the biannual meeting of the G8 Ministers for Research), which was held in Victoria, Canada (2–3 June 2005) and in New York (2–3 December 2005), founded a research and training network on green-sustainable chemistry called the International Green Network (IGN). The network was unanimously approved, following a proposal by the Italian minister for Education, Research, and University. INCA, located in Venice, Italy, was selected as the hub of IGN. INCA and the other research centers dedicate a space within their institutes to the IGN.

The IGN aims to provide know-how, coordination and sponsorship for scientific collaborations, proper training for the new generation of chemists, and support for sustainable use of chemistry in developing nations. INCA organized the kick-off meeting of the IGN on 1 December 2005 (Marghera, Venice). Delegates of all the G8 countries participated, as well as observers from other nations and prominent invited speakers. The purpose of the event was to officially inaugurate IGN, illustrate its goals (both scientific and political), and gather feedback from delegates. A document presented at the meeting, and approved shortly afterward by the Carnegie Group in New York, outlines the goals and mission of IGN.

Green Chemistry on the Rise

Another green chemistry network was founded in December 2005: the Mediterranean Countries Network on Green Chemistry (MEGREC). The network was created to further facilitate increasing collaboration between the European regions of the Mediterranean and North Africa on green chemistry issues. The official ceremony was held during the first board meeting at the University of Belgrade.

The MEGREC founding institutions include the Suez Canal University, Ismailia (Egypt); University Institute of Science and Technology, (Barcelona, Spain); Fez University (Morocco); Belgrade University (Serbia); Athens University (Greece); and INCA, Venice (Italy).

Among the objectives of the MEGREC program are the creation of a university master course (second level) on green chemistry and the recruitment of young researchers who will conduct research in the laboratories of partner institutions.

In Latin American countries, the scientific community is focusing intensively on green chemistry by developing a scientific collaboration called Chemistry for Clear Reactions and Processes: Green Chemistry. This joint project has already provided fellowship opportunities at an Italian university for researchers from Chile, Argentina, Brazil, Uruguay, Costa Rica, and Venezuela.

In 2006, INCA and the German Chemical Society organized the first international IUPAC conference dedicated to green-sustainable chemistry (see conference report, May-June 2007 *CI*, pp. 30–32). The meeting, held 10–15 September 2006, was organized under the auspices of IUPAC, the Italian Ministry of Research, Federal Ministry of Environment, Nature Conservation and Nuclear Safety, and the German Federal Environmental Ministry. The wide selection of topics offered at the conference attracted industrial researchers and representatives, university researchers, politicians, and students. The enormous effort of the organization committee fully paid off with over 450 participants attending from 42 countries. Upon conclusion of the conference, the organization committee extended an invitation to all delegates to participate in the Second International IUPAC Conference on Green Chemistry to be held aboard a luxury cruiseliner that will travel from Moscow to St. Petersburg. The conference is scheduled to take place in the last week of September 2008.

Another important step in the history of green chemistry has been realized with the introduction of REACH (Registration, Evaluation and Authorisation of Chemicals Regulation), which was formally adopted on 18 December 2006 by the European Council of Environment Ministers. This new regulation aims to improve the protection of human health and the environment through improved assessment of chemical substances. Thus, the REACH Regulation gives greater responsibility to industry as manufacturers and importers will be required to compile information on the properties of their substances and to register the information in a central database. This regulation ultimately calls for a progressive substitution of the most dangerous chemicals when suitable and greener alternatives have been identified, which is the main goal of green chemistry itself. REACH entered into force on 1 June 2007.

The "Floating Tree" by Francesco Tundo appears on the book cover of Green Chemistry Education. *Ref: Green Chemistry Series No. 3, INCA 2002 (ISBN 88 88214 00 5).*

Notes

1. In many countries the word "green" is associated with political parties primarily focused on environmental issues. In the United States, green symbolizes the color of money. Therefore, in areas that use the U.S. Dollar as currency, green carries a connotation of money, wealth, and capitalism. The flag of Libya is entirely green, the only current national flag of a single color. Green is considered the traditional color of Islam, likewise because of its association with nature. Green is a symbol of Ireland, which is often referred to as "the Emerald Isle" (Green represents also St. Patrick's Day). The color is particularly identified with the republican and nationalist traditions in modern times in balance with the Protestant orange. Green is thought to be an unlucky color in British and British-derived cultures, where green cars, wedding dresses, and theatre costumes are all the objects of superstition. In Dante's *Divine Comedy*, green is the color used to symbolize hope. In the Roman Catholic church, green is a traditional color symbolizing hope and the tree of life. The color green is often used as a symbol of sickness. In Japan, green indicates safety and luxury. In the Russian language, green is synonymous with "not ripe."

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