Report

Green Chemistry and Education

by Dennis L. Hjeresen, David L. Schutt, and Janet M. Boese

Many students today are profoundly interested in the sustainability of their world. With growing public concern over global warming and greenhouse gases, students want to understand how human actions affect the health of our planet. Students are deeply concerned about pollution. They practice recycling. Moreover, they want to secure a healthy Earth for future generations. As students of chemistry, they have a unique opportunity to start at the ground floor of the exciting and expanding field of green chemistry.

The Emergence of Green Chemistry

Green Chemistry has evolved from its roots in academic research to become a mainstream practice supported by academia, industry, and government. While Green Chemistry encompasses human health and the environment, it is guided by very specific principles of chemical practice. These principles are summarized as the Twelve Principles of Green Chemistry in the box on p 1544. The interest in using green chemistry and its practices has extended internationally to become an alternative to traditional pollute-and-then-clean-up industrial practice in developing countries. This evolution is marked by significant contributions from institutions with different goals that are being satisfied through a common mechanism.

Green chemistry is the use of chemistry for pollution prevention. More specifically, it is the design of chemical products and processes that are environmentally benign. Green chemistry encompasses all aspects and types of chemical processes that reduce negative impacts to human health and the environment. At its best, green chemistry is environmentally benign, linking the design of chemical products and processes with their impacts on human health and the environment.

In the United States, the focus on Green Chemistry began in earnest after the passage of the Pollution Prevention Act of 1990. The U.S. Environmental Protection Agency established the Office of Pollution Prevention and Toxics (OPPT) to explore the idea of developing new or improving existing chemical products and processes to make them less hazardous to human health and the environment. The Office launched a research program called "Alternative Synthetic Pathways for Pollution Prevention". This program provided unprecedented grants for research projects that include pollution prevention in the design and synthesis of chemicals.

Why Green Chemistry?

There is no doubt that our lives have been enhanced by chemistry. That is something chemists and students need to celebrate. However, environmental problems such DDT, ozone depletion, the Love Canal, Bhopal, and the Cuyahoga River are all too familiar examples of chemistry gone wrong. In responding to the growing concern, governments introduced regulations to limit pollution and exposure to hazardous chemical and materials. Green chemistry represents a fundamental shift from this model toward a pollution prevention paradigm. Its premise is that a benign process and product presents no risk.

The importance of green chemistry as an alternative in the developing world cannot be overstressed. Sustainable development depends on providing goods and services for a growing population without sacrificing environmental quality. Estimates from the United Nations put the world population as high as 10.7 billion people by 2050 and this nearly doubled population creates a huge demand for chemical goods and services in the near future. Much of the growth of the chemical industry is likely to take place in the developing world, coincident with the rising population. However, many of the global environmental impacts attributable to this population growth have ties to chemical processes or products:[1]

- loss of biological species in forests and in waters
- ozone depletion
- downstream pollution from unsustainable agricultural practices
- the pollution of fresh and marine waters, further depleting food sources
- the introduction of persistent organic pollutants into the ecosystem
- changing climate, causing as yet unpredictable changes in the hydrologic cycle with manifestations in flood, drought, sea-level change, and the spread of infectious diseases

The Green Chemistry Institute

A major force in taking the concept and the practice of green chemistry around the world has been the Green Chemistry Institute (GCI). Created in 1997, the Institute flourished by promoting and fostering the furtherance of Green Chemistry through research, education, conferences/deliberative symposia/meetings, and information dissemination including public awareness. The organization itself is made up of institutions from around the world that represent all aspects of the chemical enterprise: industry, academia, non-governmental organizations, and government.

At the 220th Meeting of the American Chemical Society in August 2000, the Board of Directors unanimously approved an alliance between ACS and the Green Chemistry Institute. A key objective of the ACS/GCI alliance is establishing Green Chemistry as a national research priority by aligning the interests of policy makers, business leaders, and the scientific community in new initiatives.

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Educational Materials and Resources

One factor that is greatly speeding the incorporation of pollution prevention into industrial manufacturing processes is the development of green chemistry curriculum materials. The chemical industry is discovering that when their chemists are knowledgeable about pollution-prevention concepts, they are able to identify, develop, and implement techniques that reduce pollution and *costs*. To facilitate the inclusion of green chemistry into the classroom, the ACS Division of Education and International Activities and EPA-OPPT jointly designed materials to provide succeeding generations of chemists with the skills and knowledge to practice green chemistry. Some of these educational materials are listed on p 1546. While the primary audience of these materials is undergraduate and graduate chemistry students, the audience may also include professional chemists, K–12 students, and the general public.

Additional key educational tools in shaping interest in Green Chemistry are dedicated fellowships, scholarships, and research grants. These funds allow students and faculty to focus sustained attention on specific research tasks (see p 1547 and p 1554). Similarly, attending workshops, symposia, and conferences allows students, teachers, and researchers alike to gain an in-depth understanding of green chemistry. A listing of upcoming conferences is available at *http://www.acs.org/education/greenchem/resources.html#conferences* and at *http://www.lanl.gov/greenchemistry/conf.html*.

ACS and GCI in partnership with the International Union of Pure and Applied Chemistry (IUPAC) will sponsor the CHEMRAWN XIV World Conference on Green Chemistry, "Toward Environmentally Benign Processes and Products".[2] The Conference, which will be held in Boulder, Colorado, July 9–13, 2001, will bring together leaders from governments, industry, and academia. The purpose is to formulate a path for sustainable development where upstream pollution prevention is used to create a balance between economic development and environmental protection. The meeting is open to the public, and a strong student program makes CHEMRAWN XIV a powerful educational and networking opportunity.

The GCI also disseminates information through a Web site and email list-server.[3] The Web site provides information on GCI; Green Chemistry activities worldwide; and links to government, industry, and academic Web sites with related information. The email list-server links more than 300 participants in a common system, allowing rapid dissemination of information such as job openings and upcoming conferences as well as a venue through which to pose questions to subject-matter experts.

The Future

There is no doubt that the emerging area of green chemistry has identified scientific principles, approaches, and methodologies that have demonstrated the most positive aspects of chemistry. While the successes of green chemistry thus far seem quite large in terms of quantitative benefit to human health and the environment, they are merely the tip of the iceberg when compared to the potential. To reach this full potential, greater awareness, adoption, and development of green chemistry practices are necessary.

Sustainable economic development depends on the chemical industry to produce a vast array of products and processes. Yet despite years of impressive improvements in

Twelve Principles of Green Chemistry[4]

Prevention: It is better to prevent waste than to treat or clean up waste after it has been created.

Atom Economy: Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.

Less Hazardous Chemical Syntheses: Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.

Designing Safer Chemicals: Chemical products should be designed to effect their desired function while minimizing their toxicity.

Safer Solvents and Auxiliaries: The use of auxiliary substances (solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.

Design for Energy Efficiency: Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.

Use of Renewable Feedstocks: A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.

Reduce Derivatives: Unnecessary derivatization (use of blocking groups, protection/deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.

Catalysis: Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.

Design for Degradation: Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.

Real-Time Analysis for Pollution Prevention: Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.

Inherently Safer Chemistry for Accident Prevention: Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

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Green Chemistry Teaching Materials

Educational Materials from ACS

The ACS Division of Education and International Activities, in partnership with the U.S. Environmental Protection Agency Office of Pollution Prevention and Toxics, is developing and disseminating educational materials related to green chemistry. In the two years of this cooperative agreement, the project worked with a number of individuals with expertise in green chemistry to produce classroom resources and to disseminate information about green chemistry through workshops, meetings, and symposia.

Available Resources

Annotated Bibliography on Green Chemistry (Version 1.0, 1999) by John C. Warner, Elizabeth Brown, and Carlos Tassa. The bibliography is intended as a general reference tool for use in the chemistry curriculum and not as an exhaustive data base on green chemistry. It has been posted as a searchable data base to the ACS Education Web page *http://center.acs.org/applications/greenchem/*. The data base will be updated and enlarged periodically. The Bibliography is available only on the World Wide Web, not on paper.

Real-World Cases in Green Chemistry by Michael C. Cann and Marc E. Connelly (published 2000). This 72-page book is designed to be used in a variety of undergraduate courses or as a resource of specific examples of redesigning chemical products and processes. It contains descriptions of ten projects that have won or been nominated for Presidential Green Chemistry Challenge awards. Also included are references and questions at the end of each case and a Notes to Instructors section at the end of the text. Additional information is at *http://www.acs.org/education/greenchem/cases.html*.

Green Chemistry: Innovations for a Cleaner World is a 15-minute videotape (May/June 2000) that features the three winners of the Presidential Green Chemistry Challenge Awards. The video can be used independently or as a supplement to *Real-World Cases in Green Chemistry.* Available fall 2000.

Green Chemistry: Economic and Environmental Benefits is a new ACS short course that was first presented at the ACS National Meeting in Washington, DC. The developers and presenters of this course were Paul Anastas, Mary Kirchhoff, and Tracy Williamson; all are affiliated with EPA.

Green chemistry articles or examples have been included in various other ACS publications:

Chem Matters, the magazine for high school chemistry students, has highlighted green chemistry through, for example, an overview of the Presidential Green Chemistry Challenge Award winners, and a feature on the use of liquid CO_2 for dry cleaning.

In Chemistry, the magazine for ACS Student Affiliates, featured green chemistry articles in 1998 and 1999.

The third edition of *Chemistry in Context*, released in the fall of 2000, includes examples of green chemistry throughout. Similarly, future texts published by ACS Education Division will include green chemistry examples.

Resources in Development

Resources in development for publication by ACS in 2001–2002 include Web dissemination of green chemistry labs, publication of green chemistry demonstrations, green chemistry teaching modules for high school chemistry teachers, a green chemistry speakers roster, publication of readings in green chemistry, and green chemistry video resource for high school classes.

JCE Resources for Incorporating Green Chemistry into Teaching

The *Journal* has published these articles on green chemistry:

Green Chemistry in the Organic Teaching Laboratory: An Environmentally Benign Synthesis of Adipic Acid, Scott M. Reed and James E. Hutchison, *J. Chem. Educ.* **2000,** *77*, 1627.

The Cost of Converting a Gasoline-Powered Vehicle to Propane: An Excellent Review Problem for Senior High School or Introductory Chemistry, Michael P. Jansen, *J. Chem. Educ.* **2000,** *77*, 1578.

Bringing State-of-the-Art, Applied, Novel, Green Chemistry to the Classroom by Employing the Presidential Green Chemistry Challenge Awards, Michael C. Cann, *J. Chem. Educ.* **1999,** *76*, 1639.

Microscale Chemistry and Green Chemistry: Complementary Pedagogies, Mono M. Singh, Zvi Szafran, and Ronald M. Pike, *J. Chem. Educ.* **1999,** *76*, 1684.

Introducing Green Chemistry in Teaching and Research, Terrence J. Collins, *J. Chem. Educ.* **1995,** *72*, 96.

World Wide Web Resources

Some Web sites that may be useful for those trying to incorporate green chemistry into their teaching appear below. All were accessed at press time (October 2000).

Green Chemistry Resources, ACS homepage:
http://www.acs.org/education/greenchem/
From there go to Web sites, Awards, Conferences, Calendars

Green Chemistry Institute:
http://www.lanl.gov/greenchemistry/

EPA's Green Chemistry Program:
http://www.epa.gov/greenchemistry/

Green Chemistry, a journal of the Royal Society of Chemistry:
http://www.rsc.org/is/journals/current/green/greenpub.htm

Green Chemistry Resources on the Internet, published in *the February 2000 issue of Green Chemistry:*
http://www.rsc.org/is/journals/current/green/GC002001.htm

Green Chemistry Network:
http://chemsoc.org/networks/gcn/

waste treatment and abatement, the chemical industry is often viewed as a significant cause of environmental degradation. Customer and regulator expectations for environmentally benign processes and products require that industry develop innovative and competitive approaches to pollution prevention. Green Chemistry provides an approach focused on the principle of moving pollution prevention upstream to change fundamental processes and emphasizes the use of chemical principles and methodologies for source reduction. Green Chemistry is a dynamic match of scientific, economic, and social interests that leads to a future where chemistry is viewed as fundamental to protecting the environment. However, the success of Green Chemistry depends directly on the training and dedication of a new generation of chemists—the students of today.

Literature Cited

1. Benedick, R. E., "Human Population and Environmental Stresses in the Twenty-first Century" *in Globaler Wandel–Global Change: Ursachenkomplexe und Lösungsansätze* (*Global Transformation–Global Change: Causal Structures, Indicative Solutions*); Kreibich, R. and Simonis, U. E. Eds.; Berlin, 2000. As reprinted *in Environmental Change & Security Project Report*, Issue 6 (Summer 2000). Washington, DC. Wilson Center.
2. CHEMRAWN XIV Web site: *http://cires.colorado.edu/env_prog/chemrawn/*
3. GCI Web site: *http://www.lanl.gov/greenchemistry/*. Listserver: *gci@lanl.gov*
4. Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*; Oxford University Press: New York, 1998; p 30.

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Fellowship Opportunities in Green Chemistry

Joe Breen Memorial Fund. The Green Chemistry Institute (GCI) and the American Chemical Society (ACS) have established the Joseph Breen Memorial Fund, which sponsors the participation of a young international Green Chemistry scholar in a Green Chemistry technical meeting, conference, or training program. "Young" is defined as above high school but below assistant professor. One or more fellowships will be awarded each year. This fund commemorates Joe Breen's commitment to and accomplishments for the advancement of Green Chemistry. See p 1553 for available details.

Hancock Memorial Scholarship in Green Chemistry. This scholarship is offered under the auspices of the ACS Division of Environmental Chemistry and provides national recognition for outstanding student contributions to furthering the goals of Green Chemistry through research or education. Kenneth G. Hancock, director of the division of chemistry at NSF, was one of the earliest proponents of green chemistry and the "environmentally benign chemical synthesis and processing" approach. He was an active advocate of emphasizing the role of chemists and chemistry not only in solving existing environmental problems but more importantly in avoiding environmental problems in an economically viable fashion. See p 1553 for application details.