Commentary

Completing Our Education

Green Chemistry in the Curriculum

by Birgit Braun, Reagan Charney, Andres Clarens, Jennifer Farrugia, Christopher Kitchens,*
Carmen Lisowski, David Naistat, and Adam O'Neil

In July 2005 the third annual ACS Green Chemistry Summer School (GCSS) sponsored by ExxonMobil and hosted by McGill University in Montréal, Québec, Canada, provided 60 graduate and post-doctoral students an opportunity to learn about the principles of green chemistry (GC) from leaders in the field. General applications of green chemistry, including sustainability, product design, and toxicology were discussed, while tools such as life-cycle analysis, atom efficiency, structure–activity relationships, and eco-design were presented. The goal of the GCSS is to educate students and enable them to incorporate these concepts into their personal endeavors.

A common belief among the GCSS participants was that our education would have been significantly enhanced with the incorporation of green chemistry, beginning at the elementary level and continuing throughout graduate course work. The field of GC has been continuously developing since the late 1990s, when most of the students at the summer school were completing their undergraduate research. However, nearly 10 years later, it is unfortunate that GC is not addressed to a greater extent in the chemistry and chemical engineering curriculum. As researchers, we strive to develop new technologies yet often fail to consider the environmental impact of our work, particularly less quantifiable dangers, such as bioaccumulation and endocrine disruption, which are seldom presented to scientists outside the environmental or medical fields. Therefore, the implementation of GC as an inherent component of the chemistry and chemical engineering curriculum is not just desirable, it is necessary. The successful implementation of GC principles into industrial processes is a formidable challenge we are forced to face in the 21st century.

As the general public, political leadership, and the scientific community continue to recognize the environmental consequences resulting from decades of industrial production, chemists and chemical engineers find themselves uniquely positioned to lead the way to a sustainable future. In this paper, we wish to express our views as graduate students with respect to the concepts and strategies for successful implementation of GC into undergraduate and graduate education.

Benefits of Green Chemistry in the Curriculum

Future chemists and chemical engineers must be equipped with the tools necessary to support and promote global sustainability. Incorporation of the 12 principles of green chemistry into class material is essential for providing a solid basis for "green" approaches that are valid in both theory and practice *(1)*. The 12 principles can be coupled with specific strategies to enhance and further complement the current chemistry curriculum. They also serve as a reminder that the chemistry we practice has social as well as environmental impacts.

An increasing number of institutions are including GC concepts in their curriculum, and some even offer degrees in GC.[1] The programs at these institutions should be adopted by others and viewed as inspiration, helping to overcome some of the persistent counter-arguments to GC in the classroom. Such arguments include "this is not the way the real world works"; "traditional material is more important than GC concepts"; "there is not enough time to cover the traditional concepts and include new ones"; and simple reluctance to change. The benefits resulting from incorporation of GC concepts are significant and applicable to all levels of education. GC concepts provide a connection between the material taught in class and the students' everyday environment, far beyond pollution, ozone depletion, and global warming. Some examples include the feasibility and limitations of recycling, sustainability aspects of consumer product design, energy efficiency, and the ecological impacts of bioaccumulation and endocrine disruption in aquatic wildlife. With the full inclusion of GC concepts, students of all disciplines, not just the chemical sciences, will have the ability to relate chemical concepts to the "real world" and to their chosen career path *(2)*.

Implementation of Green Chemistry in the Curriculum

An important consideration often mentioned when curriculum modifications are proposed is the already overwhelming amount of information incorporated in chemistry and chemical engineering education. The authors believe that GC is not meant to replace existing class material or be taught as a separate section altogether. Instead, existing classes should be taught in a new way, incorporating key concepts into the curriculum to make chemistry inherently green. In a series of discussions, the authors identified a number of concepts that should be used to enhance the chemistry and chemical engineering curriculum.

General Concepts

- GC is not intended to be a solo discipline, but rather a means for conducting science in a responsible manner. As researchers, we need to be aware that the current state-of-the-art processes are not perfect, and only the constant drive for improvement will lead to a sustainable future.

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- Knowledge of what is considered to be sustainable, renewable, and environmentally benign should be considered a requirement for professionals who design reactions and processes.
- Chemical safety is critical. Students should develop an understanding of the dangers associated with chemicals without retreating to universal fear of chemistry. Adoption of GC principles can lead to safer and more efficient work environments on both the laboratory and industrial scale *(3).*
- Objectivity and rationale are imperative when conducting scientific work. However, creativity—especially during the early stages of education—is often neglected. GC offers a systematic approach to sustainable science while promoting innovative research and creative solutions.

Chemistry

- It is not possible to track the fate of every chemical compound used and generated in a reaction or process. Environmentally benign chemicals are therefore highly desirable.
- Reactions should not only be evaluated based on conversion and selectivity, but also efficiency, sustainability, recyclability, degradation, and elimination or reduction of hazard.
- The connection between chemical structure and compound activity should be made clear to students. Chemical functionality (sterics, electronics, hydrophobicity/philicity, toxicity) can provide a basic understanding of how chemicals impact the environment.
- An enhanced understanding of ecotoxicity and fates and transport of chemicals released to the environment is essential for the overall evaluation of chemical substances.

Engineering

- All industrial processes are imperfect and can always be improved, economically as well as environmentally. Process design should include critical evaluation of current industrial processes with awareness for sustainability, stressing minimal waste production, use of renewable and recycled resources, and highest possible energy efficiency.
- Process evaluation is far-reaching and goes beyond the knowledge of just classical chemistry and chemical engineering. It includes many other disciplines, such as ecology, toxicology, biology, and environmental engineering. Multidisciplinary approaches to problem solving are essential and should be introduced early and supported throughout the curriculum.
- Processes should be designed as "green" when possible, with promotion of resource and energy efficiency, and complete avoidance of end-of-pipe treatments. Waste treatment is exceedingly expensive and its elimination is economically and environmentally beneficial.
- Cradle-to-grave evaluations are essential to the greater impact of processes beyond the immediate sphere of influence. Life cycle assessments must consider factors such as renewable feedstocks, feedstock acquisition, waste treatment, environmental persistence, energy requirements, and energy sources *(4).*

Global Issues

- The current strategy of "outsourcing" motivated by inexpensive labor and lax regulations does hold economic benefits, such as low-priced goods for Western nations, income for developing nations, and the opportunity to build new environmentally conscious facilities close to expanding markets.
- Concurrently, outsourcing will lead to the loss of 3.4 million U.S. jobs by 2015 *(5),* and extreme environmental damage in developing countries, affecting their livelihoods for many generations and depleting natural resources, including energy and clean water *(6).*
- Globalization must be environmentally responsible. GC can provide knowledge and awareness through education of scientists to develop technologies for a sustainable global economy, as well as education of policy makers for environmentally responsible diplomacy.

Including these concepts in an already crowded curriculum is certainly not a trivial task. Teaching existing courses in a new way is probably the most effective way to achieve this educational evolution. These approaches can provide motivation and opportunity for students to excel, explore, and enjoy science on entirely new levels. Nonchemistry majors will be able to relate the theory and application of chemistry to their "real world" and potentially to their chosen career paths *(7).* A curriculum that complements current teachings with the GC principles is a first step in promoting the ideal that green chemistry is inherent to chemistry. These concepts will enhance the chemistry curriculum, providing understanding of the broader impacts of the chemical sciences, bridging gaps between the classroom and the global environment, and, most importantly, helping to complete the education of future chemists and chemical engineers.

Beyond the classroom and the individual, green chemistry requires an interdisciplinary awareness. A multidisciplinary approach to green chemistry education allows students to develop interdisciplinary communication and contacts early on, thus promoting concerted efforts for attacking problems and developing sustainable technologies with global awareness. The Internet is an excellent resource that provides an incredible amount of information for global chemical and environmental news. Educators can utilize this tool to create an interactive classroom that allows students to learn in real time, to develop collaborations with students around the globe, and to teach themselves and others through peer-to-peer networks.

We encourage educators to step outside their "comfort zone" and embark on a mission of teaching these fundamental principles to their students. In doing so, many will find that they too will become students of green chemistry, just as we have. Resources are already available to aid in the incorporation of green chemistry concepts into the curriculum *(8),* including texts *(9),* lab experiments *(10–12),* discussion topics *(13),* online resources,[2] and an article in this *Journal (14).*

Conclusion—The Impacts

Today's students, and ultimately the scientific community of tomorrow, would significantly benefit from the introduction of green chemistry principles into the curriculum. Increasing communication and awareness among chemists, engineers, policy makers, and the general public will lead to a greater responsibility for environmental and global issues. Students will enter the professional world with knowledge of the weaknesses of current industrial processes, coupled with motivation for the development of solutions based on green chemistry principles in an international and interdisciplinary environment. Green chemistry education can provide the required knowledge and awareness to develop the technologies that are necessary to achieve the ultimate goal of a sustainable world.

It must be stressed that green chemistry should not be considered a discipline in itself but rather an approach for conducting science in a responsible manner so future generations are not compromised by today's actions. Green chemistry offers a systematic means to sustainable science based on chemical, environmental, and social responsibility while allowing creativity and innovative research to thrive. Interdisciplinary approaches, outreach programs, recruitment initiatives, and the creation of a global community of educators are ways in which social perceptions of chemistry can be positively influenced. What we ask is that chemical education be enhanced by incorporating the ideals of green chemistry into the curriculum, thus building a foundation that leads to a sustainable chemical enterprise and a sustainable society. With this new way of thinking about chemical education and research, students will be armed with the knowledge needed to effectively address the grand challenges of the 21st century.

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Notes

1. University of Massachusetts–Lowell, Center for Green Chemistry, Doctoral Program in Green Chemistry, Lowell, MA; University of Oregon, Green Chemistry at Oregon, Eugene, OR; University of Scranton, Green Chemistry Education, Scranton, PA; University of Illinois at Urbana-Champaign, Green Chemistry Course, Urbana, IL; Hendrix College, Green Organic Chemistry, Conway, AR; Green Chemistry and Process Engineering, University of Nottingham, UK.

2. ACS Green Chemistry Institute, *http://www.chemistry.org/portal/a/c/s/1/acsdisplay.html?DOC=greenchemistryinstitute\index.html;* ACS Education, Green Chemistry, *http://www.chemistry.org/portal/a/c/s/1/acsdisplay.html?DOC=education\greenchem\index.html;* Green Chemistry Network, *http://www.chemsoc.org/networks/gcn/;* EcoIQ.com Pollution Prevention and Reduction, *http://www.ecoiq.com/pollution/* (accessed Jun 2006); U.S. EPA Green Chemistry, *http://www.epa.gov/greenchemistry/* (accessed Jun 2006).

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Birgit Braun is a graduate student in the Department for Chemical Engineering at the Colorado School of Mines, Golden, CO 80401, and is working on biopolymer composites; bbraun@mines.edu. *Reagan Charney is a second year chemistry graduate student at Georgia Institute of Technology, Atlanta, GA 30332-0400;*reagan.charney@chemistry.gatech.edu. *Andres Clarens is a Ph.D. candidate in environmental engineering at the University of Michigan conducting research in sustainable manufacturing,* http://www.umich.edu/~aclarens; aclarens@umich.edu. *Jennifer Farrugia is a Ph.D. candidate in organic chemistry studying aqueous-phase catalytic hydrogenation of organic acids at Michigan State University, East Lansing, MI 48824;* jfarrug3@chemistry.msu.edu. **Christopher Kitchens is a postdoctoral fellow at Georgia Institute of Technology, School of Chemical and Biomolecular Engineering, Atlanta, GA 30332;* ckitchens@chbe.gatech.edu. *Carmen Lisowski is a graduate student in the Hutchison lab in the Chemistry Department, the University of Oregon, Eugene, OR, 97403;* clisowsk@uoregon.edu. *David Naistat has a Ph.D. in chemistry from the University of Miami, Coral Gables, FL, 33146,* dnaistat@umsis.miami.edu. *Adam O'Neil is a postdoctoral research associate at the University of Massachusetts, Department of Polymer Science and Engineering, Amherst, MA 01003;* oneil@ecs.umass.edu.