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Green approaches: a new horizon for future scientists Student voices from the Pan-American Advanced Studies Institute on Green Chemistry

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Introduction

It's time to accept our share of responsibility for the modern state of the world. With real concerns mounting on the state of global sustainability and newer considerations such as endocrine disruption, we must aggressively pursue the ideals of green chemistry.

We are a new generation of scientists. We have chosen *not* to ignore the potential consequences of our chosen professions. We realize that we have responsibilities in the education, acceptance, and implementation of green chemistry principles.

As a new generation of scientists and engineers, we need to recognize that our actions and decisions will affect the future well being of our planet. While we have the tools to create products and processes that improve our quality of life, we must consciously make choices to ensure that our actions do not endanger life or the environment around us. We strongly believe that by applying the principles of green chemistry to all aspects of science and engineering, we can continue to improve the society in which we live without simultaneously harming it.

In a field where one cannot always go to the literature to discover the answers that one seeks, the Pan-American Advanced Studies Institute on Green Chemistry (PASI-GC) gave us the opportunity to network with people leading their field. Through this program we gained valuable professional experiences as individuals; however, we also realized that these ideals must spread beyond our inner circle in order to be truly effective.

The dissemination of green chemistry will be no easy task. Interdisciplinary cooperation between all scientific fields will be necessary to create new methods of measuring the toxicity, environmental impact, and energy requirements of new and existing chemical compounds and commercial materials. This technology and theory must then be implemented into as many industrial, academic, and government applications as possible. This unique conference has given us the tools to aggressively pursue these goals, rather than to merely talk about them.

Two weeks of intensive presentations, discussions, and actual laboratory time pertaining to green chemistry, its theory, policy, and application, made this a conference like none before it. There were no hierarchical communication barriers between the students involved and the presenters and organizers of this event. The ability to converse casually yet meaningfully about current and future technologies with the people who were responsible for their existence was an experience previously unmatched. This event will have a special place in the memories of all involved for some time to come, as both a model of interaction and an impetus for change.

In this report, we wish to convey the ideology we have acquired through the PASI on Green Chemistry and emphasize how much is still left to be accomplished in the field. We begin with a description of the PASI-GC, followed by a discussion of why green chemistry is important, the multinational and multidisciplinary aspects of the field, and its role in education. We conclude with some specific actions we believe are important for the advancement of green chemistry. We hope to encourage all to reflect upon our actions and beliefs as scientists, ensuring that we promote the principles of green chemistry[1] to the greatest extent.

The PASI on Green Chemistry, 2003

The first PASI on Green Chemistry opened on July 7, 2003 at the Universidad de la República in Montevideo, Uruguay. The PASI was the first course of its style in the Americas, where 59 young scientists from nine different countries underwent an intensive, 10-day study of green chemistry. The directors of the course were Dr Patrick Moyna of the Universidad de la República and Dr Mary Kirchhoff of the American Chemical Society's Green Chemistry Institute. The National Science Foundation, US Department of Energy, and International Union of Pure and Applied

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Chemistry (Chemrawn) provided funding for all the participants and instructors.

The course was mostly lecture style,† with active participation from students and instructors; recent scientific papers were analyzed and discussed, educational materials were presented, and views on chemistry and sustainability were debated. The topics included the general principles of green chemistry and their applications, specific issues such as alternative solvents, polymers, catalysts and biochemistry, as well as global sustainability problems such as nonrenewable feedstocks and persistent pollutants. The chemists and engineers were exposed to each other's disciplines as processes pertaining to both fields were deliberated.

This course was unique in that it offered as many opportunities for students to contribute as the instructors. Lively poster sessions were held on three afternoons, demonstrating the extraordinary range of green research being conducted by the various participants. Collaborative activities included analyzing recent papers on ionic liquids for their potential environmental benefits and weaknesses as well as discussing green process improvements being incorporated by industry, such as Pfizer's synthesis of Zoloft®. Hands-on laboratory work was performed in the areas of solvent-free aldol condensations, enantioselective reduction using carrots, and the destruction of halogenated pollutants using the TAML® catalyst.

The PASI-GC course was quite intensive, lasting each day from sunrise until sundown. However, our group interactions continued in the evenings, with the Uruguayans introducing the foreigners to their typical activities and customs. Throughout the course of the two weeks, the North Americans were introduced to and participated in the extremely popular local tradition of *mate*, sipping a concentrated 'green tea' drink from a gourd. Several evenings, we played *Fútbol 5*, a popular sport played primarily by men in South America; however, both men and women from our group participated equally in these 'friendly' competitions. Another day, we traveled to *Punta del Este*, a popular tourist beach resort in Uruguay. We had lunch on a farm and partook of local delicacies of roasted meats, including beef kidney and intestine. The course was concluded with a visit to a winery, where we tasted the wines and reminisced on the previous weeks, with keen intentions of continuing communication between participants. Over the two weeks, our entire group became very close, unified under the same objective: to learn, strengthen and disseminate the concepts of green chemistry.

†Various presentations from the PASI-GC are posted on the Green Chemistry Institute's webpage at www.chemistry.org/greenchemistryinstitute

Why green chemistry?

The principles of green chemistry and engineering form a solid foundation as a scientific and ethical tool to assist chemists and chemical engineers in making intelligent decisions about risk and sustainability. However, in order to encourage young chemists and chemical engineers to adopt these principles, it is important to examine the underlying motivations behind green chemistry. Putting it another way, why *should* young chemists and chemical engineers decide to do green chemistry? We believe there are four fundamental reasons: necessity, responsibility, interest, and efficiency.

Necessity

Green chemistry is necessary chemistry. As things currently stand, human consumption is not a sustainable process. This problem will be exacerbated as developing countries industrialize and our fossil fuel resources become depleted. Furthermore, recent discoveries about eco-toxic effects such as endocrine disruption have made it clear that synthetic chemicals released into the environment are disrupting world ecosystems in new and terrifying ways. An approach including the green chemistry principles of sustainability and the use and synthesis of benign substances whenever possible will help mitigate the effects of man-made interference in the natural environment.

Responsibility

Green chemistry is responsible chemistry. Many workers in the chemical field, in either academic or industrial settings, have had accidents with the potential to cause long-term damage to their health and well-being. As chemical workers, however, we have knowingly chosen to accept the risks of working in a chemical laboratory and typically have the opportunity to protect ourselves by gathering as much information about the potential risks as possible. The general public, however, has not chosen to accept the same risks, and our contribution to pollution and sustainability problems amounts to an experiment carried out on an entire generation of human beings. The general public's perception of this helps to explain the staggering fact that 'trust' of scientists is at a much lower level than most scientists would like to believe.[2]

Interest

Green chemistry is interesting chemistry. Few analogues to traditional chemical practices exist using green alternatives, and the development of these analogues will provide new research areas for young chemists and chemical engineers. Furthermore, green chemistry requires a large amount of cross-disciplinary interaction, which will lead to new developments as researchers in differing disciplines interact with one another.

Efficiency

Green chemistry is efficient chemistry. The development of benign, non-wasteful alternatives to traditional chemistry has the potential to save industrial and academic interests large amounts of money due to decreased regulation compliance costs and disposal costs. Furthermore, the basic decrease in process hazards drastically increases both worker and consumer safety.

Green chemistry is necessary, responsible, interesting, efficient, and above all, good chemistry. Furthermore, a rational approach to chemistry in which attempts are made to develop and use green alternatives has no significant drawbacks, assuming reasonable societal investment in the process. For these reasons, the principles of green chemistry should form the fundamental philosophical underpinnings for the next generation of young chemists and chemical engineers. This foundation will preserve our function in society while minimizing the harm we cause to ourselves and to the world around us.

Multinational aspects of green chemistry

In the modern world, our way of living and the processes for generating consumer products can cause pollution correlating to undesirable global change. Toxic chemicals released into the environment, mostly in developed countries, eventually circle the globe and can affect everyone. Universal concerns that were presented at the PASI-GC, such as greenhouse gases, CFCs, and VOCs, have roots in past methods of practising chemistry; green chemistry proposes solutions for preventing these problems in the future.

Developed countries

In the developed nations, our relatively high standard of living often means a high resource usage along with the generation of large quantities of waste materials. The amount of waste produced per person is much higher in developed countries, resulting in numerous problems such as abandoned hazardous waste sites. Green chemistry offers strategies to help reduce or eliminate the waste in chemical processes. Industrialized countries also bear the cost of past wars; World War II and the Cold War came with a high cost for many nations, leaving behind a nuclear legacy. The sites that once were involved in weapons grade uranium and plutonium production in the US, such as Hanford and Savannah River, are now contaminated and are facing colossal costs for the evaluation and management of waste. Additionally, pollution has negatively affected or destroyed many natural habitats in the industrialized countries. Knowing the problems created by our actions in the past, it would seem only logical to turn to green chemistry to ensure that we do not go down the same path again.

Developing countries

From the perspective of the developing world, green chemistry could and should be regarded as an important tool for development. It can be used to improve the people's quality of life while avoiding poor choices for progression and depletion of natural resources. In developing countries there is a different and equally difficult situation as their immediate social and economic problems are the priority, which are often believed to be distinct from the rational use of natural resources.

In a recent editorial by Paul Anastas,[3] he presented a graph (Fig. 5) that shows that resource use upon development has historically followed an unsustainable trajectory. He also showed an alternative situation (Fig. 6) where developing countries are able to 'leap-frog' to a state of higher development without the traditionally high resource usage. This jump could be made possible by employing the fundamental principles of green chemistry in the process of development.

In this regard, the development of these countries should be a highly desirable point of interest for global citizens. However, there is an apparent contradiction, as an increase in quality of life has historically been related to increased resource utilization and degradation of the environment. Current technologies offer us an alternative: the use of scientific knowledge for a new way of development that would be more sustainable, more efficient, and more economical. Green chemistry is a practice that minimizes the impact on human health and the environment and ensures a sustainable future for the next generations. All of humanity is responsible for conservation, sustainability, and the development of the human species, in the developed and developing worlds alike.

Multidisciplinary nature of green chemistry

The field of chemistry is becoming more interdisciplinary within both academia and industry. Therefore, it is only natural for the implications of 'green chemistry' to reach beyond the traditional field of chemistry as well. The PASI-GC Conference included faculty and student representatives from various areas of chemistry and chemical engineering; roughly 1/3 of the participants involved were from departments other than chemistry, including chemical engineering, ecology, and toxicology. This diversity emphasized how readily the fundamentals of green chemistry can be integrated in areas outside the specific field.

Green chemistry is frequently considered a separate branch under the general field of chemistry, yet it is truly an entity to be included within all the traditional branches. Most branches of engineering also have begun embracing the concept of 'green engineering'. While concepts such as energy and waste minimization have long been principles in engineering design due to their economic advantages, concepts like incorporating environmental impact within process development are relatively new to the engineering fields. These same environmentally conscious concepts can be incorporated in all scientific fields, including physics, biology, ecology, and medicine.

Other 'non-scientific' fields also have green applications. Law and political science already have 'green' platforms that are becoming increasingly more important to the public. Business and economic ventures should be encouraged to add environmental impact as a factor when conducting cost assessments. During a discussion at the PASI-GC, it was mentioned that the fields of journalism, communications, and marketing would be particularly helpful in the public relations efforts necessary for educating communities on the importance of 'thinking green'.

Virtually any material project, regardless of field, has 'green' implications and applications when the ramifications of the project are considered from the raw starting materials though its end-of-use lifespan. Therefore it is imperative that we begin to look for and understand the links between disciplines because as scientists we cannot solve these problems alone. Educating ourselves, our colleagues, and our communities on the importance of incorporating 'greenness' in multiple disciplines is absolutely necessary in order to accomplish our lofty goal of a truly sustainable planet.

Green chemistry and engineering education

Education plays a pivotal role in materializing the concepts and principles of green chemistry and engineering. Integration of these ideas into mainstream education is necessary for such an endeavor.

The incorporation of green chemistry and engineering principles into chemical education and process design needs to start at least from the undergraduate level and preferably earlier in students' primary and secondary education. It is necessary to equip the present and future generations of scientists and engineers with the ideas of waste minimization, innovation of safe and energy efficient synthetic processes, real time analysis for pollution prevention, and use of inherently safer chemicals for accident prevention to sustain our current high-tech civilization further into the future.

Along with the progress in education at academic institutions, development towards an entirely sustainable civilization requires the involvement of people from every aspect of society. The responsibility lies with the scientific community to increase awareness among the general population about the need for their participation and involvement in the development and use of greener alternatives and also about the risk of existing technologies that may not sustain in the future. Also, an intimate and well-knit academia–industry relationship needs to be nurtured to obtain economically viable sustainable technologies.

Sustainable development means protecting and improving the environment and developing economic security through education–which can be fulfilled only by a strong commitment from everyone. Specific steps must be taken to ensure that the principles of green chemistry are effectively communicated both within the scientific community and to the general public so that all can benefit.

Future directions

Through participating in the PASI on Green Chemistry, we as young scientists have been empowered both to practise and teach the principles of green chemistry. We can proactively pursue these principles through the base of knowledge we have acquired and the compelling contacts we have made. We now have colleagues, ranging from new students to well-established faculty and professionals, to act as our supporters and collaborators. Thus, we can set forth goals for ourselves and others to become active members of the green chemistry community.

Before we can direct others in the

principles, we must educate ourselves, putting green chemistry into practice within our own laboratories. Examining the footprint of the labs we currently work in is an excellent place to start; solvent selection, lab energy, and water use are good places to target. When possible, we must learn about the toxicities of the chemicals available for use as well as researching and considering the potential alternative, greener reactants. In order to solve the problems, we must first understand them. To become practising ‘green chemists’, we must learn to think in new and different ways and be able to recognize and correct our past mistakes.

Next, we must educate those within the chemical community, expanding green chemistry beyond the inner circle. A paradigm shift is necessary to enable all scientists to make conscious efforts to recognize hazard as a design flaw and acquire a ‘cradle to grave’ mindset. We recognize that past mistakes have been made that scientists are held accountable for, but we also emphasize that future mistakes can be prevented with proper training and effective technical leadership. To encourage these transitions, we believe that green chemistry should be implemented at both undergraduate and graduate levels and incorporated into peer-reviewed journals; for example, the experimental section should include atom economy in place of percent yield as well as an estimate of waste production for each process. We suggest that classes, such as introductory organic chemistry, should cover the toxicity component of any chemical along with its different reactivity and spectroscopic properties with similar stress and importance. Additionally, inherently safer alternatives and hazard components of a process design might be taught with equal magnitude in a chemical engineering class. While we believe it is possible to convert all scientists to green practices, we encourage focusing on hose that are more willing to change first, such as entrepreneurs and privately held firms.

The most difficult obstacle for us as green chemists is education outside the chemical community. However, green chemistry is an easy and effective way for us to improve the public image of chemists and chemical engineers. One of the most useful and influential resources we can use is school teachers; volunteering at those levels is an excellent way to encourage students to pursue science while teaching them the value of green practices, which will continue throughout their adult careers. Additionally, we encourage collaborations outside of our respective fields. Whether this is achieved within the scientific community, such as between the chemists and engineers, or with other

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economic and public interest fields, demonstrating that green chemistry is good chemistry can be a mechanism for change in others. In any situation, we will strive to speak out and be ambassadors for green chemistry

Conclusions

We want a sustainable situation. Green chemistry is critical to that. In an ideal future, ‘green chemistry’ will cease to exist as an independent field, and instead be incorporated as a fundamental aspect within the field of chemistry. However, it will require education, leadership, and a conscious effort by all scientists for this change to occur. In general, chemists are a group of people that are not necessarily aware of the extent of their power or they take that power for granted. With action and conviction, it is in our hands to fix the problem and deliver the message.

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