CHEMRAWN XIV: World Congress on Green Chemistry

Toward Environmentally Benign Products and Processes

Report of the Future Actions Committee

June 2001

Executive Summary

CHEMRAWN XIV: Future Actions

The Future Actions Committee, composed of scientists around the world engaged in all aspects of the chemical enterprise, convened virtually and physically to deliberate on the necessary future actions required to move *toward environmentally benign chemical products and processes.* The committee recognizes the major contribution that industry both large and small , continues to make in Green Chemistry world-wide. The continuing growth of Green Chemistry involves the partnership of industry, academia, policy makers and non-governmental organizations. This report lays the foundation and framework for those future actions that will require extensive engagement and commitment of many individuals in order to make these important recommendations a reality.

The committee made the following findings and recommendations.

Findings -

- Green Chemistry and enabling approaches result in the protection of human health and the environment and helps preserve sustainability in manner that is economically profitable and increases competitiveness.
- The incorporation of Green Chemistry and related approaches into the training of current and potential science students increases the effectiveness of recruitment and retention efforts in this crucial field.
- Research investments are needed by both government and industry beyond current 'pilot program' levels to empower and enable the development and utilization of Green Chemistry technologies by the broad spectrum of private sector interests.
- Many technologies which meet Green Chemistry objectives already exist and offer immediate opportunities to reduce environmental burdens and enhance economic performance.
- Markets for next-generation innovative environmental technologies such as Green Chemistry need to be developed through international engagement and commercial promotion.
- Incentives are necessary to catalyze the implementation of Green Chemistry innovations by industry to overcome barriers especially for small and medium sized enterprises.

Action Items -

- National centers for Green Chemistry should be established or expanded and these centers should be linked to create an effective world-wide network.
- Basic research funding in Green Chemistry needs to be significantly increased.
- Educational initiative funding in Green Chemistry focused on curriculum materials development, faculty training centers, fellowships, and recruitment and retention activities
- Increased incentives for the initial implementation of Green Chemistry technologies by industry to offset investment, policy and regulatory barriers that may exist.
- Green Chemistry and next generation environmental technology market development project to build market position for commercial opportunities in international trade.
- International scientist exchange and research collaboration funding should be established . Informational outreach to educate industry, public, and environmental groups of the benefits of Green Chemistry adoption.

Table of Contents

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Chemrawn XIV: Future Actions Report
Current Status and Future Needs for Green Chemistry

Background

The International Union of Pure and Applied Chemistry (IUPAC) sponsored the organization of CHEMRAWN XIV (CHEMical Research Applied to World Needs) World Congress which brought together industry, government, academic and non-governmental organizations to chart a future course for Green Chemistry. The CHEMRAWN committee was founded in 1975 based on the recognition that chemists worldwide have skills and expertise to help address some of mankind's most pressing problems. These include the alleviation of hunger, the acquisition and conservation of raw materials, resource productivity, the development of new energy sources, and the proper management of our natural resources and environment. A major objective of the IUPAC CHEMRAWN Committee is to define priorities from a chemical perspective with the aim of providing leaders in governments, industries, universities and other concerned organizations with the information needed for effective government and private sector response. CHEMRAWN conferences are unique in that they involve a range of interested parties, focus on issues and, through a Future Actions Committee of the conference, develop a set of actionable recommendations complete with planned follow-up actions. This report describes these recommendations for CHEMRAWN XIV.

The area of Green Chemistry has been introduced as a way of using basic science to address environmental issues in an economically profitable manner. Since its introduction in the early part of the 1990s, there has been significant and dramatic evidence to support the claim that Green Chemistry is an important area for science and technology to pursue for the benefit of the environment, industry and the general public.

The greatest barrier to the wide spread adoption of Green Chemistry worldwide is the lack of general knowledge and understanding of the scientific principles, methodologies and benefits that comprise Green Chemistry. In addition, there is a need to establish or elucidate mechanisms by which international partnerships can work in the area of Green Chemistry.

Introduction

It is recognized that a comprehensive environmental program will need to contain many different aspects and approaches. One approach, which emerged in the 1990s, is Green Chemistry (also known as Sustainable Chemistry in some countries). Green Chemistry is considered an essential piece of a comprehensive program to protect human health and the environment.

In its essence, Green Chemistry is a science-based, non-regulatory and economically driven approach to achieving the goals of environmental protection and sustainable development. The approach has been utilized in a significant number of countries around the world. The results in these countries, that will be further discussed, have been that of extremely positive results in terms of protection to human health and the environment as well as significant economic benefit to the industrial interests involved.

In order to achieve these benefits a working collaboration is necessary to be established between the elements of government, industry and academia. Through this partnership can the mutual goals of all three be achieved and the full potential of Green Chemistry be attained. While it is possible to implement elements of a Green Chemistry program in a step-wise phased in approach, even these are optimally implemented through an industry, government, academia collaboration.

It is important to understand the breadth and scope of applicability of a Green Chemistry program. While it is certainly applicable to all aspects of environment concerns for chemicals, it is not limited to the chemical industry or even the manufacturing sector. Because Green Chemistry is a scientifically based approach, it addresses problems at the most fundamental level, the molecular level. Through these techniques and methodologies it can be an effective way to ensure that substance, materials, products and the manner in which they are manufactured are as environmentally benign as possible.

Definitions and Scope

While very broadly applicable, Green Chemistry has a very specific and well-defined scope. **Green Chemistry is the design, development and implementation of chemical products or processes to reduce or eliminate the use and generation of hazardous substances.** This scope explicitly does not include approaches such as waste treatment, waste control or re-mediation even though these elements are recognized as important, but separate elements of an environmental protection program.

While many countries have those elements capable of reacting to environmental problems once they are formed, there is a need for the introduction and focus on initiatives that design products and processes such that these environmental problems never occur. This is the focus of Green Chemistry.

The range of Green Chemistry includes the design, discovery and implementation of products and processes. This means that not only the molecular structures of a final product can be designed to be non-hazardous but also each of the transformations along the way to manufacture of a product are designed so that they don't use or generate hazardous substances. There is an implicit consideration life cycle impacts with the scope of Green Chemistry. Although traditionally pollution prevention was thought to focus on waste reduction and waste minimization, Green Chemistry includes and expands this focus to all stages of the life cycle. The importance of this expansion is seen through commonly reported achievements from industry. The greatest economic and environmental benefits are being realized as much in the early stages of the process or product life cycle as they are in the latter stages.

The Green Chemistry programs implemented by government, industry and academia on a voluntary basis have achieved success in reducing risk through the reduction of intrinsic hazard at the molecular level. The types of hazards that can and are being addressed by scientific and industrial concerns include physical hazards, toxicological hazards (both human and ecotoxicology) and global hazards, e.g. climate change, ozone depletion and resource depletion.

How Green Chemistry Differs from Traditional Approaches

As was previously stated, it is recognized that any comprehensive environmental protection program will have a number of components. The Green Chemistry component differs from the other program that it complements several aspects.
Science-based - While the goals of Green Chemistry are the same as many other programs, protection of human health and the environment, the methods that it uses are different. The primary methods of Green Chemistry are scientific innovations. Through the utilization of new knowledge in the manifestation of matter and biological mechanism of action of various chemical classes, Green Chemistry provides for the dramatic improvements in the environmental profile of products and processes.

Non-Regulatory - Green Chemistry programs do not have any regulatory or legal requirements as a matter of principle and for effective implementation reasons. Green Chemistry assists industry in meeting their regulatory compliance goes and assists government in assuring legally required standards are met. However, Green Chemistry has at its core continuous improvement, innovation and enhanced economic benefit. Green Chemistry allows for a dynamic changing system within a time frame not easily achievable in most regulatory frameworks. While regulatory requirements and standards can freeze innovation and incentives for continuous improvement (corresponding to the time of the writing of the regulation) Green Chemistry allows for innovation significantly beyond the regulatory standards. Green Chemistry is non-regulatory is because it is not necessary to impose legal requirements since it is economically driven. Industry does not need to be required under penalty of law to en.-age in a practice that enhances its profit.

Solution Oriented - A great deal of resources are devoted to greater assessment, measurement and characterization of environmental problems. Green Chemistry focuses its efforts on finding innovative science based solutions and alternatives to identified environmental concerns. Rather than engage in infinite study and debate on the exact nature and magnitude of an identified concern, Green Chemistry provides cost effective alternatives that have reduced the intrinsic hazard and reduced both real and perceived risk.

Scientific and Technological Challenges and Needs in Green Chemistry

There are a number of scientific target areas within Green Chemistry of high priority based on their potential for significant impact and their feasibility from a technological perspective.

- Green syntheses and manufacturing - The environmental and economic profile of a manufactured chemical-based product is often determined largely by the character of the methods to make the product rather than simply the characteristics of the product itself. It is certainly possible to manufacture, for example, a life-saving drug that is obviously beneficial to human health but do so in a way that uses extremely toxic substances and generates large amounts of waste. The scientific challenges facing Green Chemistry are how to develop the new needed scientific techniques and methodologies that are more environmentally benign. Some of the specific strategic challenges include:

Feedstocks/raw materials - New technologies to utilize biobased and other sources of renewable innocuous materials as the basic building blocks of our synthetic materials to replace the use of depleting and or toxic materials as raw materials that currently dominates our manufacturing sector.

Reagents/Reactive Materials - Through the development of catalytic multifunctional and biomimetic reagents to carry out the transformations necessary for much of our manufacturing, there can be a great reduction in the need for the reactive/toxic substances that are currently utilized.

By Products/Wastes - Through the development of atom economical chemical reactions that maximize the molecular efficiency during transformations, the generation of waste and unwanted by products can be minimized,

- Solvents/Reaction Conditions - While solvents have tended to be some of the most widely used chemicals in our economy, they also tend to be some of the most highly regulated for a variety of concerns related to human health and the environment. Also, energy requirements for the manufacturing sector including petrochemicals and chemical-related industries are currently highly intensive.

Green Solvents Alternatives The discovery of next-generation solvents such as supercritical fluids and ionic liquids or the development of solventless systems provide a future alternative to the ubiquitous use of organic and halogenated solvents that are of concern to human health and the biosphere.

Energy Minimization - The making and breaking of chemical bonds is intrinsically an energetic as well as material transformation and the basis for energy efficiency must be designed at the molecular level. New methods for improved fundamental design of reaction conditions and pathways are needed to reduce energy intensiveness.

- Design of Safer Chemicals - Through molecular structure manipulation, hazard can be treated as simply another physical/chemical property and designed to be minimized by molecular scientists.

Reduced toxicity - Greater understanding across chemical classes of the mechanism of action of toxicity and the utilization of that understanding in the design of molecular structures is needed to reduce the intrinsic toxicity of the industrial chemicals as well as the chemical based consumer products on the market.

Dematerialization - Advances in nanoscience and other molecular minimization techniques can be utilized to achieve the desired function of a material reducing the amount of resources needed to comprise it.

- Inherently Safer Chemistry - Protection from and prevention of chemical related accidents has traditionally been an engineering problem and yet can be addressed through molecular engineering as well.

Reduced accident potential - Through the types of reactions and the phases of matter that are selected to carry out the processes necessary in industry, it is possible to greatly increase the inherent safety of a chemical reaction process by design.

- Green Analytical Methodologies - Advances in chemical analytical instrumentation and techniques are required to insure that the measurement of environmental impact doesn't actually contribute to environmental degradation caused by the use and generation of hazardous substances. In addition, new analytical methods are being developed for use in industry to measure the generation of toxic by products in real time, in-process rather than wait until the generation is complete and measure the result after the fact. Two approaches to this include 1) Field Analysis and 2) Alternative Analytical Methods

International Activities in Green Chemistry

Over the course of the past several years, Green Chemistry activities throughout the world have undergone rapid growth. It is clear that currently there are Green Chemistry activities taking place on six continents involving approximately 40 countries. The activities range from research and development, educational activities, industrial adoption and outreach to the scientific community and the general public. At this point in time, the vast majority of Green Chemistry activities are located in the industrialized nations. A few of the active, but by no means only, countries participating in Green Chemistry are listed below. The list below is only to provide an illustrative sample of some Green Chemistry activities taking place in various regions.

Japan - In recent years, the Japanese government, primarily MITI, along with industrial interests have made major investments in Green Chemistry research and development. The major chemical and chemical related industries, academic societies and national institutions have formed a consortium called the Japanese Chemical Innovation Institute (JCII). The Green and Sustainable Chemistry Network (GSCN) coordinates the majority of industrial activity in Green Chemistry. Extensive peer reviewed research in Green Chemistry is being conducted within the university system in Japan. Japan has played a leading role in the OECD initiatives in sustainable chemistry especially in the R&D working group. There have been a significant number of both national and international conferences and symposia on Green Chemistry in Japan and educational materials including textbooks are being produced in Japan.

Italy - A 30-university consortium funded by the Italian government has been established to pursue research and education in Green Chemistry and more generally chemistry for the environment. The Italian National Consortium for Chemistry for the Environment (INCA) has opened three national laboratories that focus on Green Chemistry with more laboratories soon to launch. Italy has been a leading nation in the OECD initiatives in this area, especially in the educational field. The INCA consortium hosts a Green Chemistry summer school with participation from over 30 nations that is currently funded by the European Union. An international workshop on Green Chemistry education will take place in fall 2001 under the auspices of IUPAC.

U.K. - The United Kingdom's efforts in Green Chemistry are largely being coordinated by the scientific community of the professional societies and academia. The Royal Society of Chemistry launched a major initiative in 1998 to promote Green Chemistry in the form of a journal, prizes, educational efforts and conferences. Industrial engagement with university researchers has been the basis of much of the Green Chemistry R&D efforts in the U.K. A new government-funded industry/academe partnership, CRYSTAL, in Green Chemistry and Chemical Engineering is being launched to promote training, technology transfer and new research in Green Chemistry.

China - Since 1998, China has been engaged in Green Chemistry and constructed two major research centers located at the National Science and Technological University in Hefei and Sichuan Union University in Sichuan. Green Chemistry has been identified by the Ministry of Science and Technology as one of the key focus areas for chemistry R&D. There is currently a "Green Chemistry in China Workshop" annually, with the fourth conference recently completed in May, 2001 in Jinan

Australia - A Green Chemistry research center was recently funded by the government for $IOM in Melbourne at Monash University. In addition to basic research in Green Chemistry the center is also engaged in identifying industrially applicable technologies and the establishment of industry-university cooperative initiatives.

India - A major Green Chemistry conference was convened in New Delhi, India in January, 2001. International participation from industry and academia provided focus on the portfolio of Green Chemistry research currently being conducted in India. Planning for a follow-up conference in 2002 has begun as well as discussions of mechanisms for a more systematic implementation of Green Chemistry in India

United States - The U.S. has an extensive Green Chemistry program that involves government, industry, NGOs and academia to accomplish research, educational, and public outreach goals. A large number of conferences, curriculum materials, research centers and industrial projects-are on-going. In additional, the Green Chemistry Institute works both domestically and internationally in promoting research, education and outreach in Green Chemistry.

International Collaborative Program in Green Chemistry

It is often stated that sustainable development is composed of the triad of elements environmental, economic and social. For these reasons, Green Chemistry requires equal input from a variety of communities interested and effected by the relevant issues. Included in the collaborative efforts should be the following:

Industrial Community - It is only through the implementation of the new discoveries and innovations generated by the scientific community in industry that they can have a real-world impact. Commercially viable, economically beneficial Green Chemistry technologies must be adopted and utilized by industry in order to realize the potential of the Green Chemistry approach to society. Research within industry also needs to incorporate the knowledge and principles of Green Chemistry as well.

International Scientific Community - The scientific community has been responsible for developing the methods to identify, characterize, monitor, measure and assess a wide range of environmental problems that face society today. It will require the same type of creativity, innovation, and rigorous research and development to address and solve those challenges to sustainability. Green Chemistry is a science-based approach that requires a fundamental understanding of the issues at the molecular level in order to design the intrinsic properties of products and processes for reduced hazard. The scientific community, therefore, is a primary and essential element to engage in a program of Green Chemistry.

Educational - The educational community needs to be engaged on several levels in the implementation of a Green Chemistry program. First, in the training of future scientists and engineers, educators at the various stages need to expose and vigorously pursue the elements of Green Chemistry and the underlying principles of intrinsic hazard reduction. Certainly university level and post-graduate training is essential. However, early training of primary and secondary level students need to be instituted as well. Secondly, the educational community needs to expose the non-scientists to the basic principles of Green Chemistry. The citizenry will be responsible for making wise consumer choices and supporting, both politically and financially, the scientific and industrial endeavors of green science.

Governmental Community - The governmental community at the national, multi-national and local levels have several important roles in catalyzing and enabling the implementation of Green Chemistry. Through providing basic research funding, educational programs and legal non-regulatory incentives, the governmental community is a necessary partner in the collection of interests in promoting Green Chemistry. Governmental institutions alone cannot effectively implement a program such as this unilaterally, however, they are an essential and irreplaceable component that are needed to provide the enabling circumstances for the program to flourish.

Environmental/Public Interest Goals - Environmental and public interest groups are often the most aware and concerned and engaged element of the population and bring important input to the development of a Green Chemistry program. They inform industry, scientists and government of popular concerns and perspectives that need to be heard and appropriately integrated into the priorities of a Green Chemistry program.

The Elements of an International Green Chemistry Program

A Green Chemistry program has several important elements that yield optional results when they are implemented in a way so that they are integrated with one another. While maximum benefit can be obtained through implementation of the elements, a step-wise or staged implementation can also be very effective and produce significant accomplishments in the protection of human health and the environment.

The following areas are the essential elements of a Green Chemistry program. (Note: Each of these elements has a separate section devoted to how to implement that program later in this guidance.)

Research

Through academic and industrial research the new Green Chemistry methods and products are developed. With a knowledge and understanding of the scientific challenges to sustainability and the related hazards, researchers can be engaged through funding provided by the public and private sectors. Scientific advances in all aspects of the product or process life-cycle should be investigated including environmentally benign and renewable feedstocks and starting materials, solvents and reaction conditions that do not adversely impact human health and the ecosphere, reagents and transformations which are less toxic and generate zero waste and products designed for minimized hazard. The discoveries and innovations across these areas can be applicable to a wide range of industrial/commercial sectors and have a broad impact. The more fundamental the research the greater the potential for a wide variety of applications and largest potential for positive effect on contributing to sustainability.

Education

The training of scientists in the principles and methods of Green Chemistry should begin as soon as students are exposed to the concepts of the physical sciences and molecular understanding. Through classroom lectures, textbooks, case studies and laboratory experience, an educational program can introduce and train new scientists to the powerful techniques that can be used in designing for minimized hazard. It is not intrinsically necessary to introduce large volumes of new material and subject matter to what may already be a crowded curriculum. An educational program in Green Chemistry can leverage and utilize the same presentation of all of the classical chemistry concepts while including Green Chemistry perspectives and examples to illustrate how traditional concepts are used for sustainability.

Through the use of existing work in the scientific literature and the plentiful industrial case studies in the public domain, instructors can show the breadth of applicability richness of the scientific Chemistry.

Information Dissemination

An effective program in Green Chemistry, not only requires the generation of new innovative science and technology, but also the diffusion of that new knowledge. The dissemination of information from the scientific community to industry, from industry to public interest groups and from both science and industrial communities to the educational community is an important element in the full implementation of a Green Chemistry program.

New information technologies can assist in making available large quantities of relevant materials including scientific databases, curricula materials and case studies of interest to the public. Also, classical mechanisms for disseminating information through meetings, conferences/workshops, books, journal articles, etc., are important to foster the Green Chemistry community. Higher level activities such as scientist exchange or student exchanges can be extremely effective in the diffusion and dissemination of expertise in Green Chemistry.

Awards and Recognition

An important element and strategy for mobilizing the relevant communities for a Green Chemistry program is that of awards and recognition. There are several reasons for implementing awards and recognition system in Green Chemistry: 1) It provides credit where it is due and motivates scientists and businessmen to pursue these goals knowing that they are worthy and respected goals both within their peer structure and to the general public. 2) the system can be designed to provide a way of tracking and cataloging outstanding advances in Green Chemistry through the nomination process 3) awards and recognition can communicate and inspire industry by visibly showing that companies are increasing competitiveness while meeting environmental goals and responsibilities. 4) it can communicate to the general public that products and processes can be designed to be more environmentally benign and unlike current popular perception, every chemical is not toxic.

Tools

Tools for Green Chemistry include those things that enable and assist the design, development and implementation of Green Chemistry. These can include databases of physical/chemical properties or synthetic methodologies, expert systems that assist the practicing scientist in utilizing Green Chemistry, workbooks/checklists or audit sheets which guide a person through the various Green Chemistry criteria and considerations. These tools, often developed over time, are an effective method of accelerating the adoption of Green Chemistry and, once adopted, maximize the effectiveness and impact of the Green Chemistry program.

Green Chemistry: Recommendations

Goals and Objectives

In order for the economic and environmental benefits of Green Chemistry to be realized, there needs to be enhanced understanding of the area as well as increased capacity to exploit the tools of Green Chemistry to maximum advantage. This requires the following elements:

1. Clearly articulated and uniform enunciation of the techniques, terms and methodologies and benefits central to the pursuit and implementation of Green Chemistry.

2. Increased understanding of the benefits and incentives to the scientific and industrial community resulting from the research, development and implementation of Green Chemistry.

3. Effective training and awareness of Green Chemistry to the target communities through appropriate educational and outreach mechanisms.

4. Effective conduits for increased sharing of information and experience on Green Chemistry among nations.

5. Identify opportunities for obtaining resources to enable international engagement in the area of Green Chemistry.

6. Engagement with the multi-lateral governmental institutions in the area of Green Sustainable /Chemistry.

7. Establish and utilize bilateral mechanisms where appropriate to further the progress of adoption and implementation of Green Chemistry in strategically important areas of the world,

8. Promote commercial opportunities for businesses in the area of Green Chemistry technologies.

Recommendations of specific activities

1. **Industrial Implementation**

- Quantitative data should be retrieved to reflect both economical and ecological benefits when modem processes have replaced earlier ways of manufacturing. Economic benefits of Green Chemistry need to be made clear to facilitate adoption by industry including large, small and medium sized enterprises. The Future Actions Committee should work with the relevant partners including companies, trade associations, professional societies, academia (including both scientific and business schools), and others to facilitate the generation and dissemination of a "Benefits of Green Chemistry Implementation" document
- Regulatory impediments to implementation of innovative Green Chemistry processes need to be identified and removed or minimized when possible. As part of the communications strategy, the Future Actions Committee needs to meet with and inform the appropriate regulatory and legislative bodies about the need for the removal of regulatory barriers to the implementation of Green Chemistry.
- Incentives for investment in Green Chemistry technology implementation should be identified and put in place by governments where appropriate. A document should be drafted by the Future Actions Committee with significant input from industry outlining the types of incentives that would be appropriate to encourage the implementation of Green Chemistry technologies.
- Green Chemistry needs to be included in revised definitions of "environmental technologies" for the purpose of developing markets in this area while retaining its place as a process or manufacturing technology. The Future Actions Committee should facilitate meetings with national and multinational organizations e.g. ministries of trade, departments of commerce and other groups engaged in promoting trade to include Green Chemistry technologies as "environmental technologies".
- The Future Actions Committee will recommend the creation of information networks for the rapid international dissemination of information useful in the promotion and implementation of Green Chemistry including research, education, implementation and commercialization of innovative Green Chemistry technologies.
- The Future Actions Committee will encourage the development of appropriate national forums for addressing policies for the adoption of Green Chemistry technologies.

2. International Cooperation

- Multinational research collaborations in Green Chemistry should be established both through existing mechanisms and establishment of new research networks.
- International exchange of educational materials should be facilitated through professional and scientific societies and universities.
- Developing and economically disadvantaged nations should be emphasized as an area where appropriate and applicable Green Chemistry research, education and implementation is vigorously *fostered* and cultivated by industry, universities and governments of industrialized nations. The Future Actions Committee should formally inquire about the availability of funds from international development agencies e.g., UNIDO, UNEP, UNESCO and charitable organizations to pursue engagement of Green Chemistry activities in developing nations and utilize appropriate partnerships as an implementing mechanism.
- The Future Actions Committee should engage with multi-lateral governmental organizations such as OECD, APEC, NATO, UN, OAS, E-U and others to promote Green Chemistry through the development of mechanisms for international collaborations, policies and programs in the areas of research, education, commercial implementation and information exchange.
- Engage appropriate and strategic bilateral partners in collaborative efforts to advance the understanding, adoption and implementation of Green Chemistry through both formal existing protocols and through the development of both formal and informal mechanisms for collaboration.
- The Future Actions Committee will facilitate the conduct of international workshops and conferences on the areas of Green Chemistry including research, education, recognition, and tools development for the purposes of information exchange and the promotion of scientific cooperation. The Committee will also encourage learned and professional societies and institutes to instigate appropriate interdisciplinary meetings, workshops, conference and other activities to further the aims of Green Chemistry ideals.
- The Future Actions Committee will engage international scientific organizations, e.g., IUPAC, ICSU and the Nobel Foundation, to effectively utilize and leverage the communications and decision-making networks within the international scientific communities as part of a government, NGO, industrial and academic partnership in Green Chemistry.

3. **Educational** initiatives must be pursued to provide the following:

- Primary and secondary school mechanisms should be developed so that the earliest stages of scientific awareness include an introduction of the concept of the science of designing for the environment and sustainability.
- Public awareness of the benefits of basic science in achieving a sustainable future need to be engaged through popular channels.
- Professional chemists, technical managers and decision makers should be formally and systematically exposed to the principles and potential of Green Chemistry practices.
- Develop educational exchange networks to enhance the development and dissemination of materials and instructors to inform and promote the implementation of Green Chemistry practices in industrialized and developing nations.

- Materials need to be developed that support the integration of the principles of Green Chemistry into existing and new courses in the chemistry curriculum.
- Continuing education programs and materials should be developed specifically to promote the principles and the potentials of Green Chemistry practices for professional scientists, business managers and decision makers.

- Laboratory modules which demonstrate basic chemical concepts and Green Chemistry simultaneously should be incorporated into students' first hands-on experience. The Future Actions Committee should establish a Task Force specifically to identify partner laboratories where Green Chemistry lab modules can be tested, reviewed and verified.
- Business schools need to incorporate case studies and models demonstrating the economic benefits, both recognized and classically hidden, of Green Chemistry. The Future Actions Committee should generate a contact list of industry expertise in Green Chemistry that would be willing to speak in special lectures and symposia at business schools on the subject of the business advantages of green business schools.
- Undergraduate curricula need to be developed which expose all future scientists to the principles, techniques and methodologies of Green Chemistry. The Future Actions Committee should seek funding from international organizations to ensure development and dissemination of these materials to all appropriate education levels.

4. **Basic and Applied Research** must be increased. The following actions should be taken:

Funding must be increased in areas of Green Chemistry in the following representative, but not exclusive priority areas:

- Fundamental synthetic transformations that are high conversion atom economical and reduce the utilization of hazardous feedstocks and reagents and generate as little waste as feasible.
- Design of chemical products at the molecular level that incorporate minimal hazard and design for end-of-useful life, as a performance criterion.
- Chemistry-facilitated energy generation methods which are sustainable, renewable and technologically and economically viable including but not limited to solar, hydrogen and biomass.
- Solvents and solventless systems that are more environmentally benign and economically beneficial including but not limited to dense phase fluids, aqueous systems and ionic liquids.
- Utilization of feedstocks which are renewable and environmentally benign including biobased and waste conversion.
- Catalytic transformations including biocatalytic, which are both material and energy efficient through out the life-cycle.
- Reduction of materials and biomimetic chemistry including nanoscience and technology and molecular self-assembly.
- Analytical methodologies that are more inherently environmentally benign and are used for the prevention of, rather than post-facto measurement of, environmental problems.

- While pursuits within conventional chemistry areas will always be fundamental, it is recognized that the fields of Biology, Biochemistry, Physics, Chemical Engineering and Economics are central to breakthrough innovations.
- Identify the most appropriate methodology for Life Cycle Evaluation of Green Chemistry processes to be performed.
- To encourage new development in Green Process engineering and including intensification integration waste minimization and energy efficiency.
- The Future Actions Committee should work with relevant interests in Green Chemistry in industry, academia and NGOs to engage national and multinational funding sources to effect the increase of sustained basic research funding in the important areas of Green Chemistry.
- The Future Actions Committee should engage directly with industry to identify appropriate mechanisms that individual companies and industrial associations may be able to effect a greater investment in Green Chemistry research. These mechanisms could include but not be limited to direct funding, leveraging governmental funding, establishing pre-competitive research centers in various areas of Green Chemistry and the establishment of Green Chemistry research fellowship networks in partnership with universities.

Conclusions

Green Chemistry has demonstrated its effectiveness in achieving its mission of meeting environmental and economic goals simultaneously. In order to realize the potential of Green Chemistry science, technology and commerce, countries must engage internationally through *a* variety of bilateral, multilateral, private sector and scientific and educational vehicles. The current levels of resources are insufficient to sustain the Green Chemistry research and development and educational efforts necessary to bring about real change though industrial implementation and need to be increased.