Green Chemistry

Creating a Vibrant Economy

and a

Healthy Society

through

Innovative Design

Presented by the

Yale-UNIDO Global Green Chemistry Initiative

Funded by the Global Environment Facility (GEF)

UNIDO UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

EXPERTS/Clearly

CENTER *for* GREEN CHEMISTRY *and* GREEN ENGINEERING *at* YALE

FOREWORD

The Yale-UNIDO Global Green Chemistry Initiative offers this document as a vision for a prosperous and healthy future for all developing nations. It is a guide to a method of innovation that can help foster a vibrant economy, strong public health, and a clean environment. This method is called Green Chemistry.

For years, UNIDO and its partners have been working to help undo the industrial practices of the past. These practices have introduced materials such as lead, mercury and persistent organic pollutants to our environment, and into our bodies. That vital cleanup work continues. But we must also create a path forward that does not repeat those same mistakes. A path that allows developing countries to design and manufacture the energy systems, medicines, materials, and processes of tomorrow in cleaner, more efficient and more effective ways. The United Nations' 17 Sustainable Development Goals set forth a vision for this future. Green Chemistry offers a powerful way to help achieve that vision. It offers a way for developing nations to not only participate more fully in the world economy, but also to become leaders in the global push toward sustainability.

With this document, we hope to inspire you to pursue Green Chemistry for your organization, and we offer guidance in how to do so effectively. We have drawn on the knowledge of Green Chemistry experts around the world, experts who have been innovating with Green Chemistry for more than two decades.

The document itself will offer tips and ideas for fostering a vibrant Green Chemistry approach. But more importantly, you will see that it is a gateway through which you can connect to the global Green Chemistry community. The Green Chemistry community is made up of hundreds of experts and institutions from around the world, sharing information and challenging each other to new levels of innovation through Green Chemistry.

We welcome you to that community and offer our sincerest encouragement as you take your first steps into the exciting world of Green Chemistry.

INTRODUCTION

Imagine, if you will…

> … a world in which creating comfort, jobs, and economic opportunity doesn't also mean polluting the soil, water and air upon which we depend.
>
> …a textile mill that creates beautiful garments, without leaving behind any toxic dyes to contain, bury, or spill into our rivers.
>
> …a computer chip factory running at full capacity, without relying on any precious metals that are polluting to extract and are bad for the health of workers in that factory.
>
> …a range of vibrant plastic products that are made from plants rather than oil, and that dissolve harmlessly to the earth when we're done with them, rather than floating endlessly in the world's oceans.
>
> …a parent, with peace of mind that not one of the paints, adhesives, cleaning products, or foods in their home holds any hidden chemical threat to the lifetime health of that child.

Every one of these dreams is at our finger tips, ready to be more fully realized, thanks to a creative endeavor called Green Chemistry. This document is designed to help professionals understand Green Chemistry and put its transformative powers to work in your organization, town, city, region, and country. Whether you work in government, a business, a school or university, or a non-governmental organization, this document can help you use Green Chemistry to successfully meet your environmental, human health, and economic goals.

This document is offered by the Global Green Chemistry Initiative, whose mission is to increase the understanding and adoption of Green Chemistry Principles throughout the world. It is our sincere hope that you find inspiration in the pages of this document, as well as the resources needed to help you turn that inspiration into action.

Within, you will find four sections:

Part One: What is Green Chemistry? What makes it different from other approaches to environmentally friendly/sustainable technologies? What makes it such a powerful approach for turning our greatest sustainability challenges into unparalleled opportunities? Part One focuses on the aspects of Green Chemistry that allow for economic and societal benefits of innovative Green Chemistry and Green Engineering technologies.

Part Two: How can I implement Green Chemistry in my organization, city, region and nation? How can I spark and grow a Green Chemistry movement? Nearly three decades of experience in practicing Green Chemistry is summarized and shared in Part Two to help you take your first steps into the world of Green Chemistry.

Part Three: This part includes detailed references and technical information about Green Chemistry and how to implement it. After reviewing the ideas presented in Parts One and Two, each reader will select the first steps most appropriate to their unique situation. Whichever that is, this section presents more detailed examples, technical details, recommended reading, and contacts in the Green Chemistry community.

Part Four: A **Technology Compendium** that presents specific, real-world examples of Green Chemistry innovations from around the world. It will provide an in-depth information on state-of-the-art Green Chemistry technology solutions and best practice examples applicable across all sectors, industries, products, and manufacturing processes. Case studies from participating National Cleaner Production Centres (NCPCs) will be featured in this section. In addition, this section will include a discussion of persistent organic pollutants (POPs) and a methodology to estimate and demonstrate POPs savings through Green Chemistry and Green Engineering technologies.

BACKGROUND to the Global Green Chemistry Initiative Project (GGCI)

Purchases of chemicals for processing of products has dramatically grown since the 1970s. OECD's Environment Outlook notes that the global chemical purchase was worth US$ 171 billion in 1970, while it had grown to more than US$ 4.12 trillion in 2010. The report also notes that while annual global chemical sales doubled over the period 2000 to 2009, OECD's share decreased from 77% to 63% and the share of the BRIICS countries (Brazil, Russia, India, Indonesia, China, and South Africa) increased from 13% to 28%. Recent forecasts by the American Chemistry Council predict significant growth in chemical production in developing countries until 2021, compared to a more modest growth in developed countries (cited in UNEP's Global Chemicals Outlook - Towards Sound Management of Chemicals, 2013).[1]

There is a need for innovative approaches to reduce the use of hazardous chemicals throughout the industrial life cycle. Addressing the challenges posed by hazardous chemicals will require holistic, wide-ranging actions, and environmentally sound management. Amongst other aspects, innovation, application, and knowledge-transfer of environmentally benign approaches and technological solutions are essential elements of a reductionist strategy with a goal of "zero" waste.

One approach to advance the sustainable development is Green Chemistry, which is defined as the "design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances". Green Chemistry focuses on the inherent nature/properties of chemicals, materials, products, processes, or systems. It is transdisciplinary in nature, encompassing elements of chemistry, engineering, biology, toxicology, and environmental science.

Green Chemistry reduces pollution at its source by minimizing or eliminating the hazards of chemical feedstock, reagents, solvents, and products; or encouraging the invention and innovation of new and non-hazardous solvents, surfactants, materials, processes, and products. This is unlike remediation, which involves end-of-the-pipe treatment or cleaning up of environmental spills and other releases. While remediation removes hazardous materials from the environment, Green Chemistry keeps hazardous substances out of the environment in the first place. Green Chemistry has been an emerging area of sustainable design since its introduction in the 1990s. While the progress has touched virtually all sectors of society and industry ranging from agriculture and energy, to building materials and pharmaceuticals, to personal care products and cleaners, these accomplishments have taken place largely in the industrialized nations of the world. There are only nascent efforts to advance Green Chemistry in a small number of developing countries and economies in transition with the lack of awareness of the mechanisms and the potential of Green Chemistry as the single largest barrier to broad-based adoption. It is evident that Green Chemistry needs to play a larger role in accelerating inclusive and sustainable industrial development in the future in such way that Green Chemistry

[1] https://sustainabledevelopment.un.org/index.php?page=view&type=400&nr=1966&menu=35

can effectively contribute to the achievement of the Sustainable Development Goals adopted at the United Nations General Assembly in New York, on 25 September 2015, under the frame of the UN Agenda 2030 for Sustainable Development.

The Global Green Chemistry Initiative is a collaboration lead by the Center of Green Chemistry & Green Engineering at Yale and UNIDO in cooperation with National Cleaning Production Centres from Colombia, Brazil, Egypt, South Africa, Serbia, and Sri Lanka. Its mission is to increase the general global awareness and capacities on deployable Green Chemistry approaches for the design of products and processes that advance global environmental benefits throughout their life cycles. The Initiative is funded by the Global Environment Facility (GEF).

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Part ONE:

What is Green Chemistry and Why Should We Do It?

The design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances.[2]

That is the definition of Green Chemistry. From this definition flows a set of 12 Principles that guide the effective application of Green Chemistry wherever it's put to use. These Principles, and related detailed information, are presented later in this document.

For now, we hope to convince you that in theory and practice, Green Chemistry is an elegantly simple idea:

Using knowledge in chemistry, we can design products and manufacturing processes to provide us with the goods and services we want, without the pollution, health risks, and inefficiencies we don't want. Through more thoughtful design at the molecular level, we can more effectively achieve our goals for a cleaner environment, improved public health, and more innovative and resilient economies.

Why isn't this the way it's always been done?

For much of modern industrial history, chemists and the institutions they work for have really only focused on the first half of that idea: Does the chemical product do the job for which it was intended? Is the paint bright and durable? Does the adhesive hold up under any temperature? Is the plastic both incredibly strong and yet endlessly elastic? [345678]

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[2] Anastas, P. T. and Warner, J. C. *Green Chemistry: Theory and Practice*. Oxford University Press: New York, 1998, p. 30. By permission of Oxford University Press.

[3] Coish, Philip, Bryan W. Brooks, Evan P. Gallagher, Terrance J. Kavanagh, Adelina Voutchkova-Kostal, Julie B. Zimmerman, and Paul T. Anastas. "Current status and future challenges in molecular design for reduced hazard." (2016): 5900-5906.

[5] Matus, Kira JM, Xin Xiao, and Julie B. Zimmerman. "Green chemistry and green engineering in China: drivers, policies and barriers to innovation." *Journal of Cleaner Production* 32 (2012): 193-203.

[6] Manley, Julie B., Paul T. Anastas, and Berkeley W. Cue Jr. "Frontiers in Green Chemistry: meeting the grand challenges for sustainability in R&D and manufacturing." *Journal of Cleaner Production* 16, no. 6 (2008): 743-750.

[7] Matus, Kira JM, William C. Clark, Paul T. Anastas, and Julie B. Zimmerman. "Barriers to the implementation of green chemistry in the United States." *Environmental science & technology* 46, no. 20 (2012): 10892-10899.

[8] Matus, Kira, Paul T. Anastas, William C. Clark, and Kai Itameri-Kinter. "Overcoming the challenges to the implementation of green chemistry." *CID Working Paper* (2007).

If the chemical innovation worked, success was declared, and very few thought to then ask, "Do our molecular inventions also do other things we don't want?". Those "other things" have included polluted air, toxic waters, wasted energy, and sick animals and people. They have meant that in trade for the things we want, we have had to spend far too much time and money working desperately to clean up the messes that they leave behind.

Green Chemistry offers that solution. More than twenty years ago, scientists began insisting that anytime we design a product or service, we ask both "What good will it give us?" AND "What might it create that we don't want?" Thoughtful design follows, seeking to maximize the first while eliminating the second.

That is Green Chemistry.

Example

There may be no better example of this dynamic than Persistent Organic Pollutants, or POPs such as the pesticide Aldrin (see reference below). These chemicals have been used for decades for many useful applications and yet they present serious and lasting danger for humans and the environment on a global scale. UNIDO and others throughout the world have worked diligently to remove POPs from production, landfills, and the environment. The Stockholm Convention, which took effect in 2004, requires countries to eliminate the production and use of POPs.

Green Chemistry offers an ideal approach for taking on that challenge. But imagine the environmental, health and economic benefits that would have accrued if, in decades past, the chemists designing the products and processes that uses POPs had known to ask BOTH "will it work?" AND "what harm might it do?" Designing a problem out of a system in advance will always be more effective than trying to fix that problem after the fact.

Aldrin: http://chm.pops.int/TheConvention/ThePOPs/AllPOPs/tabid/2509/Default.aspx]

Why was it chemists that led this charge to create change?

Chemists practice their entire trade at the molecular level, and it is the molecular structure of the chemicals in our toys, computer chips, and other everyday items that make these items perform the way they do. It's the molecular characteristics that determine if the paint on the toys is dangerous for children, or if the rare metals in those chips are harmful to fish when released to a river during mining or manufacture. By using the Principles of Green Chemistry, chemists can identify and solve these problems.

Green Chemistry has also time and again delivered excellent economic results. The same undesirable side effects that pollute the earth and body are also financial drains on any manufacturing system. These include raw materials and waste streams that cost money, impose risk, and signal inefficiency. When a chemist redesigns at the molecular level to get more of the good and less of the bad, everything else that follows in the production, use and disposal of that product stands to improve. We get the good without the bad. We get more product and less waste. This is why business innovators have always been among the most active and vocal champions of Green Chemistry.

Example

Propylene oxide (PO) is one of the most widely used chemicals in manufacturing, with an estimated 14 billion pounds used each year. Dow Chemical & BASF together created a new way to make PO that reduced energy use by 35% and reduced wastewater by up to 80%.

LS9, Inc. (acquired by Renewable Energy Group) has developed a process that uses microorganisms to create cleaner biofuels, such as a biodiesel that is free of pollutants such as benzene, sulfur, and heavy metals, and reduces greenhouse emissions by 85%.

The Clarke company created an environmentally safe insecticide to control mosquito populations. Unlike other non-toxic approaches, it works effectively and efficiently in water environments, allowing it to compete with, and potentially replace, toxic insecticides currently in use.

[9,10,11,12]

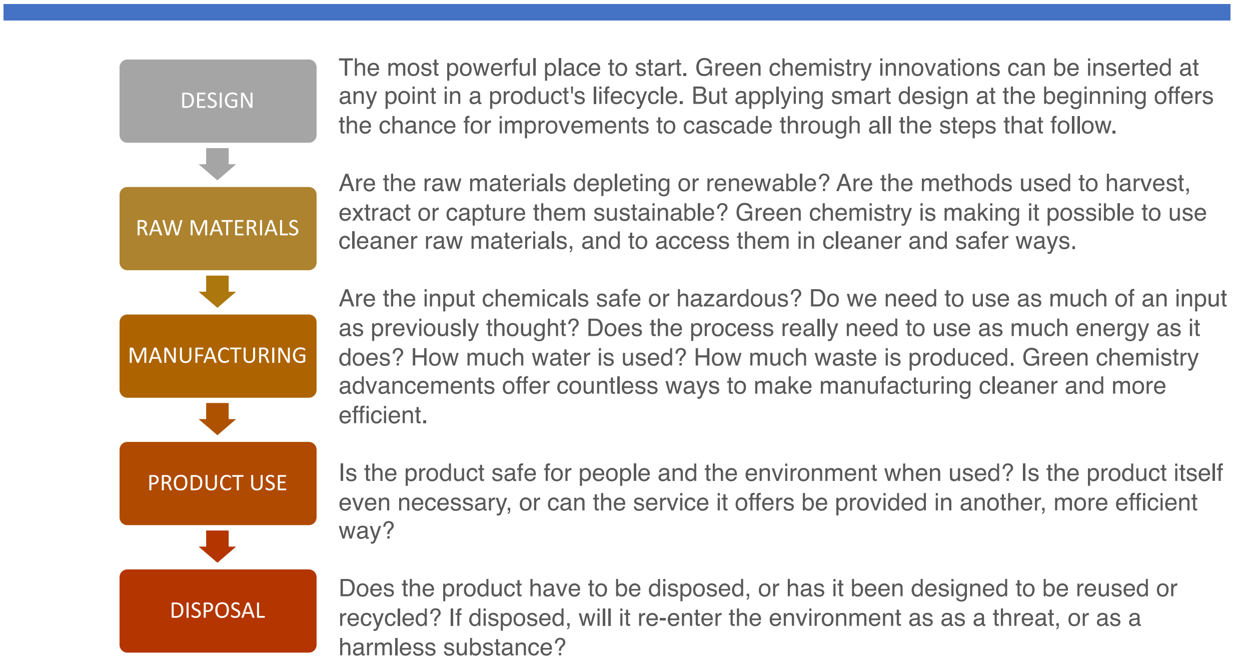
Where in the industrial enterprise can Green Chemistry make a difference?

A Green Chemistry approach can be applied for environmental, economic, and societal benefit across the entire chemical enterprises.

The following graphic introduces how Green Chemistry can be used throughout the entire lifecycle of a product.

[9] https://corporate.dow.com/en-us/science-and-sustainability
[10] https://www.basf.com/global/en/who-we-are/sustainability.html
[11] https://www.clarke.com
[12] https://www.regi.com

Figure 1. How Green Chemistry can be used throughout the entire lifecycle of a product.[13]



The 12 Principles of Green Chemistry

Green Chemistry is translated from idea into practice through the 12 Principles of Green Chemistry. These core Principles show where and how smart design can make a difference. They are the reason that Green Chemistry can impact and improve the chemicals found in commercial products and the industrial processes at nearly every stage. The 12 Principles are listed in Figure 2.

[13] Gilbertson, L. M., Zimmerman, J. B., Plata, D. L., Hutchison, J. E., & Anastas, P. T. (2015). Designing nanomaterials to maximize performance and minimize undesirable implications guided by the Principles of Green Chemistry. Chemical Society Reviews, 44(16), 5758-5777

Figure 2. The 12 Principles of Green Chemistry

1. **Prevention**
   It is better to prevent waste than to treat or clean up waste after it has been created.
2. **Atom Economy**
   Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. **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.
4. **Designing Safer Chemicals**
   Chemical products should be designed to affect their desired function while minimizing their toxicity.
5. **Safer Solvents and Auxiliaries**
   The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.
6. **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.
7. **Use of Renewable Feedstocks**
   A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.
8. **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.
9. **Catalysis**
   Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. **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.
11. **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.
12. **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.

[14]

[14] Anastas, P. T. and Warner, J. C. *Green Chemistry: Theory and Practice*. Oxford University Press: New York, 1998, p. 30. By permission of Oxford University Press.

The 12 Principles of Green Engineering

Green Engineering is an important and complementary discipline to Green Chemistry. Green Engineering takes the same invaluable approach of thoughtful design and applies it to the development and commercialization of industrial processes. Guided by the 12 Principles listed below, industry professionals can engineer systems that are better for human health and the environment, and that are economically superior. The 12 Principles are listed in Figure 3.

Figure 3. The 12 Principles of Green Engineering

1. Designers need to strive to ensure that all material and energy inputs and outputs are as inherently non-hazardous as possible.
2. It is better to prevent waste than to treat or clean up waste after it is formed.
3. Separation and purification operations should be designed to minimize energy consumption and materials use.
4. Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
5. Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.
6. Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
7. Targeted durability, not immortality, should be a design goal.
8. Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
9. Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
10. Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
11. Products, processes, and systems should be designed for performance in a commercial "afterlife".
12. Material and energy inputs should be renewable rather than depleting.

[15]

[15] Anastas, P. T., Zimmerman, J. B., Design through the 12 Principles of Green Engineering. *Environmental Science & Technology*, March 1, 2003.

A Brief History of Green Chemistry

In the early 1990s, a group of researchers at the US Environmental Protection Agency began exploring the concepts central to Green Chemistry. At the heart of their effort was a belief that we could do better than traditional "end-of-pipe" pollution control strategies, and even better than the many individual "pollution prevention" methods that were then emerging. The US EPA soon launched the Presidential Green Chemistry Challenge Awards to recognize Green Chemistry efforts of commercial and academic researchers. In 1998, Paul Anastas and John Warner codified the Green Chemistry approach, and the Principles, in their book, *Green Chemistry: Theory and Practice*.

Since those early days, Green Chemistry has spread around the world. Researchers in academic, government, and commercial institutions, guided by the 12 Principles, continue to push the boundaries, using smart design to look further and further upstream in any chemical process, and finding ever cleaner and more efficient ways to make things.

Green Chemistry and its Impact on Global Sustainability

The United Nations Sustainable Development Goals are a bold, broad-reaching exhortation for us all, working together, to help ensure that every community around the world can enjoy personal health, a vibrant environment, and lasting economic well-being. The 12 Principles of Green Chemistry offer a tangible action plan to help achieve those goals. They offer a way for researchers, operating at the most elemental levels of our industrial processes, to create changes that will yield wide and long-lasting benefits for all.

See Section THREE for more information regarding:

- The history of Green Chemistry
- More information on the Green Chemistry approach
- Seminal Green Chemistry articles
- Green Chemistry & global sustainability

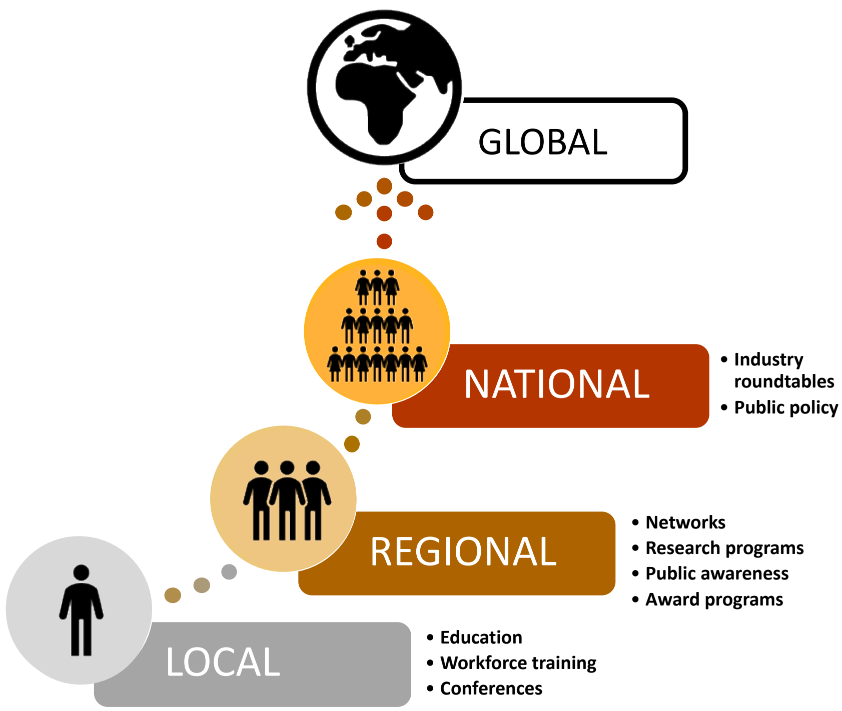
Part TWO:

How can I implement Green Chemistry?

Once you begin to understand what Green Chemistry is and what its potential can be, the natural question then becomes, “How can we do it? How can we implement Green Chemistry?”

This section will help to answer that question. There is no single “correct” way to start down the path. There are, however, several first steps that can be very effective. The advice that follows is drawn from the experience of leading Green Chemistry practitioners, and nearly three decades of experience in implementing Green Chemistry throughout the world.

Figure 4. A Roadmap to Green Chemistry Implementation



How does Green Chemistry start, and who in my organization, community, city, region, or country should lead the charge?

It starts with you.

Green Chemistry is now in practice around the world and it is producing environmental and economic improvements that can only be quantified with the word “catalytic”.

But in every location around the world where Green Chemistry now thrives, it was dedicated individuals who sparked the movement. These champions learned about Green Chemistry, believed in its potential, and set out to inspire others to the same ideals.

Example

The Green ChemisTree Foundation is a nonprofit organization based in Mumbai, India. The Foundation works to increase technical knowledge in Green Chemistry in all sectors of the economy. Through outreach efforts, collaborations, conferences, and educational initiatives, the Green ChemisTree Foundation plays a significant role in helping to grow Green Chemistry in India and beyond.

It all started with individuals who had a dream. They had an idea for how to bring Green Chemistry to others. Soon they had attracted another, and another still. This initial team began continuous efforts to both connect with the international Green Chemistry community and to spark a Green Chemistry movement in India. To ignite that movement, they worked tirelessly to establish collaborations with people in industry and government.

And so, it grew from individuals with an idea to a foundation that now inspires thousands.

[16]

Which sector should lead the adoption of Green Chemistry?

Any sector or organization. It could be business, government, academic, or non-governmental organizations. History has shown that each has the potential to lead the charge for change into Green Chemistry. In the United States, it was government that led the way. Throughout Asia, it was largely the industrial sector that led the way. In Europe, academic institutions laid the foundation for Green Chemistry activities.

What does it take to ensure that our Green Chemistry efforts thrive?

Partnerships. Collaborations across ALL sectors of society.

As noted above, the initial spark can come from passionate individuals in any sector. But soon thereafter, the idea must spread, and collaborations across the sectors must be created.

The 25-year history of Green Chemistry shows that success to each person, enterprise, city, region, and country comes in greater amounts when an *entire ecosystem* exists to develop, implement, and support Green Chemistry measures. An ecosystem in which includes industry,

[16] http://www.greenchemistree.co.in

government, and educational institutions all maximize their role in Green Chemistry, and when those efforts are in turn connected in a robust community in which members challenge each other to do better, and share the knowledge required to do so.

The history of Green Chemistry is the story of champions around the world. These are individuals from around the world who saw Green Chemistry's promise and set out to make a difference.

See Section THREE to read about some of these champions, where they started, and the results of their work.

Where to start?

There is no singular "correct" way to energize Green Chemistry in your town, city, region, or country. The "best" approaches and solutions will vary based on the specific needs, culture, politics, geography, environment, and economy of your region. Experiences around the world show that the following activities can accelerate the adoption of Green Chemistry activities.

1. Awards Programs: Raise Awareness and Recognition

One of the most powerful ways to generate increased awareness and understanding of Green Chemistry to look around and see who is already doing things right. It's likely that there will be examples. Harvest those good-news stories and share them with others.

This might mean simply writing stories about them to share with others.

You might work to create an awards program. Praise the successes of Green Chemistry innovators with an award and share that news widely.

Publicly and formally recognizing these success stories has several positive benefits for the adoption of Green Chemistry.

Highlighting breakthroughs inspires and encourages others to reach for their own innovations. The awards, when bestowed by a recognized and respected institution, become an important endorsement and sign of confidence in a field for those who might be wary. The spotlight of an awards event draws the attention of others who might not yet be aware of Green Chemistry, and might then inspire them to learn more.

An awards program allows you to create a database of Green Chemistry actors and activities. This can become a list of the people that you can turn to for future partnerships. This will also serve as a list of Green Chemistry examples; case studies for other people to look at and to strive toward.

Awards can breed constructive competition. Highlighting the good news stories has proven in the past to inspire competitors and others to say, "Hey, I can do better than that," and strive to take the successful ideas even further. Sustainable technologies are cost effective, and there are thousands of green chemistry innovations from around the world that prove this to be true. Shining a light on new examples with an award program will help carry this important message to others.

When a person or a group wins an award, they are proud of that accomplishment, and that attachment to Green Chemistry becomes a valuable part of their identity. Once you build a Green Chemistry into a person or organization's identity you will have a lasting Green Chemistry champion.

If you seek to create an awards program, it's best to ensure that the awards are bestowed by a respected, established institution. Where the awards come from will have a very important impact on how effective the awards are likely to be at generating lasting interest from the larger community. In some cases, the award program has been hosted by high ranking government officials. In other cases, it has been renowned scientific organizations.

Example

In the early 1990s, as the group at the US EPA was developing the foundations of Green Chemistry, they laid plans for the Presidential Green Chemistry Challenge Awards. The first awards were given out in 1996, and recognized excellence in the commercial and academic research communities. These awards played an immeasurable role in raising interest in Green Chemistry in the US. The awards soon attracted dozens of applicants each year, and enticed the US press to report on Green Chemistry innovations.

[17]

See Section THREE for more information regarding Green Chemistry awards programs around the world.

2. Research Programs: Stimulate Green Chemistry Research

Green Chemistry, like advancement in any scientific field, can only thrive when businesses, government, and educational institutions embrace their roles to promote and pursue research innovations. To inspire, and fund, such research, institutions should consider starting Green

[17] https://www.epa.gov/greenchemistry/green-chemistry-challenge-winners

Chemistry research programs. Around the world, these have been successfully hosted by a variety of sectors:

Government grants:

If resources are available, governmental bodies can be a natural fit for such a program. For this to work, you will need to show how Green Chemistry aligns with a governmental mission. Since Green Chemistry has significant promise for improving energy, transportation, manufacturing, human health, environmental health, and natural resource use, finding a good fit is often not difficult.

If resources are limited, governmental research grant programs can be done in partnership with industry. For the same areas of promise mentioned above, industry members have proven eager to encourage and leverage government research programs, knowing that they will, down the road, reap the innovation benefits.

Scientific societies:

With their roots in the existing scientific community and their connections to other like-minded institutions around the world, scientific societies can be a natural host for a Green Chemistry grants program.

Companies:

Companies around the world have established internal grant programs to encourage innovation in the field amongst their own researchers. Some have identified a well-defined niche in Green Chemistry where they wish to excel, and then use the program to spur competition amongst its people to meet that need. Others have looked across their entire research and development portfolio and used Green Chemistry criteria to determine which projects go forward.

See Section THREE for more information regarding Green Chemistry research programs.

3. Education: Teach Green Chemistry in Schools and Universities

At the beginning of this document we highlighted the problem of product design before Green Chemistry came along: Chemists and their peers were very good at focusing on the function of a chemical product, but rarely stopped to think about its unintended consequences.

This is not a surprise when you consider the following: prior to the advent of Green Chemistry, chemists were not required to learn about toxicology to receive their PhD. They were taught to bring brilliant new molecular inventions into the world, but never how to determine if those inventions might be harmful to human health and the environment.

Can you imagine another profession and other discipline where the people who are responsible for creating something are not responsible for or even aware of the consequences of what they are creating?

Imagine hearing statements such as this from these design professions:

> Architect: "I design beautiful buildings. They may collapse unexpectedly, but building safety is someone else's job."
>
> Car designer: "I design fast, luxurious cars. Sure, they can be prone to fiery crashes, but there are other people working on safe cars."
>
> Chef: "I create delicious meals. I suppose they may cause some diners to become sick, but there are other people working on non-toxic cooking."

It is inconceivable for those other professions, and yet, as a chemist, it's been perfectly acceptable to say, "I create new molecules, and I design new methods to make those molecules. Sure, they might be toxic, resource depleting, or bio-accumulating, but there are other people working on Green Chemistry".

For the same reason that the first three examples are absurd that last example is absurd.

To change this dynamic, it's critical to include Green Chemistry into chemistry education in a systematic way.

Certainly, you can't expect to alter an entire chemistry curriculum overnight. Change usually comes slow in universities and colleges. But there are proven ways of working Green Chemistry into exiting course structures, even as you work for larger, longer term changes.

> <u>Build it into existing courses</u>: The core concepts in the various areas of chemistry are always going to be the same, but the illustrations you choose to demonstrate those concepts in the lab or classroom can be Green Chemistry illustrations. Instead of using a traditional example of a chemical reaction, use an example of Green Chemistry where you show a reaction with high atom economy - where most of the reactants are converted into product. Demonstrate and teach that one can avoid or reduce waste, hazards, and excess inputs and steps. The illustrative examples that have been traditionally used in teaching chemistry are opportunities to highlight the concepts of Green Chemistry. They can serve a dual purpose of illustrating the underlying chemistry concept and the Green Chemistry concept as well.

Build Green Chemistry into laboratory work: Instead of just using chemical transformations in the laboratory that illustrate the transformation itself, you can look at whether that transformation is starting with a toxic input or a benign one. Is it starting with a bio-based feedstock or a depleting one? Is the reaction energy efficient? You can talk about how much waste the transformation generates. The students should then consider whether or not the resulting product or side-products are toxic. Laboratory experiments help to communicate those concepts.

You might even begin to adjust laboratory practices to further illustrate those concepts. For example, providing open access to specialized lab instrumentation such as flow chemistry reactors can facilitate Green Chemistry implementation. Also, removing duplication of chemical inventories and sharing can reduce waste.

Teach a dedicated Green Chemistry course: There are plenty of examples from schools around the world of dedicated courses that focus specifically on the Green Chemistry Principles and which complement an already-existing curriculum. Section THREE provides web links to some of this course work.

Join "Green Chemistry Commitment": Green Chemistry Commitment is a program that helps universities and colleges foster Green Chemistry education on their campuses. As a community of institutions from around the world, it challenges each school to commit to progress in Green Chemistry. It fosters collaborations among members to help make that progress possible. The program is run by the Green Chemistry education experts at Beyond Benign, and presently includes 53 schools from four different countries.

Example:

A Laboratory Sequence for Reducing Waste in a General Chemistry Laboratory:

Dr. Matthew Fountain at SUNY Fredonia has revised their General Chemistry II labs to drastically reduce waste and the use of hazardous chemicals. The sequence allows students to use "waste" from one experiment as starting material in the following experiment. The approach has reduced their lab's waste by nearly 90%. This has immediate environmental benefits and the students learn how thoughtful redesign can improve the sustainability of a chemical process. More information about their approach can be found in this case study:

https://www.beyondbenign.org/lessons/case-study-laboratory-sequence-reducing-waste-general-chemistry-laboratory/

See Section THREE for examples of how universities have brought Green Chemistry into the classroom, and for further reading and classroom materials.

4. Workforce Training: Teach Green Chemistry to the Existing Workforce

Inspiring the future generations of scientists and leaders to practice Green Chemistry is vital. However, more immediate strides toward sustainability can and must be taken, and this means equipping the people already at work throughout the economy with Green Chemistry skills and knowledge.

It's not just the chemists who will benefit from this training, or who can put that training to use to benefit the economic and environmental performance of a company. Green Chemistry is about innovation. It encourages a person to look at an entire system and ask series of very important questions: "How can this be better? What inefficiencies exist? What unnecessary costs are hiding in our inputs and processes? What wastes are we generating, and can we reduce those? What risks do our workers and customers face? How can we most effectively design our next product?" Green Chemistry training equips each employee to help answer those questions. Ultimately, it's the chemists and chemical engineers who will translate inspiration to real world innovation in the form of Green Chemistry or green engineering. The inspiration can come any member of your organization, and so exposure to the ideals and potential of Green Chemistry can benefit all.

This professional development effort has been done successfully throughout the world, using tools such as online courses and certificate programs.

See Section THREE for more information related to professional development and workforce training in Green Chemistry.

5. Conferences: Attend Existing Conferences, and Begin New Ones

Several Green Chemistry conferences have been developed through the years. Join the global Green Chemistry community at these events. At your local or regional level, you can foster new conferences, events, and gatherings to help promote green chemistry. These events will strengthen any budding Green Chemistry network, and will also serve as attractions that will draw new members into the community.

Example

The Annual Green Chemistry & Engineering Conference, hosted by the ACS Green Chemistry Institute

First held in 1996, this conference has for decades served as a valuable hub of the international Green Chemistry community. At its core it's a technical conference where innovative Green Chemistry research is on display. But the program also includes information about long-term strategic developments in the field, the interaction of Green Chemistry and environmental regulations, and Green Chemistry's place in business development and innovation.

It's an ideal place to meet Green Chemistry colleagues from all corners of the world, including people representing many of the key resources mentioned throughout this document.

[18]

See Section THREE for examples of Green Chemistry conferences held throughout the world.

6. Green Chemistry Networks: Establish a Network in Your Region

At the start of this document we established that for Green Chemistry to truly thrive you must establish and nurture collaborations and partnerships across all sectors of your economy.

As those connections between sectors begin to take shape, it's a good idea to begin thinking about forming a Green Chemistry Network to formalize and nurture those relationships.

Green Chemistry networks exist at the local, national, regional, and international levels throughout the world. Learn from them, and connect to them, to strengthen your own efforts.

[18] https://www.gcande.org

Example

The Green Chemistry Education Network

The Green Chemistry Education Network (GC Ed Net) has grown to include more than 50 members representing chemistry clubs, secondary schools, colleges, universities, and government offices. It serves as a forum for members to share ideas, techniques and materials for integrating Green Chemistry into chemical education at all levels. The members offer valuable resources, mentoring, and professional growth opportunities to the full community of chemistry educators.

Network of Early-Career Sustainable Scientists and Engineers (NESSE)

NESSE is a global movement of young academic researchers and professionals at the beginning of their careers. The network seeks to inspire research, strengthen education, train future leaders in the field, and promote advocacy. Their goal is to help emerging scientists and engineers to better address our most pressing sustainability challenges

[19,20]

See Section THREE for a list of networks that have been established in various regions and countries.

7. Industry Roundtables & Affinity Groups: Bring Industry Members Together Around Green Chemistry

While connecting players from all sectors is vital, colleagues from within a common sector can benefit tremendously by collaborating to tackle issues unique to their industry. Industry Roundtables and affinity groups have proven to be an effective way to accomplish connections at this level.

[19] http://cmetim.ning.com
[20] http://www.sustainablescientists.org/about/

Example

The ACS GCI Pharmaceutical Roundtable

In 2005, the American Chemical Society's Green Chemistry Institute and companies from the pharmaceutical industry formed a roundtable. The initial members saw that rapid and widespread adoption of Green Chemistry in their industry would benefit them all. They understood that the process would be more efficient if they collaborated to make it happen. The pharmaceutical industry has over the years been a leader in developing Green Chemistry innovations and this roundtable has played a significant role in helping to make that happen. The current members of the roundtable include more than 20 of the world's leading pharmaceutical companies.

See Section THREE for information about additional Green Chemistry roundtables and affinity groups.

8. Public Policy: Bring Green Chemistry into Public Policy Discussions

Wise and effective environmental and scientific public policy has always depended on clear and active input from the technical experts in those fields. Green Chemistry is no different.

Despite its 25-year history, Green Chemistry remains all too unfamiliar to policy experts and political leaders around the world. Green Chemistry touches on science, engineering, industry, education, innovation… and the list goes on. And the Green Chemistry approach – its unique way of seeing the problems and designing solutions – can inform more effectively public policy. Great strides have been made. But much remains to be done if the relevant laws and regulations are going to better leverage the full power of Green Chemistry.

See Section THREE for more information regarding Green Chemistry & public policy.

9. Public Awareness: Tell Stories of Green Chemistry to the Public

"Public" is just another name for every type of person who stands to benefit directly – personally and professionally—from the development and use of Green Chemistry. This includes consumers, taxpayers, voters, children, and legislators. A critical goal in the practice of Green Chemistry must be to communicate its ideals to these people. Tell stories of where and how it has been accomplished, and excite people with the innovations that Green Chemistry makes possible.

See Section THREE for more information regarding Green Chemistry & public awareness.

You are not alone

This document contains a rich store of resources. It will point you toward a useful path, and help you take your first steps down that path. And, we hope, the document will inspire you to begin that journey.

But realistically, it's not enough. No single document can capture the tremendous store of knowledge that exists in the global Green Chemistry community. We encourage you to turn to that community and make the most of what they have to offer.

As is mentioned throughout this document, it is the connections between professionals, institutions and sectors that has allowed Green Chemistry to flourish throughout the world. This will remain the case going forward.

And so, as you proceed, know that there are hundreds than have gone before you. Hundreds who are eager to welcome and help new members of the community. This guide contains references to many of those resources. Use them. Tap into that global font of Green Chemistry wisdom, and soon you too will be passing on your knowledge to others.

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Part 3

Detailed References and Technical Resources to Help Implement Green Chemistry

In this section we hope to begin to help answer the question “What’s next?”. We sincerely hope that you will continue your adventure into Green Chemistry, and we offer here concrete examples of institutions, programs and people to whom you might turn for information, advice, and inspiration.

We don’t pretend that this is an exhaustive list. The international Green Chemistry community is too large to be encapsulated in one document, and its activities are too many. In the days and weeks after we put this document into the world, another champion may have arisen, another Green Chemistry research program may have begun, and a new conference may have been announced.

Use the resources in this section as your starting point. Follow the links and reach out to the people, and as you take these next steps, the road into the exiting realm of Green Chemistry will lay itself out before you.

Green Chemistry: Further information

The Origins and Early History of Green Chemistry
https://www.worldscientific.com/doi/pdf/10.1142/9789813228115_0001?download=true

An “Changing the Course of Chemistry” by Anastas & Beach
https://greenchemistry.yale.edu/about/history-green-chemistry

A Historical Perspective
https://www.warnerbabcock.com/green-chemistry/a-historical-perspective/

More information about the Green Chemistry approach

https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry.html

https://www.beyondbenign.org/about-green-chemistry/

https://www.warnerbabcock.com/green-chemistry/about-green-chemistry/

Essential Green Chemistry Articles

These references are offered in chronological order, beginning with the most recent, based on date of publication.

1. Erythropel, H. C., et al. (2018). "The Green ChemisTREE: 20 years after taking root with the 12 Principles." Green Chemistry **20**(9): 1929-1961.
2. Bryan, M. C., et al. (2018). "Key Green Chemistry research areas from a pharmaceutical manufacturers' perspective revisited." Green Chemistry **20**(22): 5082-5103.
3. Coish, P., McGovern, E., Zimmerman, J. B., & Anastas, P. T. (2018). The Value-Adding Connections Between the Management of Ecoinnovation and the Principles of Green Chemistry and Green Engineering. In *Green Chemistry* (pp. 981-998). Elsevier.
4. Paul Anastas, et al. (2016). "“Happy silver anniversary”: Green Chemistry at 25." Green Chemistry **18**(1): 12-13.
5. Coish, P., et al. (2016). Current Status and Future Challenges in Molecular Design for Reduced Hazard, American Chemical Society.
6. Anastas, P. T. and J. B. Zimmerman (2016). "Safer by Design." Green Chemistry **18**(16): 4324-4324.
7. Anastas, P. T. and D. T. Allen (2016). "Twenty-Five Years of Green Chemistry and Green Engineering: The End of the Beginning." ACS Sustainable Chemistry & Engineering **4**(11): 5820-5820.
8. Zimmerman, J. B. and P. T. Anastas (2015). "Toward substitution with no regrets." Science **347**(6227): 1198-1199.
9. Zimmerman, J. B. and P. T. Anastas (2015). "Toward designing safer chemicals." Science **347**(6219): 215-215.
10. Matus, K. J. M., et al. (2012). "Barriers to the Implementation of Green Chemistry in the United States." Environmental Science & Technology **46**(20): 10892-10899.
11. Li, C.-J. and P. T. Anastas (2012). "Green Chemistry: present and future." Chemical Society Reviews **41**(4): 1413-1414.
12. Mulvihill, M. J., et al. (2011). "Green Chemistry and Green Engineering: A Framework for Sustainable Technology Development." Annual Review of Environmental and Resources **36**: 271 - 293.
13. Cui, Z., et al. (2011). "Green Chemistry in China." Pure and Applied Chemistry **83**(7): 1379-1390Norvig, P., et al. (2010). "2020 visions." Nature **463**(7277): 26-32.
14. Anastas, P. T. and N. Eghbali (2010). "Green Chemistry: Principles and Practice." Chemical Society Reviews **39**(1): 301-312.
15. Anastas, P. T. (2010). Preface. Biomass to Biofuels: Strategies for Global Industries. A. Vertes, N. Qureshi, H. Yukawa and H. Blaschek, John Wiley & Sons, Ltd**:** 584.

16. Anastas, P. T., Ed. (2009-2011). Handbook of Green Chemistry (9 volumes).

17. Shukla, S. S., et al. (2009). "The Need and the Quest for Developing Water Treatment Systems for Masses Which are Low Cost, Low Tech and Use Locally or Easily Available Material." Clean Technology 2009: Bioenergy, Renewables, Storage, Grid, Waste and Sustainability: 281-284.

18. Beach, E. S., et al. (2009). "Green Chemistry: A design framework for sustainability." Energy & Environmental Science **2**(10): 1038-1049.

19. Anastas, P. T. (2009). "The transformative innovations needed by Green Chemistry for sustainability." ChemSusChem **2**(5): 391-392.

20. Manley, J. B., et al. (2008). "Frontiers in Green Chemistry: meeting the grand challenges for sustainability in R&D and manufacturing." Journal of Cleaner Production **16**(6): 743-750.

21. Horvath, I. T. and P. T. Anastas (2007). "Innovations and Green Chemistry." Chemical Reviews **107**(6): 2169-2173.

22. Anastas, P. T. and E. S. Beach (2007). "Green Chemistry: the emergence of a transformative framework." Green Chemistry Letters and Reviews **1**(1): 9-24.

23. Zimmerman, J. B. and P. T. Anastas (2006). When Is a Waste not a Waste? Sustainability Science and Engineering: Defining Principles. M. A. Abraham, Elsevier Science**:** 201-221.

24. Anastas, P. T. and J. B. Zimmerman (2006). The Twelve Principles of Green Engineering as a Foundation for Sustainability. Sustainability Science and Engineering: Defining Principles. M. A. Abraham, Elsevier Science**:** 11-32.

25. Anastas, P. T. (2004). "Green Chemistry: Definition and Principles." Abstracts of Papers of the American Chemical Society **228**: U760-U760.

26. Anastas, P. T. and M. M. Kirchhoff (2003). "Green Chemistry: From command and control to pollution prevention." Abstracts of Papers of the American Chemical Society **225**: U946-U946.

27. Anastas, P. T. and J. C. Warner (1998). Green Chemistry: Theory and Practice, Oxford University Press.

28. Anastas, P. T., & Zimmerman, J. B. (2016). The molecular basis of sustainability. *Chem*, *1*(1), 10-12.

Green Chemistry and its Contribution to Global Sustainability

The 2030 United Nations Sustainable Development Goals challenge the world to do better in key areas such as food, water, poverty, materials, and empowerment. Green Chemistry offers a valuable approach to taking on these challenges. It encourages us to see that these challenges are connected parts of a larger system. And it offers ways to improve that system through thoughtful design applied as early as possible in any industrial, agricultural, policy, or sociological undertaking.

Green Chemistry has been known as "the chemistry of sustainability". Sustainable chemistry promotes, advances, enables, and empowers the implementation of the chemistry of sustainability. Sustainable chemistry refers to a broader ecosystem beyond the science that includes education, economics, policies, management and other efforts that enable the science to be implemented and make a positive impact.

As a more specific example, Green Chemistry offers methods for tackling the global challenge of Persistent Organic Pollutants (POPs).

Below are links to additional resources that explain how a Green Chemistry approach can help us achieve greater success in meeting the United Nations Sustainable Development Goals.

The United Nations Sustainable Development Goals
https://www.un.org/sustainabledevelopment/

The United Nations sustainability goals: How can sustainable chemistry contribute?
Anastas, P. T., & Zimmerman, J. B. (2018). The United Nations sustainability goals: How can sustainable chemistry contribute? *Current Opinion in Green and Sustainable Chemistry*, *13*, 150-153.

Green Chemistry and the EU's REACH Regulations
https://www.scitecheuropa.eu/eu-regulation-green-chemistry/92711/

Understanding Sustainability & Chemistry's Role
https://www.acs.org/content/acs/en/sustainability/understandingsustainability.html

The Periodic Table of the Elements of Green and Sustainable Chemistry
Anastas, P., & Zimmerman, J. (2019). The Periodic Table of the Elements of Green and Sustainable Chemistry. *Green Chemistry*.

Beyond reductionist thinking in chemistry for sustainability
Anastas, P. T. (2019). Beyond reductionist thinking in chemistry for sustainability. Trends in Chemistry, 1(2), 145-148.

The Molecular Basis of Sustainability
Anastas, P. T., & Zimmerman, J. B. (2016). The molecular basis of sustainability. *Chem*, *1*(1), 10-12.

A Sampling of Green Chemistry Champions & Experts

Paul Anastas, Yale University

Paul Anastas began his journey in Green Chemistry in the early 1990s as a mid-level manager at the US Environmental Protection Agency. As the world was beginning to turn its attention from environmental clean-up efforts to "pollution prevention", Paul thought we could do even better. He realized that chemists had the power to effect environment improvements much, much earlier in the process. He worked with others at the EPA and an industry contact named John Warner (included in this list below) to develop this idea, and the field of Green Chemistry was born.

From his position at the EPA, Paul helped to launch the Presidential Green Chemistry Challenge Awards as well as the ASC Green Chemistry Institute. Paul later became the director of that Institute, where he helped to grow the annual Green Chemistry & Engineering Conference, established industry Green Chemistry roundtables, and continued to take the ideals of Green Chemistry to individuals, organizations, and governments around the world. Paul continues this work now as a professor at Yale University, where he leads the Center for Green Chemistry & Green Engineering at Yale.

Nigist Asfaw, Addis Ababa University

Dr. Nigist Asfaw is an Assistant Professor of Organic chemistry at Addis Ababa University, Addis Ababa, Ethiopia. Inspired by the potential of Green Chemistry she developed collaborations with other champions such as Professor Sir Martyn Poliakoff & Professor Peter Licence of The University of Nottingham. With support from them and others in the international community she built the foundations for the practice of Green Chemistry in Ethiopia. Her research currently focuses on Natural Product Chemistry, Essential oils and Green Chemistry. She continues to promote Green Chemistry education and remains ever on the lookout for fellow educators who are interested in collaborating with her in these efforts.

Amy Cannon, Beyond Benign

Amy Cannon holds the world's first Ph.D. in Green Chemistry. She earned this degree at the University of Massachusetts Boston. Inspired by the opportunity she had to study in this field, Amy embarked on a mission to improve education in Green Chemistry. In the years since she has developed educational curricula, developed and led training programs for workers and educators, and fostered Green Chemistry programs at educational institutions around the world. She currently pursues this work as the co-founder and executive director of Beyond Benign.

Tomislav Friscic, McGill University

Tomislav Friscic runs the Friscic group at McGill University and is a leader in the university's push to advance Green Chemistry. His group's primary research is in developing and exploiting solid-state, solvent-free and near solvent-free reactions for the purpose of cleaner and more energy-efficient synthesis. Tomislav received his B.Sc. at the University of Zagreb, and his Ph.D. at the University of Iowa. He was a post-doctoral associate and a Herchel Smith Research Fellow at the University of Cambridge.

David Gonzalez, Facultad de Quimica Mexico City

Born in Montevideo, Uruguay, David Gonzalez studied chemistry in Uruguay and the US. His research in organic chemistry and biocatalysis brought him into the realm of Green Chemistry and he quickly became involved in the field. In addition to his research in the field, he is particularly interested in developing Green Chemistry alternatives amenable for developing and emerging countries. This international focus has also led David to become involved in such bodies as the Green Chemistry Subcommittee at the General Assembly Meeting of IUPAC (2009 in Glasgow). He currently pursues his work in Green Chemistry as an Associate Professor at Facultad de Quimica in Mexico City.

Buxing Han, Chinese Academy of Sciences

Buxing Han received Ph.D. degree at Institute of Chemistry, Chinese Academy of Sciences (CAS) in 1988, and did postdoctoral research from 1989 to 1991 at the University of Saskatchewan, Canada. He has been a professor at Institute of Chemistry, CAS since 1993. His research interests include physicochemical properties of green solvent systems and applications of green solvents in green chemistry. He has published more than 500 papers in peer-reviewed scientific journals and has presented more than 100 plenaries or invited lectures at different conferences. His published papers have been cited more than 14,000 times. He is serving on more than 10 peer-reviewed scientific journals.

Milton Hearn, Monash University

Milton Hearn is a Professor of Chemistry and the Director of the Australian Research Council Special Research Center for Green Chemistry at Monash University. His work focuses on studying biomolecular structures, the study of separation science, and using that knowledge to develop green processes. He earned his B.S, Ph.D, and D.Sc in Organic Chemistry at the University of Adelaide. He then did his postdoctoral work in Canada before working in New Zealand. From 1981 to 1985, he was a Research Fellow at the St. Vincent's Institute of Medical Research before joining Monash in 1986. Since 2002 he has been the Director of the Green Chemistry Center.

Philip Jessop, Queen's University

Philip Jessop is a professor of inorganic chemistry at Queen's University, where he leads the Jessop Group in research on homogeneous catalysis, CO_2 fixation, green solvents, hydrogen storage, and other topics. Philip also serves as technical director for GreenCentre Canada, a company that seeks to speed the adoption of important chemistry and materials science discoveries into the marketplace.

Walter Leitner, Max Planck Institute

Walter Leitner obtained his Ph.D at Regensburg University in 1989 and was a Postdoctoral Fellow with Prof. John M. Brown at the University of Oxford. After research within the Max-Planck-Society he was appointed Chair of Technical Chemistry and Petrochemistry at RWTH Aachen University in 2002. His research interests are the molecular and reaction engineering principles of catalysis as a fundamental science and key technology for Green Chemistry. This includes the development and synthetic application of organometallic catalysts and the use of alternative reaction media, especially supercritical carbon dioxide, in multiphase catalysis. Walter Leitner has published more than 170 publications in this field and co-edited among others the first edition of "Synthesis using Supercritical Fluids”.

Peter Licence, University of Nottingham

Peter License is a professor of chemistry and the Director of The GlaxoSmithKline Carbon Neutral Laboratory and the University of Nottingham. Peter studied at the University of Wales before joining the team of Martyn Poliakoff (a groundbreaking Green Chemistry researcher) as a postdoctoral fellow at Nottingham. Peter’s core research focuses on uses of alternative solvents such as supercritical fluids and ionic liquids.

Mary Kirchhoff, ACS Green Chemistry Institute

Mary Kirchhoff, Ph.D., is Executive Vice President for Scientific Advancement Division at the American Chemical Society (ACS) and Director of the ACS Green Chemistry Institute. As the recipient of an American Association for the Advancement of Science Environmental Fellowship, she worked with the U.S. Environmental Protection Agency’s Green Chemistry program. She is a co-author with Paul Anastas and Paul Bickart on Designing Safer Polymers, and co-editor with Mary Ann Ryan of ACS' Greener Approaches to Undergraduate Chemistry Experiments. She received her doctorate in organic chemistry from the University of New Hampshire.

Klaus Kümmerer, Leuphana Lueneburg

Klaus Kümmerer is full Professor of Sustainable Chemistry and Material Resources and director of the Institute of Sustainable and Environmental Chemistry at the public Leuphana University as well as Director of Research and Education of the International Sustainable Chemistry Collaboration Centre (ISC3). His research and teaching is focused on Sustainable Chemistry, Sustainable Pharmacy, Material Resources, Aquatic Environmental Chemistry, and Time in Environmental and Sustainability Research. He heads an interdisciplinary research team. Klaus Kümmerer serves on many international committees including the prestigious seminal Global Chemical Outlook by UNEP, EU Technology Platform SusChem Europe. He also advises other international organizations such as WHO and OPWC. He is a member of the Executive Board of the subdivision of Sustainable Chemistry in the German Chemical Society. He is also organizer of the

Green and Sustainable Chemistry Conference and the International Summer School on Sustainable Chemistry.

CJ Li, McGill University

Professor CJ Li directs the Li Group at McGill University, which researches "new fundamental reactions that can drastically shorten synthetic steps, more directly transform renewable biomass and abundant feedstocks (CO_2 and methane) into high valued products, and harvest solar light by chemical means and utilize photo-energy as energy input for chemical conversion". CJ also directs the FQRNT Centre in Green Chemistry and Catalysis (CGCC). This Centre brings together researchers from all major universities in Quebec to solve the key challenges in Green Chemistry and catalysis.

Nitesh Mehta, Green ChemisTree Foundation

Nitesh Mehta is cofounder of The Green ChemisTree Foundation, a nonprofit organization based in Mumbai, India. The Foundation works to increase technical knowledge in Green Chemistry in all sectors of the economy. Through outreach efforts, collaborations, conferences, and educational initiatives, Green ChemisTree is playing a significant role in helping to grow Green Chemistry in India and beyond. The seeds of this organization were planted when Nitesh and cofounder Bhadresh Padia attended the Green Chemistry & Engineering Conference in 2008. They immediately recognized that Green Chemistry could, and must, play an important role in India's growing chemical and manufacturing enterprises.

Audrey Moores, McGill University

Audrey Moores is an Associate Professor at McGill University, where she leads the Moores Research Group. The group focuses on "synthesising, characterizing and studying novel, and simple catalysts, based on metal nanoparticles, ionic liquids and/or cellulose nanocrystals in order to propose innovative and recyclable catalysts for organic reactions". Audrey also serves as co-associate director of the FQRNT Centre in Green Chemistry and Catalysis (CGCC).

Adelina Voutchkova-Kostal, The George Washington University

Adelina Voutchkova-Kostal is an associate professor of chemistry at The George Washington University, and leader of the Voutchkova-Kostal Group. Adelina's research team seeks to develop "more environmentally benign methodologies for the fine chemicals industry". Adelina came to GWU after serving as a researcher with the Center for Green Chemistry & Green Engineering at Yale.

John Warner, Warner Babcock Institute

At the same time that Paul Anastas was working at the US EPA, John Warner was working as a researcher for the Polaroid Corporation. Like Paul, John had begun to think about the unique ways in which a chemist could improve the ways in which products interact with humans and the environment. He approached the EPA to further explore these ideas, and quickly established a collaboration with Paul and the others at EPA. A significant result of their partnership was the book "Green Chemistry: Theory and Practice" which brought the ideas of Green Chemistry to the world.

John later became a professor at the University of Massachusetts (Boston, and then Lowell), where he pioneered efforts to bring Green Chemistry into high school and college classrooms. He now leads the Warner-Babcock Institute for Green Chemistry, which is a world leading Green Chemistry research center, and serves as President of Beyond Benign, which continues the charge to improve Green Chemistry education.

Awards Programs

Green Chemistry Challenge Awards (United States)

https://www.epa.gov/greenchemistry/information-about-green-chemistry-challenge

Established in 1996, this program has now recognized more than 100 researchers from industry, academia and government for this work in Green Chemistry.

Wöhler-Preis für Nachhaltige Chemie (Germany)

https://en.gdch.de/main-navi/gdch/prizes-and-awards.html

Presented by the Gesellschaft Deutscher Chemiker chemical society, this prize is awarded "for groundbreaking contributions to the development and implementation of sustainable chemistry. Innovative methods from all areas of chemistry that lead to improved, environmentally friendly processes will be considered". The prize is endowed with € 7,500.

The Royal Society of Chemistry's Green Chemistry Award (United Kingdom)

http://www.rsc.org/ScienceAndTechnology/Awards/GreenChemistry/

"The Green Chemistry Award is for the design, development or implementation of novel chemical products or processes which have the potential to reduce or eliminate the use and generation of hazardous substances."

The John Jeyes Award (United Kingdom)

https://www.rsc.org/ScienceAndTechnology/Awards/JohnJeyes/

Presented by the Royal Society of Chemistry, the John Jeyes Award is for "chemistry in relation to the environment".

Canadian Green Chemistry and Engineering Network Awards (Canada)

https://www.cheminst.ca/awards/cgcen-awards

Presented by the Chemical Institute of Canada. "A national awards program recognizing significant accomplishments and advancements in Green Chemistry and engineering made by individuals and organizations."

European Sustainable Chemistry Award (Europe)

https://www.euchems.eu/awards/european-sustainable-chemistry-award/

Presented by the European Chemical Society, this award "recognizes the achievements of individual scientists and teams. The European Sustainable Chemistry Award is intended to be a prestigious scheme which will raise the profile of sustainable chemistry and be a spur to innovation and competitiveness".

SERB-IGCW Awards (India)

http://www.industrialgreenchem.com/SERB.php

Presented in India jointly by SERB (India's Department of Science and Technology) and the Green ChemisTree Foundation, the SERB-IGCW awards "acknowledge outstanding case studies incorporating the Principles of Green Chemistry and Engineering into Chemistry routes, chemical designs and Manufacturing Practices; and steps taken towards pollution prevention while meeting the triple bottom line of People, Profit and Planet".

Elsevier Foundation Green & Sustainable Chemistry Challenge (International)

https://www.elsevierfoundation.org/programs/research-in-developing-countries/greenchem/

The Elsevier Foundation sponsors this international award, which "seeks to stimulate innovative chemistry research that helps the environment and low-resource communities. We look for proposals outlining innovative chemistry ideas that tackle some of the developing world's greatest sustainability challenges".

American Chemical Society Award for Affordable Green Chemistry (United States)

https://www.acs.org/content/acs/en/funding-and-awards/awards/national/bytopic/acs-award-for-affordable-green-chemistry.html

"To recognize outstanding scientific discoveries that lay the foundation for environmentally-friendly products or manufacturing processes at a cost comparable to or less than that of current technologies, or discoveries that deliver new applications with compelling cost/benefit profiles. To identify and recognize discovery of new eco-friendly chemistries with the potential to enable products or manufacturing processes that are less expensive than existing alternatives."

Research Programs

Center for Green Chemistry & Green Engineering at Yale

https://greenchemistry.yale.edu

Center for Green Chemistry- UMass Boston

https://www.umb.edu/greenchemistry

Department of Ecology, State of Washington

https://ecology.wa.gov/Waste-Toxics/Reducing-toxic-chemicals/Green-chemistry

Millipore Sigma

https://www.emdmillipore.com/US/en/responsibility/products/design-innovation/Green-Chemistry/uqib.qB.YJcAAAFDfo9ZXuj1,nav

University of York-Green Chemistry Centre of Excellence

https://www.york.ac.uk/chemistry/research/green/

University of Nottingham- The Centre of Sustainable Chemistry

https://www.nottingham.ac.uk/chemistry/research/centre-for-sustainable-chemistry/the-centre-for-sustainable-chemistry.aspx

Monash University- The Centre for Green Chemistry (CGC)

http://www.monash.edu.au/strip/tenants/university/centre-greem-chemistry.html

Leuphana Luneburg

https://www.leuphana.de/en/professorships/nachhaltige-chemie-und-ressourcen-englisch.html

McGill University

https://www.mcgill.ca/green-chemistry-create/

Carnegie Mellon University - The Institute for Green Science

http://igs.chem.cmu.edu

Warner Babcock Institute

http://www.warnerbabcock.com

Berkeley Center for Green Chemistry

https://bcgc.berkeley.edu

CSIR Indian Institute of Chemical Technology

https://www.iictindia.org

GreenCentre Canada

https://www.greencentrecanada.com/green-chemistry/

Michigan Green Chemistry Clearinghouse - Directory of Green Chemistry Organizations

https://www.migreenchemistry.org/toolbox/directory/

Educational Resources: Schools that have brought Green Chemistry into the classroom

Yale University

https://greenchemistry.yale.edu/education/yale-university-courses

MSc Green Chemistry and Sustainable Industrial Technology

https://www.york.ac.uk/study/postgraduate-taught/courses/msc-green-chemistry-sustainable-industrial-tech/

MSc Graduate Academic Studies - Study programme "Environmental Chemistry"

https://www.chem.bg.ac.rs/studije/17-en.html

University of Zagreb

http://www.pbf.unizg.hr/en/departments/department_of_chemistry_and_biochemistry/laboratory_for_physical_chemistry_and_corrosion/green_chemistry

University of Nottingham

https://www.nottingham.ac.uk/pgstudy/courses/chemistry/green-and-sustainable-chemistry-msc.aspx

Green Chemistry Commitment:

The steward of this program, Beyond Benign, maintains a list of the schools participating in the program, including specific information about the activities each school is pursuing.

https://www.beyondbenign.org/he-whos-committed/

ACS Summer School on Green Chemistry & Sustainable Energy

https://www.acs.org/content/acs/en/greenchemistry/students-educators/summerschool.html

Educational Resources: Sources for Green Chemistry teaching materials

Center for Green Chemistry & Green Engineering at Yale

https://greenchemistry.yale.edu/education

Beyond Benign

https://www.beyondbenign.org

A Guide to Green Chemistry Experiments for Undergraduate Organic Chemistry Labs

https://www.mygreenlab.org/gccg-form.html

CHEM 21

http://learning.chem21.eu

Molecular Design Research Network [MoDRN]

https://modrn.yale.edu

Global Green Chemistry Initiative

https://www.global-green-chemistry-initiative.com

University of Scranton

https://www.scranton.edu/faculty/cannm/green-chemistry/english/drefusmodules.shtml

The Institute for Green Science, Carnegie Mellon University (CMU)

http://www.chem.cmu.edu/groups/collins

Training the Workforce

Yale-UNIDO Global Green Chemistry Initiative

https://www.global-green-chemistry-initiative.com

Green Chemistry & Chemical Stewardship Online Certificate Program

https://osha.washington.edu/pages/green-chemistry-chemical-stewardship-online-certificate-program

Conferences

Green & Sustainable Chemistry Conference

https://www.elsevier.com/events/conferences/green-and-sustainable-chemistry-conference

IGSC

https://www.isgc-symposium.com/

Gordon Conference on Green Chemistry

https://www.grc.org/green-chemistry-conference/

Sustainable Nanotechnology Organization Conference

http://www.susnano.org/SNO2018/conference-deadlines-2018.html

A list of Green Chemistry conferences maintained by the American Chemical Society

https://www.acs.org/content/acs/en/meetings/greenchemistryconferences.html

Green Chemistry Networks

G2C2 and Green Chemistry Network

http://g2c2.greenchemistrynetwork.org

Green Chemistry Network Centre

http://greenchem.du.ac.in/aboutus.html

The Global Network for Resource Efficient and Cleaner Production

http://www.recpnet.org/overview/

European Environment Bureau

https://eeb.org/homepage/about/

SusChem

http://www.suschem.org/about

Sustainable Nanotechnology Organization

http://www.susnano.org

Green Chemistry Commerce Council (GC3)

https://greenchemistryandcommerce.org

Green Chemistry Roundtables

The American Chemical Society's Green Chemistry Institute maintains, at present, five industry-specific roundtables.

https://www.acs.org/content/acs/en/greenchemistry/industry-roundtables.html

Inform Public Policy

Green Chemistry & the European Union's REACH Regulation

https://www.scitecheuropa.eu/eu-regulation-green-chemistry/92711/

Public Awareness

Global Green Chemistry Initiative

https://greenchemistry.yale.edu/global-green-chemistry-initiative-awareness-raising-workshop-cairo-egypt-fosters-multi-faceted

"Tell a Green Chemistry Story" video competition

https://greenchemistry.yale.edu/news/winners-tell-story-about-green-chemistry-video-competition

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Section 4:

The Technology Compendium

The Technology Compendium is a survey and summary of a broad array of Green Chemistry and Green Engineering innovations that are available and commercialized today or are near-term emerging opportunities. The compendium also includes case studies from the National Cleaner Production Centres (NCPCS) from Brazil, South Africa, Colombia, Egypt, Sri Lanka and Serbia, as well as a case study from Braskem, a Brazilian petrochemical company headquartered in São Paulo. The Compendium will be available online and will be periodically updated with new GC&GE solutions.

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Disclaimer

Yale and the Center for Green Chemistry & Green Engineering ("CGCGE") have prepared this Guidance Document to inspire the reader to pursue Green Chemistry in different settings and applications, and we offer guidance in how to do so effectively. The document offers tips and ideas for fostering a vibrant Green Chemistry approach, and we have drawn on the knowledge of Green Chemistry experts around the world.

CGCGE did not conduct independent assessments, and makes no independent representations or warranties as to cost, efficacy, safety, or performance. Nor does CGCGE make any representations or warranties as to the suitability of any guidance for any particular application.

It is CGCGE's hope that this Guidance Document will serve as a useful starting place for the pursuit of green chemistry and green engineering for purposes of evaluation, assessment, and, when deemed appropriate by the user, utilization. In no case will CGCGE be responsibility for any liability or damages resulting from this guidance.