Green Chemistry in the Curriculum:
An Introduction to Green Chemistry

Teacher's Guide

This module was developed to help to introduce the concepts of Green Chemistry and to give students a chance to think about the field of chemistry from a different perspective.

Commonly Asked Questions:

What is Green Chemistry?
Green chemistry is a pro-active approach to pollution prevention. It targets pollution at the design stage, before it even begins. If chemists are taught to develop products and materials in a manner that does not use hazardous substances, then much waste, hazards and cost can be avoided. Green Chemistry is designing chemical products and processes that reduce or eliminate the use and/or the generation of hazardous substances.

Think about the simple equation of risk: Risk = Hazard x Exposure. Traditional approaches to pollution prevention focus on mitigating the hazard or end-of-pipe pollution prevention controls. These traditional technologies focus on limiting the *exposure* of a hazardous material. Unfortunately, exposure precautions can and will fail (i.e., gloves can tear, goggles can break, chemical releases can occur). Green chemistry goes to the root of the problem and aims to eliminate the hazard itself. Green Chemistry is the ONLY science that focuses on the intrinsic *hazard* of a chemical or chemical process. It seeks to minimize or eliminate that hazard so that we do not have to worry about exposure.

What is the difference between Environmental Science and Green Chemistry?
Both areas of study seek to make the world a better place. The two are complimentary to each other. Environmental Science identifies sources, elucidates mechanisms and quantifies problems in the earth's environment. Green Chemistry seeks to solve these problems by creating alternative, safe technologies. Green Chemistry is *not* Environmental Chemistry. Green Chemistry targets pollution prevention at the source, during the design stage of a chemical product or process, and thus prevents pollution before it begins.

Is Green Chemistry more expensive that traditional Chemistry?

No. A simplified analysis of the cost structure associated with any chemical process takes into account the cost of materials, equipment and the human resources necessary. But, in reality, disposal, treatment and regulatory costs associated with the buying, using and generating hazardous materials involves numerous hidden costs. When you buy and use a hazardous material you are paying for it twice, once when you use it and once when you get rid of it. It makes sense that if you use materials that are non-hazardous and thus have minimal regulatory or disposal costs associated with them, the benefit to the economic bottom line is obvious. The Presidential Green Chemistry Challenge Award has provided illustrations of several examples where industry has not only accomplished goals of pollution prevention, but has achieved significant economic benefits simultaneously.

How are Chemists taught Green Chemistry?
One way that chemists are learning how to do Green Chemistry is by following the 12 principles of Green Chemistry. They are a set of guidelines that chemists use in order to perform chemistry in a better way. As you take a closer look at them, you will find they are very intuitive and simply good practice. The powerpoint presentation that goes along with this module will help to explain the 12 principles to the students. Each is briefly described below. For more information about the 12 principles, go to www.beyondbenign.org

The 12 Principles of Green Chemistry:

1. *Prevention*
   This principle is the most obvious and over-arches the other principles. It goes back to the old adage "an ounce of prevention is worth a pound of cure". It is better to prevent waste than clean it up after-the-fact. Throughout history there have been many cases of environmental disasters that demonstrated this (Bopal, India; Love Canal; Times Beach; Cuyahoga River).

2. *Atom Economy*
   This principle gets into the actual chemistry of how products are made. As chemists, atoms are assembled to make molecules. The molecules are assembled together to make materials. This principle states that it is best to use all the atoms in a process. And, those atoms that are not used end up as waste. The atom economy is a simple calculation that can be used when teaching stoichiometry and chemical reactions. The calculation is: A.E. = Formula Weight (FW) of Product divided by the FW of all of the reactants. It is a simple measure of the amount of waste in a process.

3. *Less Hazardous Chemical Synthesis*
   This principle is focused on *how* we make molecules and materials. The goal is to reduce the hazard of the chemicals that are used to make a product (the reagents). Throughout the history of how we have invented products and developed the process for making them, chemists have traditionally not

thought about what reagents they are using and the hazards that are associated with them. Chemists have traditionally used whatever means necessary. Today we are finding that less hazardous reagents and chemicals can be used in a process to make products… and, many times they are made in a more efficient manner!

4. *Designing Safer Chemicals*
The previous principle was focused on the *process*. This principle focuses on the *product* that is made. Everyone wants safe products. Everyone also wants products that do what they are supposed to do (they have to work!). This principle is aimed at designing products that are safe, non-toxic and efficacious. A good example of this is pesticides; which are products that are designed to be toxic. Many researchers are focused on created pesticides that are highly specific to the pest organism, but non-toxic to the surrounding wildlife and ecosystems.

5. *Safer Solvents and Auxiliaries*
Many chemical reactions are done in a solvent. And, traditionally organic solvents have been used that pose hazards and many are highly toxic. They also create volatile organic compounds (VOC's) which add to pollution and can be highly hazardous to humans. This principle focuses on creating products in such a way so that they use less hazardous solvents (such as water). We use solvents regularly in our daily lives (cleaning products, nail polish, cosmetics, etc.) and in the chemistry laboratory. An example that many can relate to is that of nail polish products. Have you walked by a nail salon and caught a smell of the solvents that are used? The solvents traditionally used have potential toxicity and are certainly not pleasant to smell. A water-based alternative polish would avoid the exposure that goes along with the nail products and reduce the hazards associated with traditional products.

6. *Design for Energy Efficiency*
Today there is a focus on renewable energy and energy conservation. We use energy for transportation purposes and to provide electricity to our homes and businesses. Traditional methods for generating energy have been found to contribute to global environmental problems such as Global Warming and the energy used can also be a significant cost. This principle focuses on creating products and materials in a highly efficient manner and reducing the energy associated with creating the products, therefore reducing associated pollution and cost.

7. *Use of Renewable Feedstocks*
90-95% of the products we use in our everyday lives are made from petroleum. Our society not only depends on petroleum for transportation and energy, but also for making products. This principle seeks to shift our

dependence on petroleum and to make products from renewable materials that can be gathered or harvested locally. *Biodiesel* is one example of this where researchers are trying to find alternative fuels that can be used for transportation. Another example is alternative, bio-based plastics. PLA (polylactic acid) is one plastic that is being made from renewable feedstocks such as corn and potato waste.

8. *Reduce Derivatives*

This principle is perhaps the most abstract principle for a non-chemist. The methods that chemists use to make products are sometimes highly sophisticated. And, many involve the manipulation of molecules in order to shape the molecules into what we want them to look like. This principle aims to simplify that process and to look at natural systems in order to design products in a simplified manner.

9. *Catalysis*

In a chemical process catalysts are used in order to reduce energy requirements and to make reactions happen more efficiently (and many times quicker). Another benefit of using a catalyst is that generally small amounts (catalytic amount versus a stoichiometric amount) are required to have an effect. And, if the catalyst is truly a “green” catalyst it will have little to no toxicity and it will be able to be used over-and-over again in the process. Enzymes are wonderful examples of catalysts that have been proven to perform amazing chemistry – our bodies are wonderful examples! Green chemists are investigating using enzymes to perform chemistry in the laboratory in order to obtain the desired product. Many times enzymes will have reduced toxicity, increased specificity and efficiency.

10. *Design for Degradation*

Not only do we want materials and products to come from renewable resources, but we would also like them to not persist in the environment. There is no question that many products we use in our daily lives are far too persistent. Plastics do not degrade in our landfills and pharmaceutical drugs such as antibiotics build up in our water streams. This principle seeks to design products in such a way so that they perform their intended function and then, when appropriate, will degrade into safe, innocuous by-products when they are disposed of.

11. *Real-time Analysis for Pollution Prevention*

Imagine if you have never baked a cake before in your life and you did not have a cookbook to refer to. You mix the ingredients that you believe you need and you place the cake in the oven. But, for how long do you cook it and at what temperature? How will you know when the cake is done? What happens if you cook it too long or for not enough time? This process is similar to what chemists have to do when they make products. How long do they allow the reaction to run for? When do they know it will be “done”? If there was a way to see inside the reaction and to know exactly when it would be done, then this would reduce waste in the process and ensure that your product is "done" and is the right product that you intended to make.

12. *Inherently Safer Chemistry for Accident Prevention*
    This principle focuses on safety for the worker and the surrounding community where an industry resides. It is better to use materials and chemicals that will not explode, light on fire, ignite in air, etc. when making a product. There are many examples where safe chemicals were not used and the result was disaster. The most widely known and perhaps one of the most devastating disaster was that of Bhopal, India in 1984 where a chemical plant had an accidental release that resulted in thousands of lives lost and many more injuries. The chemical reaction that occurred was an exothermic reaction that went astray and toxic fumes were released to the surrounding community. When creating products, it is best to avoid highly reactive chemicals that have potential to result in accidents. When explosions and fires happen in industry, the result is often devastating.

Teacher's Guide to Activities

. **Activity 1**

The first activity begins with asking simple questions (that do not have right or wrong answers) to get the students to think about what a chemist does and their role in solving global environmental problems. The questions can be asked at the beginning of class and they can write down their initial answers. The questions can be asked again at the end of the Green Chemistry module to see if their perspectives have changed.

The powerpoint presentation (Introduction to Green Chemistry) allows for the introduction to green chemistry, with some illustrative examples of Green Chemistry technologies. The presentation also introduces the 12 principles of green chemistry.

. **Activity 2**

After introducing the 12 principles to the students, the second activity will help them to come to a better understanding of the principles. By working alone, or in groups, they can re-write the principles so that they are understandable to them and to their classmates. The activity sheet gives them the extended principles that are written so that a chemist can understand them. How will they re-write them so that anyone can understand?

An Introduction to Green Chemistry

Student Module

. **Activity 1**: *Questions to think about before we begin:*

1. What does a chemist do?

2. What are some chemical products?

3. What do you think about when you hear the words “green chemistry”?

4. What is environmental science?

5. Do you think our world has environmental problems? What problems?

6. How do you think we will go about solving those problems?

. **Activity 2**: *The Twelve Principles of Green Chemistry:*

Now that you have learned about what Green Chemistry is, think about what it means to you. Re-write the 12 principles in your own words so that they are understandable to you and your classmates.

1. **Prevention.** It is better to prevent waste than to treat or clean up waste after it is formed.

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 Synthesis.** Whenever practicable, synthetic methodologies 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 preserve efficacy of the function while reducing toxicity.

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

6. **Design for Energy Efficiency.** Energy requirements should be recognized for their environmental and economic impacts and should be minimized. 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 practical.

8. **Reduce Derivatives.** Unnecessary derivatization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible.

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 do not persist in the environment and instead break down into innocuous degradation products.

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.** Substance and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosions, and fires.