NEW SOLUTIONS, Vol. 21(3) 499-517, 2011

Scientific Solutions – Transforming Science

THE SCIENCE OF GREEN CHEMISTRY AND ITS ROLE IN CHEMICALS POLICY AND EDUCATIONAL REFORM

AMY S. CANNON
JOHN C. WARNER

ABSTRACT

Over the past 10 years, the science of green chemistry has continued to evolve and has been adopted in research labs in industry and academia. At the same time, new innovations in chemicals policy have widened opportunities for legislative action to protect human health and the environment. This article addresses the mechanisms by which the science of green chemistry and chemicals policy can work together to help attain a more sustainable future. It also speaks to the pitfalls of inappropriately merging these two, and explores how such a merger could inhibit the creation of sustainable technologies. Green chemistry's role in educational reform is discussed as a means for training students who are prepared to create truly sustainable technologies.

Keywords: green chemistry, chemicals policy

The field of green chemistry is entering its third decade. While there were certainly efforts to achieve goals similar to those of green chemistry through the 1960s, 1970s, and 1980s, the field of green chemistry dates back to the early 1990s, when it was first conceived at the US Environmental Protection Agency

doi: 10.2190/NS.21.3.m
http://baywood.com

(US EPA) as an evolution of the agency's grants program "Alternative Synthetic Pathways for Pollution Prevention" [1]. In 1998 the 12 Principles of Green Chemistry were first published [2]. The articulation of these principles provided a direct link to the research laboratory, and provided a framework that would place the field of green chemistry in the hands of the materials scientists, chemists, and engineers as the *science* of sustainability.

Achieving a sustainable future is an aggressive goal that will require dozens of disciplines and hundreds if not thousands of new perspectives. The field of green chemistry is a small but important part of this greater overall effort. In order for all the various pieces of the sustainability puzzle to fit together and make progress, it is important to understand what green chemistry is, and what green chemistry is not. Based on this understanding, synergies between various related *and unrelated* efforts, including chemicals policy and educational reform, can be identified and mutual benefit optimized. This manuscript will present the science of green chemistry, describe how green chemistry fits into the theme of sustainability, and address how the science intersects with policy and can help to influence science education.

GREEN CHEMISTRY AS ACTIVE POLLUTION PREVENTION

Green chemistry is clearly defined in Anastas and Warner's book *Green Chemistry: Theory and Practice* [2]. This seminal book outlined the science of green chemistry, as well as the 12 principles of green chemistry. The principles are guidelines for practicing chemists, aimed at providing a framework for the bench chemist working towards greener chemistry. They detail how a researcher at the molecular level can improve the sustainability performance of a material or process. The 12 principles of green chemistry are referenced, cited, or listed in countless books and articles and on numerous websites. The principles are somewhat general, and a nontechnical audience can certainly appreciate the major points of each. But they are primarily geared to the bench scientist.

While the focus on the bench chemist may initially appear to be overly narrow, in fact it is urgently needed. As will be discussed later in this article, it is the bench scientist who has the greatest opportunity to improve the sustainability performance of any material or process. And yet the education of this bench scientist, at the undergraduate or graduate level, is essentially void of the training and skills necessary to identify or avoid the use or generation of hazardous materials. As will be discussed below, if we hope to make advances necessary to accomplishing a truly sustainable future we must provide skills where they are absent and needed. The 12 principles of green chemistry provide the missing information needed by the practicing bench scientist.

Tools have been developed to provide a direct measurement and graphical assessment across the 12 principles of green chemistry, such as the iSUSTAIN

Green Chemistry Index [3]. This tool is a web-based program designed to be used by bench scientists to assess the sustainability of their chemical processes using the 12 principles of green chemistry. This type of assessment is best used not as a marketing tool, but as a *research and development* tool. The iSUSTAIN Index for green chemistry is different from other "scorecard" evaluation tools in that it is not designed as a retrospective analysis, but rather is an evaluative tool for assessing process improvement at the research stage, from a molecular basis.

GREEN CHEMISTRY AND THE PRODUCT DEVELOPMENT PROCESS

The goal of green chemistry is to reduce or eliminate the use and/or generation of hazardous substances or processes [2]. It is important to keep in mind that the ultimate requirement of green chemistry is to physically reduce the quantities of chemicals that have a negative impact on human health and the environment. Science and technology are incremental processes that build over time on sequential and parallel advances in related fields. It is nearly impossible for "quantum leaps" of advancement to occur without the accumulation of countless supporting pieces of scientific understanding. Sometimes these foundational steps are recognized and celebrated, and sometimes they are not. In either case, the final technological achievement is often perceived as the "quantum leap" because the preceding steps and advances were of significance to a smaller technological audience and only the aggregate of achievements was of interest to a critical mass of individuals.

To accomplish green chemistry's ultimate goal of pollution prevention, a technology must not only be less toxic or have less environmental impact, but must also be successfully adopted. Thus, in order to truly be green chemistry, a technology must demonstrate appropriate performance and cost, so as to spur its success in the marketplace and increase the likelihood of adoption. Only if the three requirements are met will a new technology be successfully adopted and thus achieve the ultimate goal of pollution prevention (Figure 1).

To better understand how green chemistry fits into the bigger picture of product development, and to understand how it relates to chemicals policy, it is beneficial to reflect on the product development process. Understanding how scientists, engineers, and industrialists bring an invention at a research lab to a manufacturing floor in a factory, and into a shopping cart at a store or into our homes, and finally out in the trash and into a hole in the ground, can help us bring this subject into sharper perspective.

The first step in the process is that a molecule (chemical) is taken from somewhere in the earth—a mine, a plant, an animal, an oil deposit—and is converted to a material. This process is called "basic research" (Figure 2). The

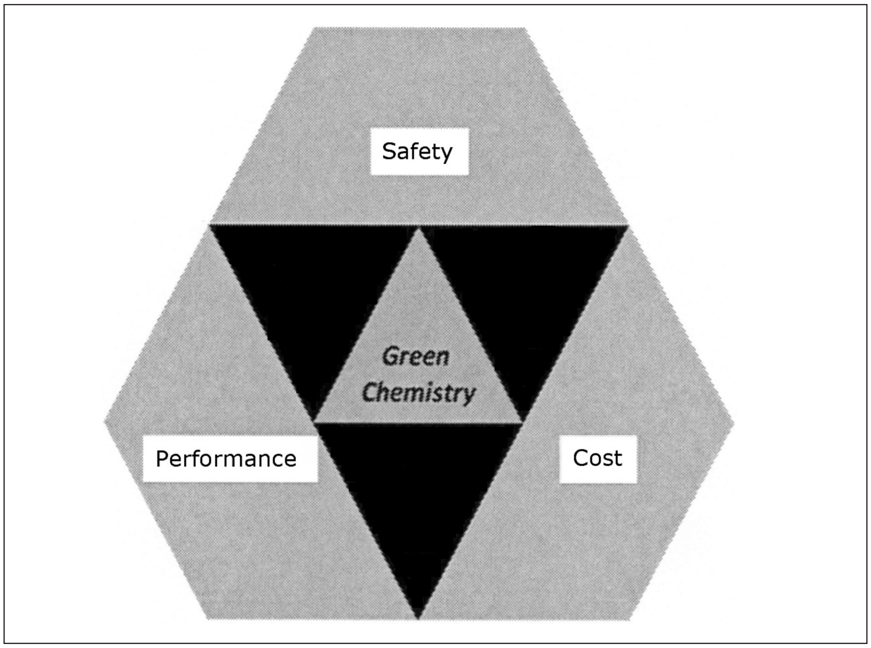

Figure 1. Three piers of green chemistry.

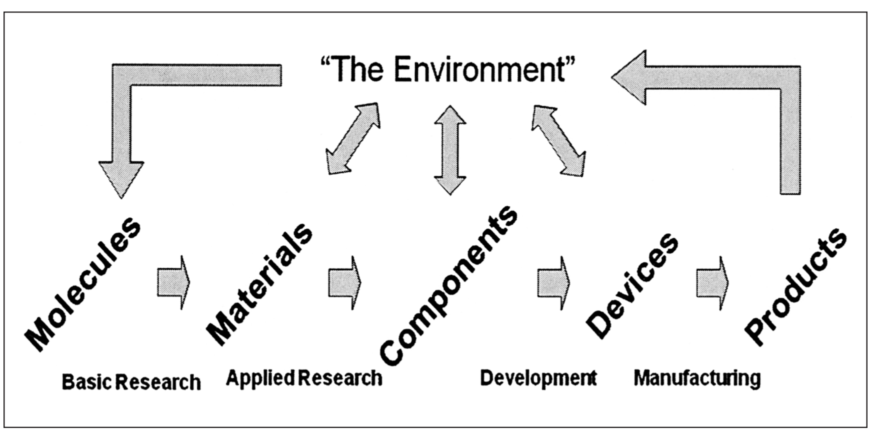

Figure 2. Product development schematic.

objective is to invent methods to make fundamental materials. The materials may or may not have any specific purpose; they reside at the frontier of research, as new and interesting "building blocks."

With these materials in hand, components are then developed. This is called "applied research" (Figure 2), and it is the heart of innovation. Components are materials that change when something happens to them. For example: when a material is heated it turns a different color; when a material is stretched, it changes the way it conducts electricity; when light is shined on a material, it changes the way it looks; when a material is smeared on a surface, it sticks. These components are not really useful for much of anything themselves, but they demonstrate a fundamental way in which the materials can be changed or manipulated in response to some input.

It is in applied research that most of the research happens within an industrial setting. And, it is within this realm where most of the environmental and human health impact decisions are made, whether consciously or not. For example, let us consider the design of an optical waveguide material for use in a touch-screen component, which will be used in a variety of devices, such as computers and cell phones. An optical waveguide is a material that guides light of a certain wavelength and functions similarly to a fiber optic material. The design criteria for developing a new waveguide material for use in a touch-screen computer (device) include many endpoints, such as solubility, mechanical properties, glass transition temperature, melting point, and refractive index. Each of these criteria ensures that a material is developed so that the performance is optimal in the end use of the device. For example, the glass transition temperature of the optical waveguide material is important in developing a touch-screen component that can withstand wide temperature ranges and that will not warp when in a hot room for long periods of time.

These types of criteria are very specific to ultimate product performance. However, throughout the history of product development, environmental and human health impacts have not typically been seen as attributes of product performance. Green chemistry is the science of pushing these into the criteria for molecular, materials, and product development. Adding toxicity and environmental impact to the list of criteria for the optical waveguide material ensures we are developing not only a high-functioning touch-screen component, but also one that has minimal impact on the environment and human health. And, just as we would go back to the research labs to redesign the component or device if it fails on one of the other criteria, we should do the same if it fails on the toxicity and environmental impact criteria.

The next stage of the product development process involves the creation of devices, in which a few, or several, components are put together. Cell phones, batteries, cars, paints, cosmetics, along with many more, are all assemblies of a few (or many) components. In the example of the touch-screen computer, the touch screen is just one component of many in the device. We call this step "development"—when several components are assembled together to make something that consumers could actually use.

When thousands or millions of the devices have to be made in order to supply the demand, technologies must be created to do this quickly and efficiently, and to work within the constraints of regulations. Producing many things over and over—that is, making products—is what happens in the "manufacturing" stage of product development (Figure 2).

For successful product development, the final product must meet three criteria. The product must have good performance. The product must have appropriate economics, which includes consideration of all of the product development steps. And the product must be socially responsible (i.e., safe for use and in the production process). The latter has not always been part of the equation, but today is becoming more and more a focus within industry. Performance, cost, and safety are the criteria for successful product development in industry, and these are the same as the criteria for green chemistry (Figure 1). Green chemistry is not an exogenous concept, but is just good business practice. It is completely consistent with the way industry does business already. Industry may not have the tools in place or an appropriately trained workforce, but green chemistry fits in with traditional successful business models.

The environment is of course, in the middle of the road from molecules to products (Figure 2). Molecules are extracted from the environment, whether from renewable or depleting resources. When the product has finished its useful life and is discarded, it is either recycled, or persists and accumulates in the environment, or degrades into harmful or innocuous byproducts. When a product is made, sold, and used, it has impacts on human health and the environment around it. The scientist who invents the material or process is in the best position to understand and avoid the use of hazardous materials. Unfortunately, as we will discuss later in this article, that scientist, who did the basic and applied research, is unlikely to have had any education or training in toxicology or environmental impacts.

With this understanding of how green chemistry relates to product development by incorporating environmental and human health criteria throughout the product development phases, we can now consider how the science of green chemistry relates to the bigger picture of sustainability.

GREEN CHEMISTRY AND SUSTAINABILITY

"Green chemistry" has oftentimes been used interchangeably with "sustainable chemistry," a term that might be more relevant and understandable within the bigger picture of sustainability. The OECD defines sustainable chemistry as the design, manufacture, and use of environmentally benign chemicals, which is consistent with the definition of green chemistry [4]. Many organizations use the terms green chemistry and sustainable chemistry in referring to the same intended end [5–7]. However, others use the term sustainable chemistry as a broader term applying to the use of chemistry within the realm of sustainability, applying it to other areas such as water use, conservation, recycling, public policy, among other sustainability-related concepts [8, 9]. This prompts a discussion on how green chemistry fits into the larger picture of sustainability and how it applies to areas such as sustainable technologies and sustainable development.

Sustainability is a nebulous concept that means something different for various groups of people. Sustainability cannot be a "one size fits all" concept. It must be a universal concept that everyone in society can participate in and contribute to. Derived from the document commonly known as the Brundtland Report, sustainability has been widely accepted as being defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [10]. One finds that the concept of sustainability applies across multiple disciplines, including economics, agriculture, education, business, chemistry, and many others.

Chemistry is applicable in many of these areas, including chemicals policy, remediation technology, exposure controls, water purification technologies, alternative energy technologies, sustainable production, green chemistry, and many other subjects. Green chemistry is but one of the many topics under the umbrella of sustainable technologies and sustainable products. However, it must be realized that green chemistry processes have not been typical within many of these "sustainable technologies." It is important to consider that one can create remediation technologies, water purification technologies [11–13], and alternative energy technologies that use high-energy processing, and use toxic and hazardous materials in the manufacture [14–19]. But these technologies are desperately needed, and these things are rightfully considered sustainable technologies. The *applications* of these technologies are sustainable, but the technologies themselves are not necessarily sustainable.

For example, solar energy devices on the market today consist mainly of silicon-based cells [14]. Silicon, while maintaining highly valuable semiconductor properties, has a melting point of 1414°C. The crystalline silicon is grown from molten, high-purity silicon in order to produce high-quality semiconductor material that is then doped with impurities to create a photovoltaic. The process uses immense amounts of energy, as well as reactive and toxic materials for purification [14], leading to high cost and the need for government subsidies for implementation [15]. Other advances in solar energy devices use hazardous elements and heavy metals such as cadmium [16], copper [17, 18], indium [14–18], gallium [19], and arsenic [19]. Each of these new devices is being developed because the end goal is to create a highly functional solar energy device capable of converting sunlight to energy in the most efficient manner possible, a noble goal indeed. The very act of converting the sun's light to electricity using these devices is a non-polluting, non-wasteful way of generating usable energy. There are no wasted inputs, no generated byproducts—and the feedstock of light from the sun is essentially never-ending. However, it must be noted that these alternative energy devices are grounded on unsustainable manufacturing principles, typically using hazardous and toxic materials, high energy, and generating much waste in the process.

The role of green chemistry is not to focus solely on the application, but to focus on the fundamental building blocks. If the basic building blocks of a technology are sustainable, then there is a good chance that the technology itself will be sustainable. Therefore, in the case of the solar energy devices, an ideal device would use less hazardous materials in the manufacture, as well as use low-energy processes in order to create devices that are truly sustainable from the building blocks through the end product. Newer solar energy devices based on dye-sensitized solar cell technology first developed in the early 1990s [20] have promise to achieve the goal of having a sustainable end product that also has a sustainable production process.

GREEN CHEMISTRY IS NOT A "BIRTH OF ETHICS"

It is incorrect to think that green chemistry somehow represents a birth of ethics in the field of chemistry. One must understand that it has been generally accepted that chemistry *must* be dangerous. Toxicity and hazard are just part of the business of doing chemistry. Chemists have traditionally relied on scientists and engineers who have developed technologies to allow the safe use of hazardous materials. When using dangerous materials, scientists wear gloves to protect their skin, wear masks to protect their lungs, wear goggles to protect their eyes, or use specialized equipment that limits their exposure to the chemicals, or to other environmental conditions (air, light, heat, etc.). Engineers have created remarkable technologies to mitigate and limit exposure of chemicals to the air, land, and aquatic environments, including scrubbers and filters, as well as other waste mitigation technologies. Accepting that chemistry *had* to be dangerous, the historical approach has been to protect human health and the environment by *limiting exposure.*

The problem with depending on technologies that mitigate exposure, of course, is that they can fail. Whenever one hears of some chemical disaster, an oil spill in the gulf, a tanker truck tipping over, an explosion at some factory, it is typically a result of some exposure control failing, or of human error. The National Response Center reports that an estimated 33,000 accidents involving oil or chemicals happened each year between 2000 and 2010. Of the 33,000 accidents, the most often reported cause is equipment failure, and human error is one of the top four causes [21]. Chemical systems are designed with the assumption that everything will happen the way it is supposed to happen. Of course, things do not always go as planned. Green chemistry asks scientists to design, not with the expectation that everything will go correctly in the future, but with the expectation that things could go wrong.

CHEMICALS POLICY AND GREEN CHEMISTRY

Green chemistry has an opportunity to transform the way that chemistry is performed and applied throughout the chemical and materials industries. The field has been held up as a model of a non-regulatory approach to pollution prevention [22]. However, chemicals policy has the opportunity to add stresses and externalities in order to define toxicological and environmental impact as product performance attributes. Market forces and regulatory pressures can influence the cost equation so as to render safer materials more valuable in the marketplace, or hazardous materials more costly. The external forces of the marketplace, chemicals policy, and regulations are inextricably linked to the field of green chemistry. But it is critical to understand that the *science* of green chemistry necessarily operates independently of these forces. Many scholarly studies have discussed the intersection of chemicals policy and green chemistry [23–26]. While we value these works, we recognize the need for further explanation on how these two important fields can work jointly, yet in separate ways, towards the same goals.

Green chemistry and chemicals policy go hand in hand. But they are not the same thing. Chemicals policy drives the demand for safer alternatives; the science of green chemistry provides the solutions. It is really an issue of semantics: if one combines the science of green chemistry with chemicals policy, the confusion that results can have negative impacts on everyone's goals. We *must* find ways to help industry develop a workforce capable of using the science of green chemistry. We need industry to be the loudest and largest supporter of changing academic institutions so that when they teach chemistry, they teach future generations about how to identify and prevent hazards. If the science of green chemistry is semantically combined with chemicals policy, we pull the rug out from under the feet of green chemistry and make it difficult for industry to support the direly needed changes in academic curricula. We will address a key point in the chemicals policy and green chemistry debate: that of chemicals policy driving demand for safer alternatives versus driving innovation.

DRIVING DEMAND FOR SAFER ALTERNATIVES

To understand how to approach green chemistry and chemicals policy, it is useful again to reflect on the product development process. We are completely surrounded by molecules (chemicals). Some are completely natural and would be there whether or not humans had ever evolved on the earth. And some of them are present solely because humans invented them, and started making them. All things being equal, there is no scientific difference between a molecule that is "natural" and an "industrial" molecule, other than the processes for obtaining the molecule (through extraction processes or synthetic procedures). It is not impossible to invent and manufacture molecules sustainably. We cannot do such things today very often, but there is no fundamental law that says it cannot be done. At the same time, just because a molecule is “natural” does not necessarily mean it is sustainable. For example, if one takes a certain species of plant, uses hazardous chemicals to promote its growth and suppress its predators, harvests it with large amounts of energy, and in the end uses a toxic solvent to extract a molecule of interest, it is clear that this is not a sustainable process. On the other hand, it might be possible to synthesize the same molecule in a chemical factory in a more sustainable way, using the 12 principles of green chemistry.

With this in mind, we can take a closer look at the products available to society: the ceiling tiles and flooring in a room, the clothes that we wear, the electronic gadgets that we work and play with, the cars we drive, the pens we write with, the soaps and cosmetics we use, the prescription drugs we take. It is reasonable to assume that most every product that we have available to us today has something “unsustainable” in its manufacture; the way it is synthesized might use a hazardous reagent, it could be derived from a non-renewable feedstock, or it might not degrade in the environment after its useful lifetime. If any one of the 12 principles of green chemistry is not being met, there is room for improvement.

To address this need for improvement, one can do an “alternatives assessment” to seek out replacement technologies. One can search to find companies offering safer alternatives. For moral, ethical, and economic reasons, this must be done, and it is highly valuable for organizations to perform alternatives assessments to ensure that they are using the best available technologies. Unfortunately, such an assessment will often come up empty because the safer technology *has not been invented yet*.

This absence of safer technologies changes the discussion. Protecting human health and the environment is not at odds with industry; rather, through green chemistry the two are aligned. There is a big difference between identifying alternatives and inventing solutions. Because of this reality, we must realize that alternatives assessment alone will not solve our problems of wasteful, hazardous processes and products. We require chemical regulation to help channel these alternatives to the marketplace. However, chemical regulation directing the use of safer, non-toxic alternatives will not succeed in solving the problems if new, innovative solutions are not being invented. The fact remains that most alternative technologies do not yet exist.

An example of this is the state of Washington’s ban on the use of brominated flame retardants. Polybrominated diphenyl ethers (PBDEs) have been widely used as flame retardants in a number of consumer products. The heavy use of these materials has resulted in their being found in high concentrations in the human body, breast milk, and other biological systems [27]. PBDEs are bio-accumulative and pose a potential threat to humans and the environment [27, 28]. The state of Washington proactively approached this issue and successfully passed a law[1] that phased out the use of PBDEs in a number of consumer products, with a focus on products used in the home [29]. However, the successful passing of a ban was not enough to effectively phase out the use of PBDEs. At the time the bill was passed, in April 2007, no alternatives had been identified for deca-BDE (one form of PBDEs) in upholstered furniture and in plastic used in televisions and computers; therefore, the legislature postponed the implementation of the ban on these uses until less toxic alternatives were available [30]. It was not until 2009 that safer alternatives were approved by the legislature, triggering the ban to take effect and phasing out the use of PBDEs in upholstered furniture and computers and televisions by January of 2011 [30]. Despite the successful reduction in the use of PBDEs in many consumer products in the state of Washington, the use of PBDEs continues in many products where suitable, effective alternatives do not yet exist. By focusing on green chemistry to help to invent safer, non-hazardous alternatives, we can ensure that the alternatives that are developed are indeed more benign than the traditional counterparts. As in the case of brominated flame retardants, it has been found that many times industry welcomes the ban of one form of PBDEs, and substitutes that banned form with another form of PBDE, therefore not actually removing PBDEs from the product, but instead changing the form (e.g., moving from deca-BDE to octa-BDE).

Another example of the need for viable alternatives in regulation is the case of asbestos; the regulation of asbestos has been debated for over 20 years, and a full ban has still not been implemented in the United States. In 1989 the EPA issued a ban and phase-out of asbestos, which was vacated and remanded by the US Fifth Circuit Court of Appeals in 1991. The Court determined that the EPA "failed to sustain its burden under TSCA section 6(a) of showing that the products banned by the rule present an unreasonable risk and that a less burdensome regulation would not adequately protect against that risk" [31]. The ban remained in effect only for new uses of asbestos and for products containing asbestos that were no longer being manufactured in the United States in 1989. There has been no further reversal on this decision, and any product that contained asbestos, and was being manufactured in the United States in 1989, can still legally contain asbestos, provided there is disclosure of the use.

These examples certainly are filled with controversy and there are many different views on the validity of statements on each side. And, the debate over the ban of asbestos still continues today [32, 33]. However, essentially we feel that if a viable alternative had been invented for asbestos then the discussion would end and the use of these materials would drop significantly. The Court of Appeals' decision clearly recognized the health impacts and the risks of asbestos

[1] The law bans the manufacture, sale, and distribution of three types of PBDEs in the following products only: televisions, computers, and residential upholstered furniture.

[31]. What was disputed was the "application of the least burdensome means of adequately protecting against the unreasonable risk" [34]. In this case, as in many other cases, if an efficacious, cost-effective, safe alternative material existed that could replace asbestos in each product where it is found, then this would lower the burden associated with banning a problematic substance and would allow for easier implementation of the safer alternative.

The revolution that is green chemistry proposes that instead of turning to lawyers and lobbyists to debate regulations and bans, we can instead turn to chemists and scientists to invent safer alternatives. Packaging traditional chemicals policies and calling them "green chemistry regulations" must be avoided. For example, a ban for phasing out asbestos or PBDEs should be called exactly that: a ban. Describing a ban and phase-out as a "regulation implementing green chemistry" is incorrect. For example, in California there has been a push for increased regulation of hazardous chemicals with the goal of safer products for consumers. This is a noble goal and certainly important. Many people have worked tirelessly to create regulatory language around a new initiative being called the "Green Chemistry Proposed Regulation for Safer Consumer Products" [35]. However, a close look at the proposed regulation and conceptual flowchart shows that the regulation would provide a structure for identifying chemicals of concern, understanding their hazards, and following up with an alternatives assessment, which would then provide a framework for a regulatory response. This is a wonderful and much-needed regulatory approach that will help to ensure the safest alternatives are available to consumers. Yet, it is not green chemistry. As stated previously, green chemistry is the *science* of inventing alternatives that reduce or eliminate the use or generation of hazardous substances. Therefore, it would be suitable to propose an alternative name to the California "green chemistry" regulation.

This is not to say that chemicals policy is not necessary and important; it is extremely important and very necessary. It is certainly a mistake to come to the conclusion that green chemistry is somehow an alternative to chemicals regulation. This is not the case. Society unequivocally needs stronger chemicals policies and regulations to protect human health and the environment. This fact allows no doubt or compromise. The point is that it will be much more difficult—or even impossible—for chemicals policy to be successful without having safer alternatives available first.

We find that when viable alternative technologies are available, chemicals policy is very effective in driving the adoption of these alternative technologies—for example, in the case of the catalytic converter. The 1988 California Clean Air Act is often cited as an example where chemicals policy "forced" industry to invent a technology. People point to this example with great (and justifiable) pride as the mechanism to bring about safer products. And in fact the chemicals policy was absolutely critical for the adoption of the catalytic converter by the auto industry. This mandated adoption of the technology enabled the reduction of air pollution by staggering amounts [36]. This is an excellent example of how things can work. The mistake people make is in the timeline. The regulation did not cause the invention of the catalytic converter; it caused the adoption of the catalytic converter by the auto industry. The patent for the catalytic converter was filed in 1950 and issued in 1954 [37]. Invention and adoption are not the same. The technology to enable the catalytic converter had already been invented before the policy was enacted. The chemicals policy accelerated its use throughout the industry, along with implementing other methods for reducing smog and air pollution [36]. However, the policy did not accelerate its invention, but only mandated its adoption. When chemicals policy precedes invention of an alternative technology, it could in fact delay the invention, and certainly delay the passage of the regulation, as in the previously stated examples of asbestos and PBDEs. This is the reality of most cases that claim that policy drives innovation: when taking a closer look at the alternative technologies and the innovative timeline, we find that policy actually drives the *adoption of alternative technologies* and not the invention itself.

Chemicals policies and green chemistry research together can help to ensure the creation and adoption of green chemistry alternative technologies, but also they can help in identifying areas where no safer alternative exist. These policies also have the potential to influence much-needed educational reform, as will be discussed further.

EDUCATIONAL REFORM

In this article we have delved into the science of green chemistry and how it relates to chemicals policy. A key piece of successful implementation of green chemistry within industry and in our society is education. Sustainability as a theme is being introduced throughout educational systems. However, as was mentioned previously, our current educational systems lack training in fundamental environmental and toxicological concepts for chemists and scientists.

Thanks to the herculean works of people like Tony Cortese from Second Nature, and others, there has been a growing awareness of the need to introduce the concepts of sustainability on college campuses. Cortese's American College and University Presidents' Climate Commitment is a testament to catalyzing change [38]. At last count more than 670 college presidents had signed on to a pledge to review the infrastructure of their institutions, and commit to a path toward carbon neutrality. After years and years of hard work, Cortese's vision is becoming a reality.

When one visits most college campuses, one really gets a sense that they take sustainability very seriously. People working in the administration and facilities review utilities and services to minimize impacts. Recycling and waste reduction efforts are visible everywhere. It is spectacular to see this change happening. Some of the academic departments are even getting involved, with more and more courses being offered in the realm of sustainability [39]. And as a result, more students today are taking these courses.

But in a way, the fact that many students are taking introductory courses in sustainability is a double-edged sword. While faculty from the humanities, social sciences, political sciences, business, environmental health, and perhaps biology and physics participate in the teaching of these courses, the chemistry faculty are, for the most part, absent. And the absence of these faculty members has serious implications. We need chemists at the table discussing these issues. It is one thing to identify the problems and consider social and political solutions. But at the end of the day, we need new materials and technologies to be *invented* to replace the existing technologies. If the conversation occurs without the inventors of the next generation of materials at the table, then we are missing the biggest part of the solution.

University dynamics are tricky. The work and effort of faculty, including eligibility for tenure, are typically calculated and rewarded within one department, making interdisciplinary efforts challenging. There is plenty of literature and discussion about this issue [40, 41] that does not need to be repeated here, but we do need to identify better mechanisms to break down the compartmentalization of education.

The focus on bringing sustainability into courses must include the practitioners of chemistry. In the academic year 2008–2009, U.S. colleges and universities that offer a chemistry degree approved by the American Chemical Society (ACS) granted 14,577 bachelor's degrees in chemistry, 1,986 master's degrees, and 2,543 doctoral degrees. Thus more than 19,000 students were trained in chemistry in the United States in just one year. More than 600 colleges and universities offer ACS-approved degree programs in chemistry [42]. Only one of these programs requires classes in toxicology or environmental impacts: the University of Massachusetts Boston's Ph.D. program [43, 44], from which two Ph.D. students graduated in the academic year of 2008–2009 [42]. Learning about how to identify and avoid using or making toxic materials is essentially absent from the education of chemists.

If a student is intending to have a career in environmental sciences or toxicology, he or she may have some coursework related to the mechanisms of toxicity. However, if a student wants to be an industrial chemist and get a job working at a company inventing new products, it is highly unlikely that he or she will *ever* have had a course about how to identify or avoid using hazardous materials.

There is a great need for an organized effort to bring green chemistry and sustainability into the education of a chemist. The ACS accredits chemistry programs for over 600 colleges and universities that offer chemistry degrees through the Committee on Professional Training (CPT). This accreditation is based on ACS guidelines developed by the Committee, which include the following requirements: curriculum coursework, undergraduate research, and student skills development. The curriculum coursework includes introductory chemistry, analytical chemistry, biochemistry, inorganic chemistry, organic chemistry, and physical chemistry, along with in-depth coursework in these main areas and laboratory experience. The ACS CPT mentions green chemistry as an option for a degree track or concentration, recommending it as one option of several for an area of focused study [45]. However, the very nature of green chemistry is not to be a sidebar in a textbook, or a mere recommended course for a focus of study, but to be integrated into existing coursework and change the very nature of how we teach and study chemistry. By integrating green chemistry into each chemistry course and placing it at the center of a chemistry student's study, we can begin to change how students are trained, making them better prepared to enter the workforce with skills that will enable them to truly make more benign chemical products.

The good news is that chemistry education is changing, though it comes from a grassroots level. A growing network of green chemistry educators are sharing experiences and best practices through the Green Chemistry Education Network (GCEdNet) [46], an initiative led by Dr. Julie Haack from the University of Oregon, who is a leader in current thinking about green chemistry education. Through this network, informal regional networks have been formed based on a foundation of educators already implementing green chemistry in their courses and laboratories. Much of this work has been led by four-year academic institutions with forward-thinking faculty, such as Professor Irv Levy at Gordon College (Wenham, MA) and Dr. Rich Gurney at Simmons College (Boston, MA). Professor Levy has been teaching his organic chemistry course with green chemistry infused throughout the course for the past several years. He even integrates a student project, which he named GOLum for Green Organic Literacy Forum, where students take on a year-long project in the area of green chemistry. At Simmons College, Dr. Gurney teaches green chemistry throughout his organic chemistry course. He is also leading the effort to create a mechanistic toxicology course, which will be required of undergraduate chemistry majors at Simmons. To our knowledge, Simmons is the first college to require this of undergraduate students.

CONCLUSION

Green chemistry continues to grow and is being implemented in many laboratories around the globe. People often look for "success stories" and want to document examples of the use and implementation of green chemistry. The EPA's Presidential Green Chemistry Challenge Award has been in existence for 15 years, and more than 75 awards have been given out [47]. These case studies document some of the visible and public advances being made. But it is important to recognize that this is just the tip of the iceberg. There are significantly more success stories that are *not* being told, and for marketing reasons an organization may choose to not broadcast its sustainability innovations (because in so doing it also broadcasts what it did before implementing greener, safer alternatives). In the end, for sustainability and green chemistry to be successfully integrated into all aspects of research, development, and manufacturing, the words themselves must vanish. Growing and nurturing a field is important in the early days. Green chemistry must mature to a point where its integration becomes seamless and unsurprising. There is still much to do with respect to academic adoption and curriculum development. The business case for green chemistry has been made. As time passes, markets change and technologies evolve. Some businesses and organizations adapt to change and thus thrive and grow, but others are incapable of such change and will require more support to transition to safer technologies and more sustainable science. The science of green chemistry is similar to many earlier innovations in technology and business: external incentives can help stimulate dissemination and education, but in the end it is up to the business or organization to embrace the change.

But there is still much to do. New materials and processes must be invented. To find solutions, we need new eyes and ideas focused on the problems. The collaboration between green chemistry and chemicals policy leaders can be powerful and effective if done through well thought out planning and strategy. And, by strengthening and reforming our educational systems to reflect the true needs of industry and our global society, we can ensure that the next generation of scientists in the workplace will be much better equipped to create materials and products that are truly sustainable.

NOTES

1. U.S. Environmental Protection Agency, "Green Chemistry Program at EPA," http://www.epa.gov/gcc/pubs/epa_gc.html (accessed February 20, 2011).
2. Paul T. Anastas and John C. Warner, *Green Chemistry: Theory and Practice* (New York: Oxford University Press, 1998).
3. iSUSTAIN™ Green Chemistry Index, "Welcome to the iSUSTAIN™ Green Chemistry Index v2.0," www.isustain.com (accessed February 20, 2011).
4. Environmental Directorate, Organisation for Economic Co-Operation and Development (OECD), *Sustainable Chemistry*, 2004, http://www.oecd.org/dataoecd/16/25/29361016.pdf (accessed June 17, 2011).
5. U.S. Environmental Protection Agency, "Green Chemistry," http://www.epa.gov/gcc/ (accessed June 8, 2011).
6. Green and Sustainable Chemistry Network, http://www.gscn.net/indexE.html (accessed June 8, 2011).
7. R. Sheldon, "Green and Sustainable Chemistry: Challenges and Perspectives," *Green Chemistry* 10(4) (2008): 359-360. DOI: 10.1039/B804163F
8. Dow Chemical, Inc., "Sustainable Chemistry," http://www.dow.com/sustainability/goals/chemistry.htm (accessed June 8, 2011).

9. European Association for Chemical and Molecular Sciences, *1st Meeting of the Working Party on Green and Sustainable Chemistry*, February 28, 2008, http://www.euchems.org/binaries/1stWPGreenandSus28Feb08_tcm23-127739.pdf (accessed June 17, 2011).
10. United Nations, *Report of the World Commission on Environment and Development: Our Common Future,* 1987, http://www.un-documents.net/wced-ocf.htm (accessed February 20, 2011).
11. K. P. Lee, T. C. Arnot, and D. Mattia "A Review of Reverse Osmosis Membrane Materials for Desalination—Development to Date and Future Potential," *Journal of Membrane Science* 370(1-2) (2011): 1–22. doi:10.1016/j.memsci.2010.12.036
12. O. B. Akpor and M. Muchie, "Remediation of Heavy Metals in Drinking Water and Wastewater Treatment Systems: Processes and Applications," *International Journal of Physical Sciences* 5(12) (2011): 1807–1817.
13. E. N. Peleka and K. A. Matis, "Water Separation Processes and Sustainability," *Industrial & Engineering Chemistry Research* 50(2) (2001): 421–430. doi:10.1021/ie100079s
14. M. Gratzel, "Photovoltaic and Photoelectrochemical Conversion of Solar Energy," *Philosophical Transactions of the Royal Society* 365(1853) (2007): 993–1005. doi:10.1098/rsta.2006.1963
15. M. A. Green, "Recent Developments in Photovoltaics," *Solar Energy* 76(1–3) (2004): 3–8. doi:10.1016/S0038-092X(03)00065-3
16. M. Raugei and V. Fthenakis, "Cadmiun Flows and Emissions from CdTe PV: Future Expectations," *Energy Policy* 38(9) (2010): 5223–5228. doi:10.1016/j.enpol.2010.05.007
17. M. Page et. al, "Copper Sulfide as a Light Absorber in Wet-Chemical Synthesized Extremely Thin Absorber (ETA) Solar Cells," *Energy and Environmental Science* 2 (2009): 220–223. doi:10.1039/B813740D
18. J. S. You et. al, "Copper Metallization for Crystalline Si Solar Cells," *Solar Energy Materials and Solar Cells* 79(3) (2003): 339–345. doi:10.1016/S0927-0248(02)00470-1
19. K. Tanabe, "A Review of Ultrahigh Efficiency III-V Semiconductor Compound Solar Cells: Multijunction Tandem, Lower Dimensional, Photonic Up/Down Conversion and Plasmonic Nanometallic Structures," *Energies* 2(3) (2009): 504–530. doi:10.3390/en20300504
20. M. Gratzel, "Photoelectrochemical Cells," *Nature* 414 (2001): 338–334. doi:10.1038/35104607
21. National Response Center, "Statistics/Incident Causes," http://www.nrc.uscg.mil/incident_causes_2000up.html (accessed February 22, 2011).
22. J. B. Manley, P.T. Anastas, and B. W. Cue, Jr., "Frontiers in Green Chemistry: Meeting the Grand Challenges for Sustainability in R&D and Manufacturing," *Journal of Cleaner Production* 16(6) (2008): 743–750. doi:10.1016/j.jclepro.2007.02.025
23. K. J. M. Matus, J. B Zimmerman, and E. Beach, "A Proactive Approach to Toxic Chemicals: Moving Green Chemistry Beyond Alternatives in the 'Safe Chemicals Act of 2010,'" *Environmental Science & Technology* 44(16) (2010): 6022–6023. doi:10.1021/es102149j
24. M. Poliakoff et al., "Green Chemistry: Science and Politics of Change," *Science* 297(5582) (2002): 807–810. doi:10.1126/science.297.5582.807

25. M. P. Wilson and M. R. Schwarzman, "Health Policy: Toward a New U.S. Chemicals Policy: Rebuilding the Foundation to Advance New Science, Green Chemistry, and Environmental Health," *Environmental Health Perspectives* 117(8) (2009): 1202–1209. doi:10.1289/ehp.0800404
26. J. Sjostrom, "Green Chemistry in Perspective—Models for GC Activities and GC Policy and Knowledge Areas," *Green Chemistry* 8(2) (2006): 130–137. doi: 10.1039/B511316D
27. A. P. Vonderheide et al., "Polybromited Diphenyl Ethers: Causes for Concern and Knowledge Gaps Regarding Environmental Distribution, Fate and Toxicity," *Science of the Total Environment* 400(1-3) (2008): 425–436. doi:10.1016/j.scitotenv.2008.05.003
28. C. E. Talsness, "Overview of Toxicological Aspects of Polybrominated Diphenyl Ethers: A Flame-Retardant Additive in Several Consumer Products," *Environmental Research* 108(2) (2008): 158–167. doi:10.1016/j.envres.2008.08.008
29. Washington State Legislature, Polybrominated Diphenyl Ethers, Wash. Rev. Code Ann. §§ 70.76.005-70.76.110 (2008), http://apps.leg.wa.gov/documents/billdocs/2007-08/Pdf/Bills/Session%20Law%202007/1024-S.SL.pdf (accessed June 17, 2011).
30. Washington State Department of Ecology, "Washington's Toxic Flame Retardant Ban to Take Effect," January 21, 2009, http://www.ecy.wa.gov/news/2009news/2009-017.html (accessed June 17, 2011).
31. U.S. Government Printing Office, *Asbestos; Manufacture, Importation, Processing, and Distribution Prohibitions; Effect of Court Decision; Proposed Rule*, 52 Fed. Reg. 11364, April 2, 1992.
32. Committee to Ban Asbestos in America, "BanAsbestos.us," http://www.banasbestos.us (accessed February 22, 2011).
33. U.S. Environmental Protection Agency, "Asbestos Ban and Phase Out," http://www.epa.gov/asbestos/pubs/ban.html (accessed February 22, 2011).
34. U.S. Environmental Protection Agency, "TSCA Section 6 Actions," http://www.epa.gov/opptintr/existingchemicals/pubs/sect6.html (accessed February 22, 2011).
35. California Department of Toxic Substances Control, "Proposed Regulation for Safer Consumer Products," http://www.dtsc.ca.gov/PollutionPrevention/GreenChemistryInitiative/Proposed-Regulation.cfm (accessed February 22, 2011).
36. W. D. Van Vorst and R. S. George, "Impact of the California Clean Air Act," *Int. J. Hydrogen Energy* 22(1) (1997): 31-38. do:10.1016/S0360-3199(96)00081-X
37. E. J. Houdry, "Catalytic Converter for Exhaust Gases," United States Patent 2,674,521, April 6, 1954, http://www.freepatentsonline.com/2674521.pdf (accessed June 17, 2011).
38. American College and University Presidents' Climate Commitment, "Home," http://www.presidentsclimatecommitment.org (accessed February 22, 2011).
39. Association for the Advancement of Sustainability in Higher Education (AASHE), "Courses on Campus Sustainability," http://www.aashe.org/resources/courses-campus-sustainability (accessed February 24, 2011).
40. W. G. Wraga, "Interdisciplinary Education in K-12 and College: A Foundation for K-16 Dialogue," *NASSP Bulletin* 86(633) (2002): 68–70. doi:10.1177/019263650208663307
41. Barbara Leigh Smith, John McCann, and Alexander W. Astin, eds, *Reinventing Ourselves: Interdisciplinary Education, Collaborative Learning, and Experimentation in Higher Education* (Bolton: Anker Publishing Company, Inc., 2001).

42. David J. Hanson, “Gains Continue for Chemistry Grads,” *Chemical and Engineering News*, August 23, 2010, http://pubs.acs.org/cen/email/html/8834acsnewsl.html (accessed June 17, 2011).
43. University of Massachusetts Boston Center for Green Chemistry, “Ph.D. program in Green Chemistry,” http://www.greenchemistry.umb.edu/phd.html (accessed February 2011).
44. Maureen Rouhi, “Green Chemistry Earns a Ph.D.,” *Chemical and Engineering News*, April 22, 2002, http://pubs.acs.org/cen/education/8016/8016educational.html (accessed June 17, 2011).
45. American Chemical Society, Committee on Professional Training, *Undergraduate Professional Education in Chemistry: ACS Guidelines and Evaluation Procedures for Bachelor’s Degree Programs*, Spring 2008, http://portal.acs.org/portal/fileFetch/C/WPCP_008491/pdf/WPCP_008491.pdf (accessed June 17, 2011).
46. University of Oregon, “Green Chemistry Education Network (GCEdNet),” http://cmetim.ning.com/ (accessed February 24, 2011).
47. U.S. Environmental Protection Agency, “Presidential Green Chemistry Challenge Awards,” http://www.epa.gov/gcc/pubs/pgcc/presgcc.html (accessed February 24, 2011).

Direct reprint requests to:

Amy S. Cannon
Beyond Benign
100 Research Drive
Wilmington, MA 01887
e-mail: Amy_Cannon@beyondbenign.org