10-18-2016

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Recommended Citation

Green, S. A. (2016). Green Chemistry: Progress and Barriers. *Physical Sciences Reviews, 1*(10).
http://doi.org/10.1515/psr-2016-0072
Retrieved from: https://digitalcommons.mtu.edu/michigantech-p/14766

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DE GRUYTER Physical Sciences Reviews. 2016; 20160072

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Green Chemistry: Progress and Barriers

Abstract:
Green chemistry can advance both the health of the environment and the primary objectives of the chemical enterprise: to understand the behavior of chemical substances and to use that knowledge to make useful substances. We expect chemical research and manufacturing to be done in a manner that preserves the health and safety of workers; green chemistry extends that expectation to encompass the health and safety of the planet. While green chemistry may currently be treated as an independent branch of research, it should, like safety, eventually become integral to all chemistry activities. While enormous progress has been made in shifting from "brown" to green chemistry, much more effort is needed to effect a sustainable economy. Implementation of new, greener paradigms in chemistry is slow because of lack of knowledge, ends-justify-the-means thinking, systems inertia, and lack of financial or policy incentives.

Keywords: environment, green chemistry, policy, safety, sustainability

DOI: 10.1515/psr-2016-0072

When I first encountered the term green chemistry as a graduate student, I naively decided that it was too late for me to commit my career to the topic because the concept was so obvious that by the time I graduated it would be thoroughly embedded into the enterprise of chemistry. Sadly, the world moves at its own pace and the common sense of green chemistry that seemed so obvious to me in the 1990s has taken decades to penetrate into the daily life of chemists. At least now the idea of green chemistry is broadly recognized, although still very far from universally implemented. Reaching this level of penetration has required hard work by many people and organizations. Looking back from a few decades of experience, I can better identify some of the reasons that change is slow, as well as see the successes since the term green chemistry was introduced.

To understand the trajectory of green chemistry we can consider how it fits into the traditional practice of chemistry, how it aligns with our ideas of the progress of chemistry, and what factors impede its more rapid implementation.

Green chemistry, as defined by the 12 principles [1], has incorporated techniques from many branches of chemistry, as well as from other areas of science and engineering, and has spawned entirely new lines of inquiry. There can be no doubt that the increasing obligation to consider environmental impacts in all human endeavors, including chemistry, has spurred advances in catalysis, toxicology, processes chemistry, safety procedures, separations, biotechnology, novel feedstocks, analytical methods, synthesis, and many others.

A recurring question in the research domain is whether green chemistry constitutes its own branch of chemistry like the traditional divisions of organic, inorganic, analytical, and physical chemistry, or is a guideline defining how *all* chemistry should be performed, akin to safety and ethical standards. I suggest that currently it is the former, but ultimately it needs to become the latter. At its current stage of development, both technical and cultural advances are required before green chemistry can become thoroughly embedded into all chemistry endeavors, as it ultimately should be.

Currently, green chemistry is not yet mature enough to be automatically integrated as a baseline expectation into every activity. Research focused specifically on the topic remains essential because the chemistry community is still inexperienced in the holistic thinking that is required to assess processes according to green chemistry principles. Additionally, many tools and techniques that will increase the "greenness" of existing processes are yet to be developed. More excitingly, entirely new inventions and creative strategies are emerging that will supersede current practices to make this transition a reality.

Eventually, green chemistry should evolve from an independent branch of science into a guideline, like safety, that is incorporated into everything a chemist does. While we still need experts in chemical safety we expect that all chemists know and implement safe practices in all their work. The parallels between laboratory safety and green chemistry are clear. Consider, for example, the basic safety goal of preventing chemical explosions in research laboratories. Fundamentally, achieving that goal requires a thorough understanding of the underlying chemistry of explosions (thermodynamics, gas evolution, ignition, vapor pressures, etc.), the ability to anticipate the formation of explosive mixtures, and the technical means to handle and manage potentially explosive substances. A more advanced effort assesses whether the explosive substance is really essential to the final goal and redesign products or processes to eliminate the hazard altogether. Equally important for safety

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are changes in laboratory culture that enable practitioners to recognize that explosions are not an inevitable result of chemical procedures, learn to anticipate dangerous situations, and move to engrain safety consciousness into every stage of their activities. A similar progression can be seen in greening a chemical process. The preliminary step is to understand the underlying chemistry of the environmental risks of substances employed (fate and transport in the environment, degradation pathways and rates, toxicology, greenhouse gas potentials, etc.). Then one considers how to manage, minimize, and mitigate those environmental risks. Finally, processes and products may be entirely redesigned to achieve the desired goals while eliminating hazards.

Surprisingly, the parallels between safety and green chemistry are rarely articulated. Green chemistry is really the next step in safe practices, extending the net of safety beyond immediate laboratory occupants to encompass global populations and ecosystems. Yet often teams in a chemical enterprise focused on safety have little interaction with those concerned with green or sustainable chemistry, and they typically don't recognize their overlapping goals.

1 Brown versus Green Chemistry: Aligning the Goals of Traditional and Green Chemistry

To develop a sustainable chemistry framework, it's helpful to consider what chemists do and how they define progress. To achieve a sustainable chemistry enterprise we need to recognize that advances in green chemistry simultaneously advance chemistry as a whole.

Chemistry can be broadly divided into two primary activities: understanding things and making things, both contingent on a third, measuring things. All have their roots in the "brown" chemistry of the industrial revolution [2]. Yet a sustainable future requires that all three of these endeavors transform from brown to green. This stance is not anti-chemistry; instead it is a challenge to do new and better chemistry. In fact, greening is synergistic with the fundamental pursuits of chemists: understanding, making, and measuring. More sustainable chemistry requires a deeper chemical understanding, better ways of making, and improved measurements. The fundamental philosophy of chemistry is solving problems with molecular tools; green chemistry insists that a molecular approach to problem solving does not entitle us to be blind to the global impacts of the solutions.

As a primary goal chemists aim to understand the molecular basis of the world, including biotic and abiotic phenomena in nature, human-made materials, and the interactions among them. Our drive for understanding extends from molecular to macroscopic scales and asks how the first defines the second. Chemists want to know how atoms are transferred between molecules and into materials, and how energy is transferred through molecular and atomic processes. We want to understand how pharmaceutical molecules interact with human biology, how soil microbes manipulate nitrogen compounds, how paint reacts to photons, how ions travel through membranes, how electrons align with fields, and how individual atoms contribute to nanoscale properties, and infinite other fundamental questions. The search for chemical understanding isn't inherently brown chemistry, although many of the questions chemists have sought to answer in the past 100 years were driven by the technologies of the time: they knew how to apply heat and pressure to macroscopic systems and measure the results.

The general public is perhaps most familiar with the second aim of chemists: making things. We want to find new ways to make substances that nature has invented and make new substances that are unknown to nature. Both are about reorganizing atoms and molecules in a deliberate fashion. Traditional chemistry relied on a few brute force methods described in first year chemistry textbooks: heat to break bonds, pressure and heat to shift equilibria, and manipulating concentrations and solvents to modify reaction rates. Only with the (usually brief) introduction to catalysts do first year students glimpse the fact that the classical two-dimensional reaction coordinate diagram is not etched in stone and that clever chemists can circumvent the activation energy mountain. Until very recently, chemists have relied largely on brown chemistry to make nearly every one of the over 100,000 chemical substances in use today [3].

We enhance our abilities to both understand and make substances through the development of new analytical tools and techniques that allow us to map the molecular and atomic world at ever-finer detail and to make, purify, and identify substances never seen before. Analytical chemistry has not traditionally focused on green processes. Indeed many of the U.S. Environmental Protection Agency (EPA) methods for measuring pollutants use large volumes of toxic organic solvents, and often include organic or metal reagents that may also be environmentally unfriendly [4]. Of course, the three main chemistry goals of measuring, understanding, and making are not independent. Rather they are iterative. When we understand we can better make and vice versa. Green chemistry has the potential to advance all of these activities by framing them within the global context of improving human and planetary health. By analyzing each effort at multiple scales, green chemistry aims to avoid implementing a solution to a narrow problem that in fact creates more or bigger problems elsewhere.

As a starting point, we can examine the intersection between progress in chemistry as traditionally viewed and the goals of green chemistry. In our search for chemical understanding, progress can be defined as an enhanced ability to predict, design, control, and anticipate chemical behavior. This fundamental understanding is an essential component to the practice and theory of green chemistry. Indeed many chemists who might initially deny that they practice green chemistry actually contribute substantially to the field. For example, computational chemistry is perhaps the ultimate waste prevention strategy. Our increasing ability to understand and predict chemical behavior in silico reduces waste of both materials and time because uncountable unproductive experiments are avoided while chemists focus on the most promising pathways to successful synthesis. Similarly, nearly every chemist who studies catalysis contributes to the field of green chemistry because the goals of developing catalytic materials with enhanced selectivity and durability, improved efficiency, mild reaction conditions, and reduced toxicity fit the very definition of green chemistry [5, 6]. Understanding toxicity at the molecular level is essential for both green chemistry and to advance the ancient goal of employing chemistry to better human health and well-being. Both green chemistry and health-related chemistry demand an understanding of how exogenous molecules interact with human biology. Thus, there is strong synergy between green chemistry and the long recognized aspiration of chemists to understand how the world works. An effort to make that link explicit will both expand our chemical understanding and advance environmental health.

While some chemists are doing green chemistry without realizing it, others may think they are doing green chemistry without the necessary global perspective. For example, chemists who are specifically pursuing chemistry for sustainability may assume they are engaged in green chemistry. However, green chemistry requires more than a green goal such as better batteries, fuel efficiency, or material recycling. It requires that the means to the end be conducted with minimal environmental impact and that the entire lifecycle of the substances be considered. A notorious example is the widespread addition of methyl *tert*-butyl ether to gasoline to reduce tailpipe emissions without considering its potential to contaminate groundwater. To avoid this type of "solution" it is essential to comprehensively consider impacts at all scales from the laboratory to the planet.

Understanding chemistry on a planetary scale is essential to avoid dangerous global experiments such as the infusion of ozone-destroying chlorofluorocarbons into the stratosphere. We now have the ability to anticipate ozone destruction or global warming impacts of gaseous compounds released to the atmosphere and promote policies to limit their releases before planet-wide effects are felt. Assessment of ozone-depleting substances is ongoing by the Montreal Protocol, which now evaluates global warming potentials of halogenated compounds [7]. Although enormous advances are being made, a similar depth of understanding and predictive ability is lacking for less volatile synthetic compounds that are widely dispersed in water and soil, much more complex environments. An enormous challenge is tracking and assessing the impacts of molecules that move among air, water, and solid phases, are taken up by biota, and undergo transformations to new substances along these pathways. Anthropogenic molecules are now intermingling with the vast reservoir of natural materials on the Earth with unknown consequences for the biosphere. Much progress in understanding fundamental chemistry has been driven by our need to understand chemical processes in the environment. An ongoing dialogue between laboratory chemists and those engaged in understanding Earth's chemistry is required to truly fulfill the mandate of green chemistry.

In the more concrete chemical enterprise of making things, the first measure of progress is typically defined as increasing efficiency, measured in material, energy, time, and cost. In that realm progress is fundamentally aligned with green chemistry, and indeed many successes have been driven by efforts to reduce waste disposal costs or replace inefficient processes. Great advances are also being made in the conversion of biomaterials into traditional and novel chemical feedstocks. These topics are well represented in the pages of the journal *Green Chemistry* and by winners of the Presidential Green Chemistry Awards.

A second measure of progress in this realm is innovation: making completely new things or designing radically new ways of making known substances. New techniques in nanotechnology and DNA editing provide ever-more sophisticated methods for control at the molecular scale. We have only begun to explore the incredible variety of pathways and shortcuts generated as evolution drives organisms to operate with optimal energy and material efficiency, even as they make novel materials with unique functionalities. Chemists are only beginning to harness those methods. We can now manipulate individual atoms and molecules, and harness the exquisite precision of biological machinery to make materials of our own design. It remains to be seen if these powerful tools will be deployed with a green chemistry ethos.

Finally, measuring progress requires defining the metrics of success. Many people have recognized the challenge of identifying clear measures that allow easy comparisons and a comprehensive evaluation of sustainable practices in chemistry. The concept of percent yield was published as early as 1867 [8] and hasn't changed much since. In contrast to that simple measure of reaction efficiency, one single calculation cannot capture the many impacts defined in the 12 principles of green chemistry. Metrics are therefore still evolving, and several have been proposed. Dicks and Hent [9] recently summarized several common metrics. Of those, the E factor comes closest to a direct comparison with percent yield [10]. Jiménez-González et al. [11] compiled a selection of green metrics for the pharmaceutical industry, and many of which apply more broadly in chemistry. Some companies are developing their own metrics. For example, the French flavorings company, MANE, aims for a universally applicable score by assigning points to various individual metrics defined as "Green Motion" [12]. Looking beyond the laboratory, Jiménez-Gonzálex et al. [13] have developed a life cycle analysis tool for pharmaceutical syntheses. The authors admit that the life span considered is confined to sources of materials only through product production, rather than its ultimate fate. A full systems view would link the green chemistry of drug design and manufacture through distribution, use (and misuse), to the fate of these molecules in water treatment facilities and waste streams.

Economics certainly drives much progress in greening chemical manufacturing and use. However, economics also inhibits green improvements when they are seen as too expensive to implement. A challenge to move forward is to align greenness with economics by both decreasing the cost of greening and increasing the cost of employing unsustainable processes.

2 Outlook: Roadblocks to Progress

If so much green chemistry is already happening, why does progress seem so slow? Why is the revolution that I, as a graduate student, expected to be completed in a few years still unfolding at a glacial rate? Of course, my expectation of an instantaneous change in the 1990s says more about my naïveté at the time than about any fundamental problem with the approach. Nevertheless, even after the general recognition of green chemistry as an aspiration, roadblocks are apparent throughout the chemical enterprise. We can identify several. I classify them as (1) lack of knowledge or ability; (2) ends-justify-the-means thinking; (3) systems inertia; and (4) lack of financial or policy incentives.

The lack of knowledge or ability to undertake green chemistry reform can result from a lack of education about available methods or techniques. Most obviously, an enterprise may not have personnel who are knowledgeable enough to evaluate possible replacement solvents or catalysts. A related problem is uncertainty in selecting the appropriate metric of greenness, or lack of well-defined metrics that apply to the process in question. This issue is primarily one of education and outreach. Over the long term, it will be solved by embedding green chemistry into all chemistry education so that tomorrow's practitioners integrate it throughout. However, we don't have time to wait for the current workforce to retire. Our goal should be to empower practitioners to examine their processes, assess problem points, and identify and implement solutions. Many tools are becoming available to assist in greening various steps, for example, the EPA's solvent substitution program [14], and the green chemistry literature is growing rapidly. For large firms the savings in waste reduction undoubtedly offset the investment in green chemistry, but smaller companies and research laboratories may find it difficult to invest up-front efforts for later savings, indeed they may have few, if any, chemists on staff. One solution would be to deploy a Green Chemistry Extension Service, modeled on the U.S. Department of Agriculture's cooperative extension system. Such a program could train a cadre of green chemistry emissaries to visit, by invitation, enterprises engaged in chemical processes to assist practitioners in identifying key points of improvement and share successful methods.

A different type of knowledge gap, infinitely more challenging and interesting for researchers, is the set of problems for which green solutions do not yet exist. Here a true bottoms-up green chemistry approach needs to look not only at individual steps in a process, but consider whether the process is needed at all.

A second impediment to rapid conversion to greener techniques is ends-justify-the-means thinking. An example was the idea, expressed or not, in the pharmaceutical industry that "We're about saving lives, so we don't have the luxury to think about green chemistry." Similarly, academic researchers are guilty of feeling their work is too important or their time and funds are too limited to allow diversions into greening their laboratory procedures. By definition, traditional companies must prioritize profits as their ultimate objective; thus, they have a built-in end goal that can eclipse environmental means to reach it. That attitude has been changing and progress is visible in all these areas. In particular, the pharmaceutical world is demonstrating that green chemistry is fully compatible with their goals, most notably through the American Chemical Society Green Chemistry roundtable. Even the intense time-critical process of making radiolabeled pharmaceutical compounds can be transformed by green chemistry [15].

Common barriers to all kinds of change are systems inertia and historical decisions that "lock-in" operational steps. Simply stated, we are loath to tinker with methods that work. That hesitation is magnified for chemical processes, which often require many interconnected steps, each dependent on the others. Changing a solvent or a catalyst may require different equipment, a different separation method, a different suite of analytical methods subject to new interferences, and a new set of quality control procedures, as well as a reanalysis of safety considerations. Many of those steps seem auxiliary to the main purpose or product in question. Systems inertia applies to research laboratories as well as production sites. If my goal is to develop a new synthetic scheme, I don’t want to divert energy to reinventing a greener analytical procedure for every step. Overcoming embedded systems inertia requires more than good intentions; it requires investments in time and effort that must be supported by incentives at an institutional level.

Systems inertia may also take the form of historically locked-in decisions, which present enormous barriers to change. The locked-in problem is made visible as physical infrastructure that is difficult and costly to change, but locked-in mind-sets may be equal to blame for inhibiting innovative solutions. Perhaps the biggest form of locked-in infrastructure is our commitment to fossil fuels as our primary energy supply. Coal drove the industrial revolution but it cannot fuel the twenty-first century. With the help of cheap and abundant fuel, chemical synthesis achieved dramatic gains over the past 150 years mainly through application of brute-force methods to break and recombine bonds through heat, pressure, and strong acids, bases, oxidants, and reductants. The traditional brown chemistry approach has been remarkably successful and has undergone many improvements since first being employed by early alchemists. However, as John Warner of Beyond Benign and others have pointed out, innumerable complex molecules are made every second by biological processes operating at ambient temperature and pressure in mostly aqueous environments. We should not allow the history of energy-intensive processing to lock-in our thinking and constrict our perceived universe of possible solutions. The fact that refluxing a mixture in an organic solvent has worked before does not mean it is the only method to effect a transformation. Indeed, the recent surge in reports of solvent-free synthetic procedures illustrates how reconsidering the simple notion, long considered gospel, that organic reactions proceed in organic solvents can be revolutionary [16].

Overcoming the impediments of knowledge or ability gaps, ends-versus-means myopia, and systems inertia requires a multipronged approach. Policies and incentives that are misaligned with sustainability goals contribute to all these roadblocks. At the foundation of each roadblock is the difficulty in balancing a narrow focus on a specific problem with a systems view that considers the global impacts of chemistry.

A comprehensive systems approach needs to account for the continuum of cumulative local actions that lead to planet-wide effects. Thus, policies and incentives must be coherently designed to influence small and large decision points across the enormous spectrum of chemistry activities. Incentives can act at the level of a single person in a single laboratory and extend up to the international scale of multinational corporations or multilateral treaties. A single researcher or laboratory team may select a target molecule to synthesize, a reaction solvent, or an analytical procedure, based on local and immediate incentives of design needs, cost, availability, or familiarity. Greening that process requires devising individual incentives for that person or laboratory. At the other extreme, a CEO’s choice to invest (or not) in improving a global company’s environmental footprint can be swayed by many factors, including, apparently, its executive compensation structure [17]. The impact on the global environment is the cumulative result of innumerable decisions, each of which may be nudged in a positive direction through both top-down and bottom-up pathways.

Historically, policies for managing the environmental impacts of chemicals have been seen as punitive. Strict rules were perhaps an inevitable first policy response to the widespread uncontrolled pollution of the early twentieth century. Obsolete attitudes that are still fixated on equating policy with constricting rules exemplify the concept of locked-in thinking. The idea that policies to improve human and environmental health always mean restrictive mandates on business is outdated and yet persists conspicuously in political rhetoric. In forward-looking business environments those attitudes are gradually going extinct, but their endurance over decades illustrates how difficult change can be. Of course, even as attitudes about successful policies evolve, existing policies are slow to change when they are locked into inflexible laws. Newer forward-thinking policies are flexible, adaptive, and iterative and include incentives as well as restrictions.

An example of a win–win business innovation is the emerging concept of “chemical leasing” promoted by the United Nations Industrial Development Organization [18]. The idea is that a company sells the service a chemical substance provides, rather than selling the substance itself, therefore, aligning the incentives of both provider and buyer to use chemical substances as efficiently as possible [19, 20]. These types of programs can be promoted by public policies. Ongoing assessment to understand which policies lead to the desired results is critical to their wide dissemination, adoption, and success.

Chemists in all types of institutions can personally promote the more rapid uptake of green chemistry. To return to the analogy with safety, in the pursuit of laboratory safety, many chemical journals have guidelines that require a description of hazards when they publish new chemical syntheses or procedures. Publishers could similarly support sustainability by demanding that authors report some key green metrics such as atom economy, types and amounts of waste generated, energy intensity, sources of feed stocks, and reasons for choosing solvents or materials that are less benign than typical. Initial steps in this direction would be easy: a description of a new synthesis is certainly expected to report percent yields, an extension to include atom economy would be trivial. Likewise, a listing of the waste materials produced is straightforward, while volume of waste per gram of product requires only slightly more effort. Similar steps should be designed and promoted for publications on other chemistry topics. Which analytical techniques are more environmentally benign? What standard green metrics should be reported for new catalysts?

Steps we can all immediately take as authors, reviewers, and student mentors is to continually raise questions about green chemistry and sustainability to keep these issues in the forefront. Authors who regularly receive reviews asking about the green aspects of their work will begin to incorporate those ideas into their papers, and more importantly, into their thought patterns. Students learn what is important by what is emphasized by their professors. Inclusion of green chemistry topics in class and on exams throughout the curriculum demonstrates their centrality to our field.

3 Summary

Moving the global economy to achieve net-zero carbon emissions requires a dramatic restructuring of the flow of energy and materials that are fundamental to the chemical enterprise. The goals of green chemistry are well aligned with those of traditional chemistry. While much progress has been made, obstacles remain to the full integration of sustainability into the chemical enterprise. This planetary imperative will employ scientists and engineers of all kinds for the foreseeable future. We recognize that solutions that lead to a sustainable world are based on chemistry. As contributors to both the problems and the solutions, and as inhabitants of the planet Earth, all chemists must be engaged in this project.

Acknowledgment

This article is also available in: Benvenuto, Sustainable Green Chemistry. De Gruyter (2016), isbn 978–3–11–044189–5.

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