



Fordham University
Fordham Research Commons

Student Theses 2015-Present

Environmental Studies

Spring 5-10-2022

Remedying Renewable Energy Research: Implementation of Green Chemistry in Laboratories

Julia Mayes

Follow this and additional works at: https://research.library.fordham.edu/enviro_2015

**Remedying Renewable Energy Research: Implementation of
Green Chemistry in Laboratories**

Julia Mayes

Abstract

One of the pillars of environmental studies is the analysis of the natural world and the research being done to rectify harmful human activity on it. Laboratory components in the fields of chemistry, biology, ecology, among others, are powerful tools for learning about the way our environment works and assessing how human activities harm it. More advanced laboratories conduct research in the pursuit of new technologies to mitigate anthropogenic climate change. Concurrently, this work yields large quantities of waste. While laboratories are inherently valuable to the field of environmental science, the waste created by them raises a question of net benefit. This paper explores the question: Do scientific laboratories produce more good than bad? Chapter 1 takes a quantitative look at scientific waste in terms of plastic, hazardous materials, water, and energy. After getting a grasp of how sizable the problem is, I investigate the history of laboratory protocol and waste disposal as it relates to reducing environmental impact in Chapter 2. In addition, I consider the history of chemistry itself and its transformation into an industry tool. This leads to the foundations and principles of green chemistry, as a result of increasing environmental awareness, which are laid out in Chapter 3. Chapter 4 uses data from peer-reviewed journal articles to assess economic, political, and ethical considerations of scientific waste and green chemistry. This includes discussions of how socioeconomic status correlates with hazardous waste harm, the sense of urgency in science to make leaps against the new climate regime, and how policymakers play a critical role in the future of sustainable scientific research. Finally, Chapter 5 builds on the previous chapter and gives potential policy recommendations for further implementation of green chemistry in laboratories.

Keywords: climate change, hazardous waste, renewable energy, scientific research, green chemistry

Table of Contents

Introduction: Are Scientific Laboratories a Problem or Solution?

Chapter 1. Laboratory Waste by the Numbers

Chapter 2. A History of Chemistry & Waste Disposal

Chapter 3. A New Hope: The Principles of Green Chemistry

Chapter 4. Ethics & Economics

Chapter 5. Powerful Policymakers

Bibliography

Introduction. Are Scientific Laboratories a Problem or Solution?

Much of my undergraduate career has been spent in the laboratories of Fordham University's John Mulcahy Hall, home of the chemistry, mathematics, and computer science departments. Whether doing experiments for my courses or performing extracurricular research, I am extremely familiar with the laboratory environment and processes. However, a question has always lingered in my mind: how much waste am I creating, and where does it go? This question has been pondered by many other researchers, including Mauricio Urbina, a biologist studying the effects of plastic waste when consumed by crabs (Koerth 2019). Many of us, including Urbina and myself, have a passion for environmental research, but realize that in working towards solutions, we are part of the problem (Koerth 2019).

The prevalence of single-use plastic and glassware in laboratories might surprise some. Often, the possibility of cross contamination is too high a risk for the experimental goal. A reaction could be completely thrown off by the presence of unwanted ions from using tap water instead of deionized water, or a poorly washed test tube could react unwantedly when the desired chemical is poured in. For these reasons, it is understandable why we fill boxes with glass waste, and our trash bins with plastic droppers, petri dishes, and weighing boats. This leads to the fact that scientific laboratories are a largely ignored consumer of single-use plastics and glassware (Bell 2019). In addition to material waste, students obediently follow chemical waste protocols, avoiding the drain and using designated waste bins instead, but never actually see where this waste goes. As a student researcher, I have gotten a glimpse of the process by accompanying my faculty mentor to the basement to get rid of a full waste container and retrieve a new one, but even the faculty are simply following protocol they were once told. After bringing the container of metallic waste to the corner of a room in the basement, I never see it again. The hidden nature

of chemical waste disposal makes it easier to ignore, or to simply go unexamined. However, there needs to be more responsibility for such wastes.

The goal of this paper is to uncover and address the issue of scientific waste. In chapter 1 I will examine the issue of laboratory scientific waste quantitatively, and highlight the harmful effects of waste on human health and ecosystem services. Chapter 2 will highlight the history of the chemical laboratory, detailing how the development, and in particular industrialization, of chemistry led to increased waste production. In response, scientists became more aware of the health and environmental risks associated with waste, and sought ways to minimize it. The chapter will end with a discussion of the roots of green chemistry in practice and law. This transitions into chapter 3 which will discuss the twelve principles of green chemistry and important examples of green chemistry in practice. Chapter 4 will then examine the ethical and economic concerns regarding scientific laboratory waste, and how green chemistry potentially combats them. I will conclude with recommendations for policy in chapter 5, advocating for the widespread implementation of green chemistry in scientific practice through revised risk analyses, education, and research funding.

Chapter 1. Laboratory Waste by the Numbers

The unexamined nature of scientific laboratory waste is amplified by the fact that there are no comprehensive quantitative statistics regarding *how much* waste is created. Laboratories consume large amounts of water and use significantly more energy than similarly-sized buildings, in addition to the plastic and chemical waste produced. Experts interviewed by Koerth for her article had no knowledge of a comprehensive audit done to produce these numbers (Koerth 2019). In 2015, researcher Urbina extrapolated data from the University of Exeter to

estimate that research could be responsible for 5.5 million tons of plastic waste annually, which accounts for around two percent of the total annual amount. Which, they also reported, is equal to 83% of the plastic recycled worldwide in 2012 (Bell 2019). This estimate solely considered biosciences and medical research, not taking into account analytical, physical, organic, inorganic, or environmental chemistry research. This is also significant when the fact that scientists account for only 0.1% of the population, meaning they produce a disproportionately large amount of waste compared to their non-scientist equivalents. According to Martin Farley, sustainability officer, a scientist's impact on the environment is 100 to 125 times more than at home, depending on the research area.

According to the U.S.'s Environmental Protection Agency (EPA), laboratories typically consume "5 to 10 times more energy per square foot than do office buildings" (U.S. EPA 2008). They also estimate that if half of all American labs reduced their energy consumption by 30%, the nation could reduce its use by 84 trillion Btu, which is the equivalent of 840,000 households going dark (U.S. EPA 2008). This reduction would save \$1.25 billion and decrease CO₂ emissions by 19 million tons (U.S. EPA 2008). The large energy consumption is mostly contributed to the high air ventilation requirements, along with running chemical equipment and storage units.

In a 1989 report to Congress, officials examined the production and disposal of wastes at both secondary schools and colleges and universities. The report found that there are approximately 16,000 secondary schools in the United States, which view hazardous waste management as an element of school safety, as opposed to "a materials handling and disposal issue" (U.S. EPA Office of Solid Waste 1989). They found that high school personnel have less awareness, concern, and knowledge of regulations and proper disposal procedures than

university personnel. The reason for this could come down to funding—a study by Tufts University found that several high schools simply lacked a budget for handling hazardous materials. The disposal practices of secondary schools were largely using the drain or dumpster. While secondary schools often substitute less hazardous materials into their curricula, it is for the goal of student safety, not the goal of waste management (U.S. EPA Office of Solid Waste 1989). The report concurs with much of my previous discussion of the lack of quantitative data for academic waste disposal. They found one study claiming in Minnesota in 1983, there were 78 high schools that generated an annual waste average of 40 kg each (Ashbrook and Reinhardt 1985).

The report suggests some reasons for the difficulty in determining quantitative data. First, some personnel at these secondary schools lack the knowledge of what constitutes hazardous waste. Secondly, there are a number of practices that complicate quantification. For example, some secondary schools perform a one-time cleanout of stockpiles of unused chemicals. This type of cleanout could happen as infrequently as once every 10 years. There has been no systematic study of the volume of waste generated in such a disposal practice. In addition, hazardous waste is often disposed of by “using the sewer system as the dumpster,” thus making it impossible to quantify (U.S. EPA Office of Solid Waste 1989). Finally, some volatile compounds are stored under fume hoods until they vaporize (Stanley 1987, Kizer 1987).

The storage of chemicals at secondary schools typically occurs in stockrooms or closets, and often demonstrates improper protocol, such as alphabetizing chemicals which can result in incompatible chemicals being stored next to each other. Three disposal categories of waste disposal at secondary schools include: nonhazardous wastes that are disposable at the school, hazardous wastes that are treatable at the school, and hazardous wastes that must be treated at a

commercial facility. The final option also poses a difficulty to secondary schools because of its cost. Since secondary schools usually produce such small volumes of variable compositions of waste, they face higher disposal costs since waste transporters can only operate cost-effectively if they have full loads (U.S. EPA Office of Solid Waste 1989).

In comparison to secondary schools, there are roughly 3,300 universities in the United States with varying degrees of awareness of hazardous waste management. As logic suggests, larger schools with highly developed research programs have the most comprehensive knowledge of waste management. At one university, the majority of waste, 75%, was produced by research laboratories, followed by 20% in teaching laboratories, and 5% in machine shops. Another university found that 75% of its waste came exclusively from its chemistry department, college of pharmacy, engineering and physics, and vehicle maintenance and arts (U.S. EPA Office of Solid Waste 1989). The quantitative data of waste produced at colleges and universities depends on the specific college or university, and the degree of knowledge varies greatly. Some colleges know exactly how much waste they are producing, while others have no data at all. For example, the University of Illinois at Urbana-Champaign reported 27,500 kg waste in 1984 and 37,000 kg waste in 1985, demonstrating that the amount of waste is increasing (U.S. EPA Office of Solid Waste 1989). This trend was supported by data from other universities. Compared to secondary schools, colleges and universities have more advanced storage and disposal practices, but there is great variation depending on the specific college or university.

There is a distinction between the disposal processes of hazardous waste from academic laboratories compared to industrial waste generators. According to the EPA, the main differences are the quantity of waste generation points, the volume of each hazardous waste, and the variation of wastestreams at each point of generation. Academic laboratories tend to have a large

number of points of generation, that is, points where the waste originates from. This is because each individual laboratory, of which there are many on a single campus, can have multiple benchtops. Furthermore, there may be multiple buildings with laboratories. So there are three levels to consider: the number of buildings on campus containing laboratories, the number of laboratories in each building, and the number of benchtops in each laboratory. From this it is clear to see that points of waste generation are widespread in the academic environment. On the other hand, industrial waste generators tend to have few generation points. A second factor to consider is the volume of waste. Academic labs tend to generate smaller volumes of each hazardous waste while industrial labs create larger volumes of a few types of waste. Finally, the number of wastestreams differs between the two types of laboratories. Academic labs tend to have many different wastestreams at each point of generation, while industrial labs have only a few that produce a large amount of waste (EPA¹).

The nature of the people that work in each of these laboratory settings differs greatly as well. Researchers in academic laboratories have a transient nature. Students will pass through laboratories, usually only staying in the same one for one to five years. With people constantly passing through, the training in hazardous waste disposal is less consistent or comprehensive. Industrial laboratories tend to have relatively stable long-term employees, who are thoroughly, professionally trained in the disposal of their specific hazardous waste(s) (EPA¹).

Scientific waste is managed by the Occupational Safety and Health Administration (OSHA), which sets lab standards, and the Office of Environment, Health, and Safety (EHS), which monitors the implementation of those standards. They divided waste into two main categories: non-hazardous or hazardous to health. Non-hazardous waste includes solvents, glass, and paper and plastic. Solvents account for almost half of the total waste generated in a chemical

process because they are the substances used to dissolve another substance, and are usually present in a much larger amount. While water is the most common solvent, other organic solvents include methanol, ethanol, acetone, and toluene. Often, solvents can be recycled or purified by distillation. Recycling of laboratory glass waste is a bit more complicated as they contain a variety of borosilicate blends, more resistant to thermal shock than common glass. In addition, they could be contaminated with hazardous chemicals in which case they must get buried or burnt. In some cases, glassware can be cleaned and reused. Paper and plastic can often be recycled, and most institutions have detailed recycling programs, yet they still produce a disproportionate amount of plastic waste annually (Shi & Sarangi 2021). Hazardous wastes, on the other hand, are characterized by ignitability, corrosivity, reactivity, and toxicity (National Research Council Committee on Prudent Practices in the Laboratory 2017).

With the rise of environmental awareness, many scientific research groups have paid more attention to the waste they produce. In September of 2019, scientists took to twitter to share how much waste they produced in a single day with the public under the hashtag #LabWasteDay, as organized by the eLife community group. Today, users can still see the tweets and jarring images of plastic waste under the hashtag. For example, user @z_pogacar shared that “after one short hour in the tissue culture lab [they] produced 400g of plastic waste! That would be more than 100kg per year!” (@Z_pogacar, September 17, 2019). Dozens of similar anecdotes can be found, demonstrating the pervasiveness of the issue.

Furthermore, it is important to consider the effects of hazardous waste. The environment provides several necessary and beneficial ecosystem services, many of which are adversely affected by the issue of scientific laboratory waste. These include provisioning services, regulating services, habitat or supporting services, and cultural services. To begin, the

provisioning services describe how ecosystems provide food, raw materials, fresh water, and medicinal resources, which are all of immense value to humans. Regulating services include cycles and organisms that regulate the quality of air, water, and soil. Underlying all aforementioned services are the habitat or supporting services. Ecosystems provide living spaces and maintain species diversity. Finally, cultural services are intangible benefits provided to humans, such as aesthetics, support of mental and physical health, and spiritual connection.

Toxic waste and pollution directly harm each and every one of these services. Water pollution by hazardous and non-hazardous wastes is one of the most insidious effects of a provisioning service: the provision of fresh water to all organisms. Hazardous waste and chemicals can seep into the soil or permeate water supplies, which can be detrimental to plants and animals in the area, affecting their habitats. For example, one important regulating service is waste-water treatment, in which microorganisms in soil and wetlands decompose human and animal wastes, as well as some pollutants (Miller 2015). However, when overloaded with hazardous waste, the system cannot keep up. Furthermore, groundwater pollution is a major concern due to the fact that a large percentage of individuals rely on groundwater for drinking water. Groundwater is the result of when rainfall permeates the earth's surface, and fills the porous area of an aquifer. This water then gets pumped to the surface for human use and consumption (Denchak 2018). If an aquifer becomes contaminated due to improper waste disposal, it can no longer provide drinking water, sometimes for thousands of years. According to studies conducted by the EPA, 70% of all U.S. hazardous waste storage areas lack proper lining and therefore pose a risk to groundwater supplies (Miller 2015). Groundwater pollution also runs the risk of spreading contamination to other streams, lakes, and even oceans (Denchak 2018).

There is also the bioaccumulation and biomagnification of leaked chemical wastes in the food chain, an effect on a regulating service. The food chain describes the mechanism by which living organisms are nourished. They generally show the linear passage of energy from a producer, to primary, secondary, tertiary, and final consumers, and ultimately through decomposers. Food webs show the nonlinear connections between multiple food chains. However, just as nutrients are passed through food chains and webs, contaminants can also be transferred from one level to another, and through entire food webs (EPA²). Some contaminants introduced to the food web by humans include mercury, cadmium, lead, and zinc. More recently, synthetic organic compounds have become causes for concern. Bioaccumulation describes the absorption of a contaminant by an organism which occurs at a rate faster than that of excretion (EPA²). Biomagnification describes the process of trophic magnification, in which substances increase as they pass through trophic levels. According to the EPA, “contaminants may only be found in small amounts at the lowest levels of food webs but still have impacts on top predators that eat large quantities of other organisms” (EPA²). Therefore, even if hazardous chemical wastes are primarily absorbed by the lower trophic levels, their impact permeates throughout entire food webs.

Finally, there are increasing levels of chemical pollution in human bodies and effects on physical and mental development, a cultural service. Related to both the previous discussions of groundwater pollution and bioaccumulation of chemical waste, increasing levels of chemical pollution can have detrimental effects on the cultural services provided by ecosystems. Physical and mental development are impacted by chemical pollution. In 2007, the EPA estimated that 41 million people lived within 4 miles of a National Priority List (NPL) site, comprised of 1240 hazardous waste sites at 157 federal facilities (Fazzo et al. 2017). Adverse health effects from

chemical exposure are thought to be greater for fetuses, children, and adolescents. This is because these age groups are still in the ages of development. Thus, if impacted by chemical waste their organ development may be permanently stunted. There are eight major body systems that can be affected by toxic chemicals: the respiratory system, the renal system, the cardiovascular system, the reproductive system, the nervous system, the immune system, the skin, and the hepatic system (*ATSDR*).

The effects of hazardous chemicals on each of these systems are numerous. Possible health effects on the respiratory system, which consists mainly of the lungs, include asbestosis, lung cancer, chronic bronchitis, fibrosis, and emphysema. The renal system includes the kidneys, urethra, bladder, and ureter, and its job is to excrete waste. Possible risks include decreased urine formation, decreased blood flow to the kidney, decreased blood filtration, kidney damage, and kidney cancer. The cardiovascular system is responsible for a wide variety of functions, including the transfer of nutrients, gasses, and wastes; stabilization of body temperature; and fighting diseases. Possible effects include heart failure and difficulties with the transportation of oxygen throughout the body. The reproductive system includes male and female reproductive organs and exposure to toxic chemicals can affect one's ability to reproduce, increase the risk of baby deaths, birth defects, and infertility. The inability to move, loss of feeling, confusion, as well as decreased speech, sight, memory, muscle strength, and coordination are possible effects on the nervous system, made up by the brain, spinal cord, and nerves. The immune system can be slowed down or fail due to chemical exposure, as well as increased risk of allergies and autoimmunity. Some of the most commonly observed effects of chemical exposure appear on the skin, and include irritation, rash, redness, and dermatitis. Finally, the hepatic system, which consists of the liver, is responsible for purifying the body from drugs, contaminants, or

chemicals. Thus, possible health effects include liver damage, tumors, accumulation of fat, and death of liver cells (*ATSDR*).

While this list is substantial, it is important to note that exposure to chemical waste will not always result in these effects. The purpose of this overview is to show how widespread the health risks of chemical exposure are, and demonstrate the importance of research regarding the negative effects of each and every chemical on the human body. Given the complicated nature of the human body and the number of variables, studies regarding the health effects of exposure to chemical waste are not confirmed. These studies point out certain scenarios that suggest a connection between the two, which could be causation or correlation.

One famous historical example of chemicals posing risks to human health is the case of PCBs: polychlorinated biphenyls. PCBs are a class of organic compounds containing multiple chlorine atoms that were widely produced and used from 1929 until 1979. In 1979, the Toxic Substances Control Act banned their production due to the discovery of toxicity to human health. They found that exposure to PCBs caused cancers in test animals, particularly liver cancer. In addition, research found that pregnant women who were exposed to PCBs had underweight babies with “permanent neurological damage, sharply lower-than-average IQs, and long-term growth problems” (Miller 2015). Although their production was banned, they were present for decades, and their impact will be seen for decades to come. Since PCBs are very stable substances, they break down slowly, and can travel far from where they originated. Furthermore, PCBs are fat-soluble, posing the risk of bioaccumulation and biomagnification in food webs as previously discussed (Miller 2015). The EPA estimates that about 70% of all PCBs produced in the United States are still present in the environment—in the air, soil, lakes, rivers, and even most human bodies (Miller 2015).

According to an article published in the *Environmental Health* journal, “several investigations indicate poor and illegal waste management as the most important world-wide cause of contamination of soil and groundwater” (Fazzo et al. 2017). In addition to acids, metals, solvents, and chemicals of known toxicity, research laboratories are often synthesizing new chemical products, whose toxicity is unknown (Nascimento & Filho 2010). There exists also the risk of unknowns, or chemical substances that end up unlabeled and unidentifiable that then require disposal. According to HWH Environmental, 13 tons of hazardous waste are produced every second, which is 400 million tons per year. The rate of increase in chemical waste is staggering— production of man-made chemicals has increased 40,000% in one generation (HWH Environmental 2021). Although only a small fraction of this waste is contributed by scientific laboratories, it is not negligible. The EPA highlights some immediate health effects of hazardous substances, as previously discussed, which include irritation of the skin and eyes, difficulty breathing, headaches, and nausea, in addition to severe health effects including behavioral abnormalities, cancer, genetic mutations, physiological malfunctions, physical deformations, and birth defects (EPA³). Not to mention the environmental impacts such as “killing organisms in a lake or river, destroying animals and plants in a contaminated area, causing major reproductive complications in animals, or otherwise limiting the ability of an ecosystem to survive” (EPA³). It is for these reasons that waste management has become increasingly more regulated over the years, as I will discuss in the next chapter.

Chapter 2. A History of Chemistry & Waste Disposal

Generally when the history of chemistry is discussed, the conversation focuses largely, if not entirely, on scientific theory. While the development of chemical knowledge is fundamental,

it is also beneficial to consider the history of chemical practice and chemical culture as that has transformed entirely over time as well (Morris 2016). The practice and culture of chemistry are often seen in the laboratory, where chemists are taught, trained, and often spend much of their careers. Thus it is worthwhile to examine the history of the chemical laboratory, and how it has transformed in response to the differing needs of chemistry since as early as 1600 (Morris 2016). Some important distinctions can be drawn, such as academic versus industrial, and individual versus national (Morris 2016). The very first alchemical laboratory with documented evidence was that of Wolfgang von Hohenlohe in Germany. The origins of the chemical laboratory can be traced back to the pharmacy, with the first lab being constructed concurrently with Paracelsus's concepts of iatrochemistry, or chemical medicine (Morris 2016). There were also smaller-scale industrial forerunners, including spirit distilleries and soap boileries. The early days of the laboratory consisted of "making [and] quantity," but in the late eighteenth century the focus was largely shifted to "investigating [and] precision" (Morris 2016). This resulted from the growing study of gases, termed pneumatic chemistry, during that time.

During the eighteenth century the boundary between lecture hall and laboratory became fluid. Some professors opted to teach in their laboratories, while others lectured only in designated lecture halls. Still others had laboratories attached to lecture halls but each in their own distinct spaces (Morris 2016). The development of organic chemistry and advanced analytical techniques in the mid-eighteenth century led to further changes in the nature of chemical study and research. During this time, there was further recognition of the need for danger mitigation in the laboratory. In 1836, Robert Bunsen, the chair of chemistry at the Höheren Gewerbeschule in Kassel, began studying the "evil-smelling substance Cadet's liquid" (Morris 2016). He performed many experiments in open air, but used a thin glass tube to breathe.

In one instance, a combustion reaction caused an explosion that left Bunsen blind in one eye (Morris 2016). The increasing danger of chemical reactions, mostly recognized due to direct harm to human health, led to mitigation efforts. In the nineteenth century, the lab developed into entire new buildings suitable for several researchers with a focus on organic synthesis, instead of analysis. This new purpose led to the supply of running water and gas to the lab, which simultaneously increased the energy requirements of laboratories. These types of laboratories were the foundation for laboratories in the twentieth century (Morris 2016).

The industrialization of chemistry is also the major contributor to the accumulation of human-made, synthetic, long-lasting chemicals in our environment. In the book *Pandora's Poison*, Joe Thornton examines the massive issue of toxic pollutant accumulation in our world today. Thornton's motivation, similar to my motivation for writing this paper, was his personal experience. When Thornton and his wife were expecting their first child, they became alarmingly aware of the accumulation of industrial compounds in their bodies and its potential effects on their future child. Emerging evidence showed that a child's exposure to even low levels of these chemicals can have numerous effects, including cancer, reduced IQ, infertility, and a compromised immune system. They questioned *how* these chemicals could have accumulated in their bodies? (Thornton 2000). A major misconception in our world is that only people that produce these chemicals, working with them day in and day out, could experience negative consequences. For those who do not work in a chemical-intensive industry, why would there be a problem?

The reality is that these chemicals are *pervasive*—they invade our food supply, the air we breathe, and the water we all share. These natural resources are not excluded from the reach of chemical compounds; in fact, they are particularly susceptible to pollution given the failures of

policies regulating the production and disposal processes. The production of synthetic organic compounds has grown over thirty-fold since the 1940s. Today, over seventy thousand chemicals are synthesized and sold in bulk, some in amounts greater than one billion pounds per year (Thornton 2000). Since so many of these synthetic chemicals are resistant to natural degradation, they accumulate in the environment over time and are further distributed by currents of wind and water (Thornton 2000). Thus, the production of even one individual synthetic chemical in one location becomes a worldwide concern. Thornton lists a few of the many news stories regarding environmental pollution: “DDT and the decline of bald eagles, toxic waste at Love Canal, cancer among Vietnam veterans exposed to Agent Orange, chlorofluorocarbons and the ozone hole, PCBs in polar bear tissue, herbicides in groundwater throughout the Midwest, dioxin in fish downstream from pulp and paper mills” (Thornton 2000). If this list alone does not incite alarm, there are hundreds of other cases to learn about.

Thornton focuses on the major group of chemicals that are responsible for each of the cases listed above: organochlorines. Organochlorines are chlorinated organic compounds that are of primary concern given they “dominate all lists of global contaminants and environmental health hazards” (Thornton 2000). Organochlorines are used in a wide variety of industries, including the chemical, paper, and waste treatments industries. They can be found in plastics, solvents, refrigerants, and are most commonly known for their use in pesticides. While the properties of the chlorine atom give rise to uniquely useful chemical products, they also are responsible for toxicity. For example, chlorine is highly reactive which makes it a good bleach and disinfectant. However, this reactivity also means that its use accidentally creates thousands of organochlorine by-products (Thornton 2000). Additionally, chlorination’s increase in toxicity is what makes organochlorines good antibiotics, for example, effective at killing unwanted

organisms. However, this inherently makes them good at killing necessary and beneficial organisms in our bodies and in nature (Thornton 2000).

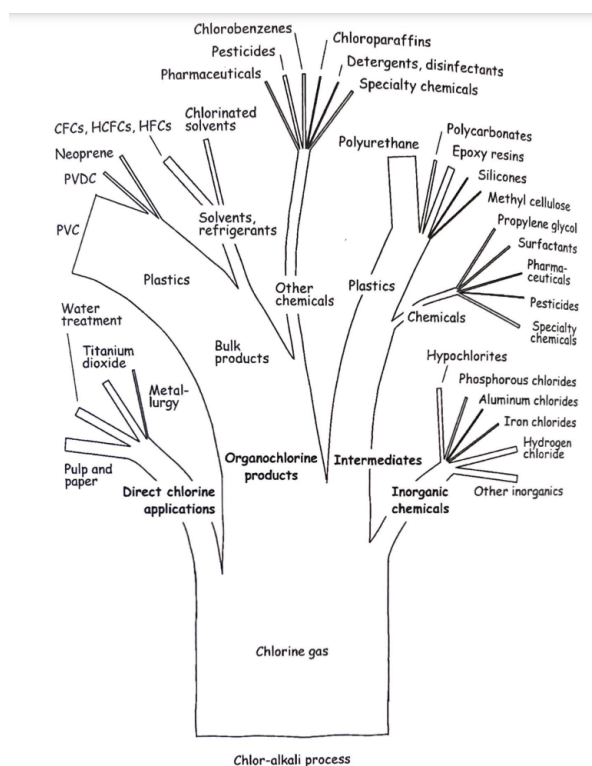


Figure 1. The “tree of chlorine uses” as provided by Thornton. In this graphic the width of a branch is proportional to the amount of chlorine used in the following applications (Thornton 2000, page 248).

Organochlorines make for an insightful case study because they demonstrate the major failures of toxic chemical regulation. To begin, the framework for evaluating toxic chemicals was originally created by industrialized countries in the 1970s, and remains almost *unchanged* since. Thornton names this framework the “Risk Paradigm,” and describes its method as: managing “individual pollutants using scientific and engineering tools, including risk assessment, toxicological testing epidemiological investigations, pollution control devices, and waste disposal technologies” (Thornton 2000). The major issue with these methods is that they focus on severe local health risks, thus failing to address the potential for subtle, long-term, global hazards.

In the case of organochlorines, the subtle, long-term, global hazards finally came to light. Production of these chemical compounds on a large scale began during World War II, and it took years to see their full range of hazards, both to the environment and human health. Later findings show that even low levels can cause many health effects by interfering with biological processes. The levels that were once thought of as “safe” have now been shown to subtly damage the human body and accumulation of them to be passed on through the placenta and breast milk, posing even greater risk to vulnerable newborns. The full of range of effects includes reducing sperm counts, disrupting female reproductive cycles, causing endometriosis, inducing spontaneous abortion, altering sexual behavior, causing birth defects, impairing the development and function of the brain, reducing cognitive ability, interfering with the controlled development and growth of body tissues, causing cancer, and compromising immunity (Thornton 2000). A discovery that was particularly alarming was that some of the levels for toxicity were extremely low, “in parts per trillion concentrations, a ratio equivalent to one drop in a train of railroad tank cars ten miles long” (Thornton 2000). Such low doses are difficult for us to even conceptualize.

So, while the previous “Risk Paradigm” found certain levels of these chemicals individually safe for production and use, a more accurate risk assessment, focused on “multigenerational, population-wide erosion of our ability to have healthy children, fight off disease, and function to our full biological and intellectual potential,” would give rise to considerable concern (Thornton 2000). Furthermore, a sense of hopelessness may be induced when we recognize that even if we halted all production and pollution by organochlorines today, they would remain in the environment, the food web, our tissues, and those of future generations for centuries to come (Thornton 2000).

By the 20th century, it was clear that the practice of chemistry, particularly industrial chemistry, was inherently linked to the use of hazardous materials and resulting pollution. As a result, there have emerged many techniques to combat the dangers associated with hazardous waste. One such approach was termed solidification/stabilization (S/S) technologies (Barth 1990). Solidification involves the conversion of liquid waste into a non-liquid material, while stabilization involves a purposeful chemical reaction that renders waste constituents less leachable (Barth 1990). These techniques can be drawn back to early transportation developments, and research done by the U.S. Army Corps of Engineers (Barth 1990). Road construction was commonly stabilized with lime. In addition, S/S processes can be traced back to the 1950s with the disposal of low-level radioactive waste, which only involved solidifying liquid waste for ease of transport and disposal (Barth 1990). Common methods developed at the time involved the use of urea-formaldehyde and asphalt systems which provided “more consistency, lower weight, and better space efficiency” (Barth 1990). However, mandates for hazardous waste management practice did not come until about twenty years later, in the 1970s. Prior to these, solidification additives were evaluated for the treatment of industrial waste streams, for convenience and reduced pathogens, and there were limited S/S techniques established for organic waste, such as that of organochlorines (Barth 1990). There was little environmental concern at the time.

Thornton identifies the failures of these processes described by Barth as being rooted in the “Risk Paradigm” framework. The reason organochlorines went largely unexamined for decades was because the framework did not have built-in steps to address their hazards. This framework was built such that pollution was managed by determining a level of “acceptable” pollution or contamination. Therefore, pollution was permitted as long as it did not exceed that

quantitative standard. The underlying assumption is that “ecosystems have an “assimilative capacity” to absorb and degrade pollutants without harm [and] that organisms can accommodate some degree of chemical exposure with no or negligible adverse effects” as long as the levels of pollution and exposure is below the determined threshold (Thornton 2000). This assumption is seen in action by pollutant discharge permits, which are licenses to pollute that set maximum legal release rates of individual chemicals from individual facilities (Thornton 2000). Other examples include pesticide registrations and occupational exposure limits. The method to determine these levels is called “quantitative risk assessment” which looks at the accepted level of exposure to calculate the maximum release rate before the threshold is exceeded. In rare extreme cases, the Risk Paradigm has banned chemicals, but only if epidemiological and ecological studies overwhelmingly conclude that a specific substance is responsible for severe health and environmental damage (Thornton 2000).

The notion of “acceptable” levels of pollution is deficient, to say the least. To begin, it fails to acknowledge the lifespan of chemicals beyond immediacy. Chemicals do not just contaminate their immediate surroundings. Instead, they are absorbed by the ambient environment and bodies of living organisms. Through processes of bioaccumulation and biomagnification, as discussed in Chapter 1, these synthetic chemicals reach higher concentrations over time. So, even if there was an acceptable threshold, it would eventually be surpassed. But ultimately there is little to no evidence that these acceptable levels exist. Thornton reveals that more recent studies show that many of the negative effects, such as cancer and birth defects, do not have a clear threshold. Instead, any exposure contributes to the incidence or severity of disease or malfunctioning. Finally, the notion of “pollution control devices” that work to maintain the acceptable level is false. These devices only function to shift pollutants, not to

prevent their formation or eradicate them. Thus while they may reduce local pollution, they have no impact on reducing global contamination (Thornton 2000).

The response to organochlorines over the years presents an interesting case study because it shows how deep the connections run between chemistry, industry, politics, and society. The issue of organochlorine contamination is not purely scientific, but raises numerous social and political questions. For example, in the 1990s when concern about organochlorine pollution began to grow, one of the biggest responses came from the Chlorine Chemistry Council (CCC) which is a part of the Chemical Manufacturers' Association. The CCC, along with the rest of the chlorine industry, spent around 130 million dollars annually on "an ambitious public relations and lobbying counteroffensive" (Thornton 2000). Arguments by the CCC and chlorine industry state that policy must be based on "sound science," which precludes all social considerations. This "sound science" is limited to the calculation and use of risk-derived discharge limits for chemicals on individual bases. Chlorine defenders argue that any other method is bad science, perhaps rooted in emotion rather than logic. In addition, the declaration that policy should be based on "sound science" excludes anyone but *scientists* from the decision-making process. It is inadequate at best, and unjust at worst.

The truth of the matter is that environmental policy is not strictly a question of science, but an interdisciplinary question of how the natural and the social interact. At this intersection, we find moral questions such as: how much health or environmental damage is acceptable, how should health threats be weighed against the benefits of a technology, and so on (Thornton 2000). The latter question is the question that led me to research this topic and write this paper. I found myself in the lab wondering if the work I was doing would actually serve to help the purpose of sustainability, or if I was creating too much waste in the process, thus bringing more harm than

good. That question cannot be answered by scientific fact or reasoning, instead it presents social and philosophical considerations.

Building on that point, Barth describes how mandates, including the Solid Waste Disposal Act (SWDA), Resource Conservation and Recovery Act (RCRA), and the Hazardous and Solid Waste Amendments (HSWA), were largely amended in the 1980s, giving further guidance to S/S processes (Barth 1990). However, by this point, there was a suggestion of environmental consideration in such amendments. This demonstrates how change in policy did not result purely from new scientific research or discovery, but because there were now social and ethical considerations being made. In Barth's 1990 publication, he states that "before any S/S technical research need is discussed, academia must focus on reuse, recycling, or pre-concentration techniques," in addition to declaring that "alternate uses of waste products need to be evaluated and proven environmentally acceptable" (Barth 1990). This focus on reuse, recycling, and preconcentration techniques demonstrates that the focus was on how to make waste *management* more environmentally friendly, and that the conversation had not yet shifted to waste *prevention*. These shifts in environmental policy can be attributed to the consideration of science, ethics, and politics in decision-making processes, and I will discuss the importance of all three in the following chapters.

There is a big distinction between waste management and waste prevention. The former, sometimes called remediation, deals with the aftermath of pollution, seeking ways to reuse or recycle waste, or simply trying to minimize harmful effects of waste on the environment and human health. The latter seeks to eradicate pollution from the source, preventing the generation of pollution. Some common methods of waste remediation include in-process recycling, waste storage, and a plethora of technologies classified as either ex-situ or in-situ. In-process recycling

is recycling that happens onsite, in this case, in the laboratory, throughout the ongoing chemical processes. One big type of in-process recycling is solvent recycling, in which a solvent is recovered and its purity refined for reuse in the same, or a new, process. When a solvent or other chemical cannot be recycled, it must be stored. Generally chemical waste storage begins in the laboratory in suitable, labeled containers. It then gets transported to a hazardous waste management facility where it can be treated, further stored, or disposed of in landfills (EPA⁴). Other technologies exist for remediation: ex-situ technologies involve extraction of contaminated soil or groundwater and treatment at the surface, while in-situ technologies seek treatment without removal. Ex-situ approaches include soil excavation and disposal to landfill and the “pump and treat” method for groundwater (Wikipedia). In-situ technologies include solidification and stabilization, soil vapor extraction, permeable reactive barriers, monitored natural attenuation, bioremediation-phytoremediation, chemical oxidation, steam-enhanced extraction, and thermal desorption (Wikipedia).

An initiative with the goal of prevention in the scientific research community is termed *green chemistry*. Green chemistry can be seen as a result of the Pollution Prevention Act of 1990, which demonstrates America’s policy transition to pollution *prevention* instead of remediation. This act promoted source reduction, recognizing the missed opportunities that arose from existing regulations’ focus on waste treatment and disposal. Since there was so much emphasis on the latter, there was little thought about how to reduce pollution in the first place. According to the EPA, this act raised the idea of “reducing the amount of pollution through cost-effective changes in production, operation, and raw materials use” (EPA⁵). The organization also lists three important points about source reduction. First, that it is “fundamentally different and more desirable than waste management or pollution control,” which is intuitive (EPA⁵). Second, that it

involves practices that reduce hazardous substances from being released into the environment. And finally, that it includes modifications to equipment, technology, and procedure; redesign and reformulation of chemical reagents and products; and improvements in housekeeping, maintenance, training, or inventory control (EPA⁵). All of these aspects also include increasing efficiency in terms of energy, water, and natural resource use, thus making green chemistry a sustainable practice.

The EPA further established the Office of Pollution Prevention and Toxics (OPPT), which is responsible for researching the development of alternative chemical products and processes (Hjeresen et al. 2000). They even launched a program called “Alternative Synthetic Pathways for Pollution Prevention,” which included unprecedented grants for projects interested in pollution prevention (Hjeresen et al. 2000). This program, in partnership with the U.S. National Science Foundation (NSF), was responsible for providing funds for basic research in green chemistry throughout the early 1990s (Anastas 2009). The shift from waste management to waste prevention was a critical moment in the history of chemistry, and green chemistry has important implications for the future of laboratory work.

Chapter 3. A New Hope: The Principles of Green Chemistry

Green chemistry, as defined by the Environmental Protection Agency (EPA) is “the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances” (EPA⁶). Its practice considers the entire lifecycle of a chemical product: design, manufacture, use, and disposal (EPA⁶). Green chemistry is composed of twelve founding principles, as defined by Anastas and Warner in 1998 (Sheldon 2016). In its essence, it is chemistry that is “benign by design” (Sheldon 2016).

The twelve principles are: prevent waste, maximize atom economy, design less hazardous chemical syntheses, design safer chemicals and products, use safer solvents and reaction conditions, increase energy efficiency, use renewable feedstocks, avoid chemical derivatives, use catalysts instead of stoichiometric reagents, design chemicals and products to degrade after use, analyze in real-time to prevent pollution, and finally, minimize the potential for accidents (EPA⁶). While a rather long list, each of these twelve principles is important for the reduction of pollution generation in chemical experiments.

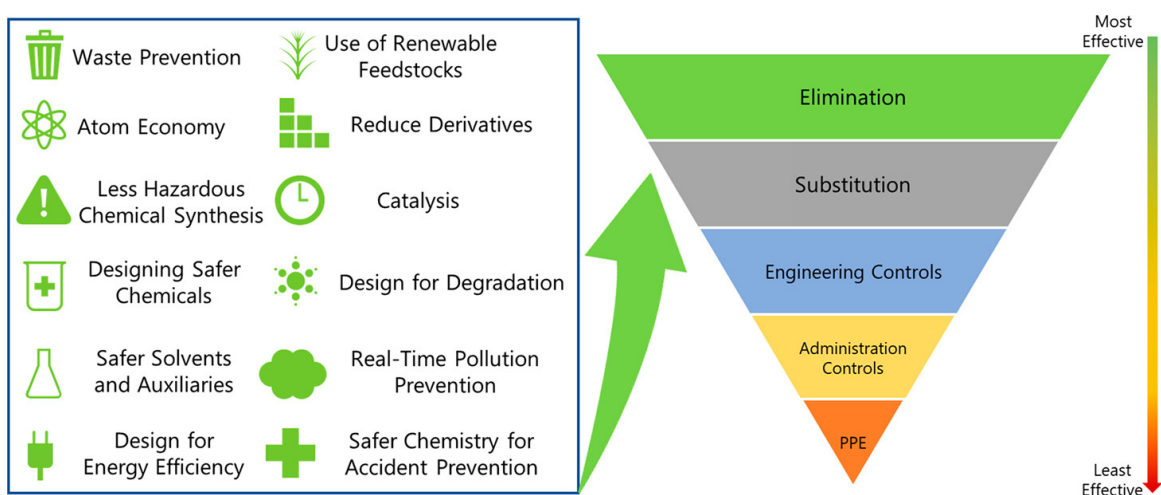


Figure 2. The twelve principles of green chemistry and how they accomplish the most effective levels of the National Institute for Occupational Safety and Health (NIOSH) Hierarchy of Controls Pyramid (O'Neil et al. 2021).

The first six principles are rather self-explanatory. Principle 1 calls for designing chemical syntheses processes such that there is no waste to treat or clean up. Principle 2, “maximize atom economy,” involves designing chemical reactions so that few atoms are wasted, with the final product containing the maximum proportion of the starting materials. These principles essentially involve careful calculation of reagents and knowledge of reaction mechanisms. One can easily calculate how much of each reactant is needed, thus minimizing any excess chemicals. Principles 3 and 4 consider the design of chemical syntheses such that less

hazardous substances, with little or no toxicity to humans or the environment, are generated, *or* the design of safer chemicals to begin with. Principles 5 and 6 focus on reaction conditions. Principle 5 calls for the avoidance of solvents, separation agents, or other auxiliary chemicals, which are not involved in the actual chemical reaction. These chemicals are not incorporated into the final product, but are used during the synthesis. Furthermore, principle 6 encourages running reactions at room temperature and pressure to minimize external energy requirements. This way, tools like hot plates or vacuums, which require energy, are not used (EPA⁶).

The following principles involve more in-depth chemistry discussion. Principle 7 talks about renewable feedstocks, which are starting materials that are not depletable. According to the EPA, the source of these materials “is often agricultural products or the wastes of other processes,” while “the source of depletable feedstocks is often fossil fuels (petroleum, natural gas, or coal) or mining operations” (EPA⁶). Principle 8 advocates for the avoidance of chemical derivatives. Derivatives include blocking or protecting groups, or any temporary chemical modifications. A blocking/protecting group is a chemical group that prevents a reactive site on a molecule from reacting so that only the desired site on the molecule participates in the chemical reaction. Since these are additional chemicals, they result in additional waste. Principle 9 similarly minimizes waste by promoting the use of catalysts over stoichiometric reagents. This is desirable because catalysts “are effective in small amounts and can carry out a single reaction many times,” whereas stoichiometric reagents “are used in excess and carry out a reaction only once” (EPA⁶). Principle 10 advocates for chemical products that degrade on their own, breaking down to innocuous substances, so they do not accumulate in the environment. The final two principles emphasize real-time monitoring and control in the laboratory to prevent the generation

of pollutant byproducts and designing chemical forms to prevent explosions, fires, and releases to the environment (EPA⁶).

It has been acknowledged by many that the emergence of green chemistry is largely due to the rise of students who express profound interest in the sustainability of their world (Hjeresen et al. 2000). There is growing public awareness about climate change, specifically anthropogenic climate change, and a louder call for action to “secure a healthy Earth for future generations” (Hjeresen et al. 2000). While rooted in academic research, green chemistry has evolved to a practice supported by government, academia, and industry. Part of the reason for this is the recognition and remembrance of infamous instances of “chemistry gone wrong” (Hjeresen et al. 2000). Many are familiar with at least one of the following environmental problems: DDT, ozone depletion, the Love Canal, Bhopal, and the Cuyahoga River (Hjeresen et al. 2000). Given such events, science (and government) had to respond. Green chemistry resulted with the premise that “a benign process and product presents no risk” (Hjeresen et al. 2000).

Beyond its previously mentioned roots in the Pollution Prevention Act of 1990, the formation of the Green Chemistry Institute (GCI) in 1997 has been instrumental in the international spread of the practice. The institute was further boosted by its approved alliance with the American Chemical Society (ACS) in 2000. The ACS/GCI alliance holds the key objective of “establishing Green Chemistry as a national research priority by aligning the interests of policymakers, business leaders, and the scientific community in new initiatives” (Hjeresen et al. 2000). The incorporation of green chemistry practices into industrial settings can be attributed to a few key factors. First, there is growing consideration that chemists who are knowledgeable about pollution-prevention concepts are able to reduce pollution and *costs* for firms. This additional cost incentive will be further discussed in chapter 4 along with other

economic and ethical considerations. Furthermore, the development of dedicated fellowships, scholarships, and research grants in green chemistry has helped boost interest, along with workshops, seminars, and conferences (Hjeresen et al. 2000).

The creation of the annual Presidential Green Chemistry Challenge Awards in 1996 highlighted major academic and industrial successes in the field of green chemistry (Anastas 2009). In the academic sphere, a major success was the first university course offering dedicated entirely to the subject of green chemistry. Beginning in 1992, Professor Terry Collins at Carnegie Mellon University taught the course to graduate students, along with advanced undergraduate students. The course included objectives as straightforward as understanding the history and founding principles of green chemistry, but also its broader implications such as identifying “reagents, reactions, and technologies that should be and realistically could be targeted for replacement by green alternatives” and understanding the “history, meaning, and importance of persistent bioaccumulative pollutants and endocrine disruptors which present major environmental and health threats” (Anastas 2009). A course like this proposes an ideal opportunity for “real world” learning. Fundamental concepts such as bond-dissociation energy can be taught in the context of ozone depletion, flame retardants, and bleaching technologies. Similarly, substitution and elimination reactions can be discussed in the context of the “persistence of organochlorine pollutants in the environment,” as discussed more extensively in chapter 2 (Anastas 2009). A positive note for the future is that courses like this one are growing in popularity and demand. Furthermore, green chemistry topics resonate more with students, for some even to the degree of pursuing a major in chemistry when they otherwise would not. This resonance could even contribute to the improvement of gender and racial diversity in STEM programs (Anastas 2009).

Furthermore, the University of Oregon is largely responsible for pioneering the green chemistry curriculum for the teaching laboratory in the mid-1990s (Anastas 2009). This effort resulted in the publication of a laboratory manual titled *Green Organic Chemistry: Strategies, Tools, and Laboratory Experiments*. This manual was transformative in that it redesigned traditional organic chemistry experiments, teaching the fundamentals of organic chemistry in the context of green chemistry. The desire to use fewer fume hoods, less toxic solvents, and to phase out microscale lab equipment were the primary motivating factors for this curriculum, and its success in each of those areas makes chemistry more accessible to community colleges and K-12 institutions (Anastas 2009).

Since its founding in 1996, the Green Chemistry Challenge Awards have seen major success. According to the EPA website about the challenge, in the past 25 years there have been 128 winning technologies which have eliminated 830 million pounds of hazardous chemicals and solvents, saved 21 billion gallons of water each year, and eliminated 7.8 billion billion pounds of carbon dioxide equivalents from being released into the atmosphere. While these amounts might be difficult to conceptualize, the EPA offers examples to aid your understanding. Eight hundred thirty million pounds of hazardous chemicals and solvents would be enough to fill a train nearly 47 miles long, 21 billion gallons of water is equivalent to the amount used by 980,000 people annually, and 7.8 billion pounds of carbon dioxide eliminated is equivalent to taking 770,000 automobiles off the road (EPA⁷).

There are several examples of green chemistry in practice; in this paper, I will discuss a few major ones. To begin, solvents are often culprits of hazardous waste. Green chemistry introduces green solvents, which are less harmful to the environment and to human health, more sustainable, derived from renewable sources, and ideally biodegrade to innocuous substances.

Green chemistry particularly emphasizes environmental neutrality “from cradle to grave” (or to cradle if recyclable), examining the whole life cycle (Abraham 2017). Determining the greenest solvent depends entirely on the solute and specific application. Water is commonly regarded as the “universal solvent,” due to its distinct polarity which allows it to dissolve an abundance of chemicals and consumer products (USGS n.d.). However, for many organic products, such as the polymer polytetrafluoroethylene, supercritical carbon dioxide has been declared the greenest solvent due to the fact that it does not require any surfactants (Jessop 2017).

In addition, the development of greener synthetic techniques has been a large focus of scientific research in the past five decades. In 2005, the Nobel Prize in chemistry was awarded to three chemists for “the development of the metathesis method in organic synthesis” (The Nobel Prize Foundation 2005). Their names were Yves Chauvin, Robert H. Grubbs, and Richard R. Schrock, and their work took place over the span of 20 years. In 1971, Chauvin outlined a detailed reaction mechanism for metatheses reactions and what metal compounds could function as catalysts. Schrock built on that foundation and produced an efficient metal-compound catalyst in 1990. Shortly thereafter, in 1992, Grubbs improved the catalyst, developing one that was stable in air. These developments were particularly important considering the abundance of applications that use metathesis, such as the development of pharmaceuticals and advanced plastic materials (The Nobel Prize Foundation 2005). The Nobel Prize organization highlights three major accomplishments of this synthetic method, that it is: “more efficient, simpler to use, and environmentally friendlier” (The Nobel Prize Foundation 2005).

More recently, the 2021 Nobel Prize in Chemistry was awarded to Benjamin List and David MacMillan for the development of organocatalysis, which has “had a great impact on pharmaceutical research, and has made chemistry greener” (The Nobel Prize Foundation 2021).

It was previously thought that catalysts could be one of two categories: metals or enzymes. However, in 2000, List and MacMillan each developed a third type of catalysis, asymmetric organocatalysis, which utilized small organic molecules (SOMs). Essentially, these organic catalysts are composed of a stable framework of carbon atoms. In turn, more active compounds, such as oxygen, nitrogen, sulfur, or phosphorus, can attach to this framework. Not only are these catalysts environmentally friendly, but they are also cheap to produce—a commonly occurring theme that will be discussed further in the following chapter (The Nobel Prize Foundation 2021). The work done by List and Fuller led a generation of further organocatalysis research and development.

While most of the literature focuses on green chemistry's successful adaptation and development in an academic setting, particularly in the research laboratory, there have been many success stories in industry as well. In 2021, one of the Green Chemistry Challenge Awards went to XploSafe, a company that provides “critical safety solutions for homeland security and chemical safety,” creating safe environments through chemical detection and neutralization (XploSafe 2021). In 2021, the small business was awarded for their creation of PhosRox, a novel sorbent. According to the EPA site on the award, PhosRox is a “single material uniquely capable of simultaneously capturing ammonia, phosphate, and nitrate from wastewater and other contaminated waters,” in addition to being used as a time-release fertilizer (EPA⁸).

This material is a promising technology to combat the widespread and costly issue of eutrophication. Eutrophication is the process of uncontrolled algae growth in bodies of water that harms ecosystems by decreasing levels of dissolved oxygen, which has negative effects on both the habitat and human health when they consume contaminated fish or water. XploSafe's new material, PhosRox, not only removes ammonia, phosphate, and nitrate from aquatic ecosystems,

but goes many steps further. First, the granules that PhosRox turns into when it removes those compounds can be used as a fertilizer. Even the process of manufacturing the material is thoughtful—the formation of its precursor gel results in byproduct aqueous potassium nitrate which can be used to make quick-release fertilizers with “minimal additional energy input” (EPA⁸). The recycling of nutrients in this technology lowers cost and provides utility advantages over industry-standard treatment solutions. Further down the line, the material has the potential to “enhance the nutrient-holding capacity of the soil, preventing fertilizer runoff and protecting the watershed” (EPA⁸).

For the design of greener chemicals, Colonial Chemical Inc. won the award for their development of Suga®Boost, which are surfactant blends that use more environmentally friendly chemicals than their traditional counterparts. These cleaning supplies “consume less energy to create, are biodegradable, and are derived from plant-based materials, with performance that demonstrates potential to replace EO-containing surfactants such as SLES and APEs” (CCI 2021). Traditional cleaners use surfactants derived from petroleum-based raw materials and cause manufacturers to face high environmental toxicity and high-energy processes. APEs, alkylphenol ethoxylates, are often found in cleaners and have been classified by the EPA as toxic to aquatic habitats and able to induce endocrine disruption in organisms. Their toxicity to aquatic life is exacerbated by bioaccumulation in mollusks, soils, and sediments (EPA⁹). The new surfactants are made up of blends of functionalized alkyl polyglucosides, and only require water as a solvent during their preparation and cleanup, a major triumph. This new development opens the door for new wipe products, disinfecting cleaners, dish washing, carpet cleaning, and fabric care; thus making the cleaning industry more sustainable with its new chemicals and their underlying chemistry (EPA⁹).

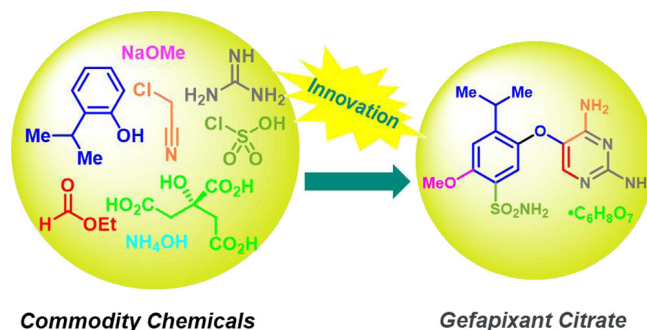


Figure 3. The greener synthesis of gefapixant citrate from commodity chemicals (Ren et al. 2020).

Another industrial success was the development of a green commercial manufacturing process for gefapixant citrate, a medicine that has been shown to treat refractory and unexplained chronic cough. This greener synthetic pathway for manufacturing gefapixant reduces both costs and waste, which could make major strides in facilitating its worldwide access (EPA¹⁰). This new synthetic pathway was developed by biopharmaceutical company Merck & Co., Inc.’s research and development team to combat the high process mass intensity (PMI) of gefapixant, which is essentially a measure to describe its process efficiency for biopharmaceutical production. While its initial PMI was 366, Merck’s improved process brought that number down to 88. The four key innovations are described as follows: “(1) the implementation of a highly efficient two-step methoxyphenol synthesis; (2) an innovative diaminopyrimidine synthesis using a hybrid flow-batch process; (3) a simplified direct sulfonamide synthesis; and (4) a novel and robust salt metathesis approach to consistently deliver the correct salt form with high productivity” (Ren et al. 2020). These innovations led to greater product yield and a six-fold reduction in raw material costs, in addition to reducing the use of highly hazardous chemicals and reducing carbon dioxide and carbon monoxide emissions.

It is clear to see in these examples that green chemistry has already led the scientific community in a progressive direction towards sustainability. Whether it be the development of

greener solvents, Nobel Prize winning metathesis reactions and organocatalysts, a small business developing new materials, chemical industry's creation of environmentally friendly cleaning supplies, or a major biopharmaceutical company's improvement of commercial manufacturing processes, the principles of green chemistry can be seen and applied in every facet of life. Therefore, its future impact and contributions are simply a matter of time.

Chapter 4. Ethics & Economics

Ethics. Discussion of hazardous waste and pollution would be incomplete without the inclusion of ethics. It has become clear, very much so in recent years, that environmental hazards, including those discussed in the first chapter, are not distributed equally amongst all groups of people. There are so many ways that racism, sexism, and classism intersect with environmental degradation, exploitation, and harm. Incinerators and toxic chemical plants are found in neighborhoods across the country, along with disposed plastic, glass, and electronic waste (Harris 2013). "The grim reality," as author Harris acutely describes "is exacerbated by the fact that environmental hazards disproportionately affect poor communities, communities of color, and other marginalized communities" (Harris 2013). This disproportionality has been termed environmental inequality, environmental racism, and environmental injustice. The response to this uneven nature of exposure to environmental hazards is called environmental justice, and believes the notion that "all people and communities are entitled to equal protection of environmental health laws and regulations" (Bullard 1996).

One famous example of environmental injustice was highlighted in a 2016 *New York Times* article, "The Lawyer Who Became DuPont's Worst Nightmare," later adapted as a film titled *Dark Waters* in 2019. The article describes a long history of pollution in a local community

by the chemical manufacturing company DuPont. The pollutant was unregulated and documentation of it by DuPont was largely kept private, until legal action was taken. PFOA, or perfluorooctanoic acid, was used by DuPont for manufacturing of Teflon. Since the government did not classify it as a hazardous substance, there were no strict guidelines for its disposal. Instead, the company that invented and sold the chemical, 3M, sent recommendations on how to dispose of it: “it was to be incinerated or sent to chemical-waste facilities” (Rich 2016). However, DuPont ignored these recommendations and flushed thousands of pounds of PFOA powder through the pipes into the Ohio River, and dumped 7,100 additional tons of PFOA-laced waste into “digestion ponds” which are simply pits in the ground that permit the waste to seep into the ground (Rich 2016). As a result, the chemical polluted the drinking water of over 100,000 residents living in the Parkersburg, Vienna, Little Hocking and Lubeck communities (Rich 2016).

To make matters worse, medical studies conducted by 3M and DuPont had found PFOA to have biological effects on rats and rabbits, including cancerous tumors. Blood tests indicated high levels of PFOA in DuPont employees at the Washington Works location, but the company still refrained from alerting the EPA. Later on, DuPont established an internal safety limit for PFOA in drinking water to be one part per billion, which was only one-third of the concentration found in a nearby local district; yet they still chose to withhold this information from the public or authorities. Eventually, the information came to light and the work of lawyer Bilott resulted in a large-scale medical study which proved links between PFOA ingestion and illness, and thousands of personal-injury lawsuits. When reflecting on the case, Bilott remarked, “I think about the clients who have been waiting for this, many of whom are sick or have died while waiting. It’s infuriating” (Rich 2016). Furthermore, there are 60,000 unregulated chemicals that

could be unknowingly causing similar harm to human health and the environment (Rich 2016). Unfortunately, cases of injustice like these are not as rare as one might hope. Although this example of environmental injustice deals with industry, lines are often blurry between academia and industry. For example, DuPont is known to collaborate closely with academic research laboratories, and particularly did so during the chemical revolution when new synthetic materials were being discovered (*Powerbase* 2008). And, at least some of the PFOA waste would have been initially generated in research labs.

There are three types of speculated causes of environmental injustice: economic explanations, socio-political explanations, and racial discrimination (Harris 2013). The economic explanation does not assign the blame to outright discrimination, but instead states that industry firms are motivated by maximizing profit. Thus, they place hazardous waste sites and facilities in areas with cheap land and available labor pools (Harris 2013). In turn, members of the community with the financial ability to move away do so, and those with insufficient finances remain (Harris 2013). In addition, there is the idea that modernization drives a cycle in which new wealth is generated from invention, but this comes with negative byproducts. Industries dedicate much of their resources to research and development, often without knowing the risks of new technologies. In doing so, the negative byproducts and risks affect marginalized communities the most (Harris 2013).

Socio-political reasons also exist that could potentially explain this environmental inequality. For example, it is possible that industries and corporations choose “the path of least resistance” (Harris 2013). If they were to place a hazardous facility in an affluent neighborhood, it is very likely the community would have both the resources and social capital to fight back. On the other hand, marginalized communities, generally lower-income and communities of color,

lack such resources and would produce minimal resistance (Harris 2013). While industries, corporations, and other special interest groups are highly involved in policy-making and urban planning, marginalized communities are often excluded from such processes (Harris 2013). Two examples of the negative effect of the invisibility of marginalized communities in mainstream environmental movements were demonstrated by researchers Szasz and Pellow (Harris 2013). Szasz showed that the mainstream environmental movement's negotiation of anti-pollution laws resulted in "the shift of certain industries and toxics into low income and minority communities," exacerbating the issue (Harris 2013). Similarly, Pellow demonstrated that globally, hazardous waste production was shifted to the global South partly because of regulations supported by the mainstream environmental movement (Harris 2013). Both of these examples, as well as the "path of least resistance" explanation, illustrate the socio-political considerations involved in environmental injustice.

Finally, environmental inequality is regarded by many scholars as an issue of institutional racial discrimination. This explanation is embedded within both the economic and socio-political explanations. There is abundant evidence of racial divides in environmental policy-making (Bullard 2000). Racial disparities also pervade many other U.S. institutional issues such as education, health care, and criminal justice (Harris 2013). However, it remains difficult to pinpoint or measure particular acts of racism and discrimination, as racism "is not a specific thing whose effects can be neatly isolated or extracted from social life" (Harris 2013).

In addition to breaking down Harris's three speculated causes of environmental injustice, Dr. Robert Bullard, often referred to as the father of environmental justice, points out the prevalence of environmental injustices in our society and considers how to best address these injustices going forward in his paper "Decision Making." Bullard describes three types of equity

and how unequal environmental protection undermines them. Going forward, Bullard introduces five principles for environmental justice to guide future policies and decision-making, in hopes of achieving a more equitable and just world.

The three types of equity are procedural, geographic, and social. First, procedural equity refers to the extent to which governing rules and enforcement are applied in a nondiscriminatory manner—essentially fairness (Bullard 1998). Next, geographic equity encompasses the fairness of the siting of environmental hazards in proximity to certain communities (Bullard 1998). Finally, social equity refers to the role of sociological factors in environmental decision making (Bullard 1998). Bullard declares that environmental injustices go against each of these types of equity. Procedural equity is undermined by the fact that communities of color are not given equal environmental protection, geographic equity is undermined by the unequal and disproportionate placement of environmental hazards, and social equity is undermined by the targeting of poor and non-white communities for environmental harms because they are poor and non-white. For example, Catherine Salvin in the Yale National Initiative describes how not only do communities of color shoulder a disproportionate burden of toxic hazardous waste, but “their right to protection is enforced in a similarly inequitable manner” (Salvin). This is seen in the fact that fines are five-hundred percent higher in predominantly white communities compared to communities of color and the fact that being listed on the EPA’s National Priority List takes twenty percent longer for a community of color with severe hazardous waste issues than for an abandoned site in a predominantly white community, and an additional forty-two percent longer to be cleaned up after being listed (Salvin).

In order to combat these inequities, Bullard introduces five principles for environmental justice: the right to protection, prevention of harm, shifting the burden of proof, obviating proof

of intent to discriminate, and targeting resources to redress inequities (Bullard 1998). Notably, Bullard declares that environmental justice requires a legislative foundation, and suggests enacting a federal “fair environmental protection act” (Bullard 1998). Bullard believes this act could be modeled after previous landmark civil rights legislation and would accomplish making environmental discrimination *illegal* and *costly* (Bullard 1998). The legislation would follow his five principles of environmental justice, including measures to emphasize the importance of preventing harms before they occur, shift the burden of proof to the polluters, allow disparate impact and statistical weight to determine if an act was discriminatory, and dedicate more resources to places where environmental and health problems are greatest. This idea for legislation will be addressed further in chapter 5.

The environmental justice movement has progressed to a large, interdisciplinary cause with a vision of 4 main points: “(1) all people have the right to protection from environmental harm; (2) environmental threats should be eliminated before there are adverse human health consequences; (3) corporations, not communities, should be responsible for proving that a given industrial procedure is safe for people and the environment; and (4) grassroots organizations should challenge environmental inequality through political action” (Harris 2013). The environmental justice movement is doing important work to address the unequal harms of waste and pollution, and coincides nicely with the movement to make scientific research more sustainable (green chemistry). One way to reduce these social injustices is to reduce, or eliminate, the production of waste.

An article in a 2019 volume of Taylor & Francis “Green Chemistry Letters and Reviews” explores this intersection of green chemistry and environmental justice. Authors Lasker and Brush recognize how the twelve principles of green chemistry “shift accountability toward

environmental impact consideration,” but note that ultimately only one of the principles directly considers human health (Lasker & Brush 2019). Because of this, they argue that more needs to be done to raise awareness of the disproportionate impact of chemicals on disadvantaged communities, namely communities of color or those of lower socioeconomic status. Lasker and Brush declare that “It is implicit that green and sustainable chemistry contributes to social equity and environmental justice because these innovative technologies have excellent potential to offer solutions to achieve equity” (Lasker & Brush 2019). Furthermore, they believe this interconnected mission complements the ACS Mission Statement to ‘advance the broader chemistry enterprise and its practitioners for the benefit of Earth and its people’ (American Chemical Society). Thus, green chemistry and its advancement of environmental justice should be embraced by ACS and the broader community of chemistry. The authors of this article recommend these principles be instilled into chemists beginning in their education, which will be discussed further in chapter 5 as a policy recommendation.

The importance of interdisciplinary conversation on the topic of chemistry and environmental justice was recognized in June 2016 at the 20th Green Chemistry and Engineering Conference, and has grown in popularity since. Their mission was, and remains, to “begin exploring the racial and socioeconomic disparities in how hazardous chemicals impact society” (Lasker & Brush 2019). Chemistry professionals join this conference with a variety of backgrounds and interests, including science, education, and business perspectives. The range of professional fields that connect to the topic is wide ranging—public health, toxicology, occupational health, policy, government, engineering, and industry all have considerations in the discussion. One particular note from these discussions is that they never conclude that chemicals are all bad. They recognize the good that chemistry has done, but do not turn a blind eye to the

bad. Instead, they recognize the injustices that have resulted from the practice of chemistry and hope to invigorate a new generation of scientists and thinkers to discover, innovate, and design new, more sustainable, chemistry.

Economics. In discussions about sustainability and renewable technologies, there exists a pervasive myth that sustainability is “too expensive,” thus environmental protection must be sacrificed for economic profitability (Adam et al. 2020). However, when examining the feat of making scientific laboratories more sustainable by implementing green chemistry, the opposite seems to be true. The goals of green chemistry align with the current goal for a waste-free, circular economy (Sheldon 2016). This type of economy differs from the linear “take-make-use-dispose” economy which is extremely inefficient (Sheldon 2016). The reason that the push for a circular economy has not progressed faster is because economic assessments fail to accurately measure costs of the linear economy. True costs must include the costs of resource use/depletion and the costs of waste management and environmental pollution, which are usually externalized and thus not considered (Sheldon 2016).

The field of environmental economics is doing substantial work to create models that internalize these costs, but it is far from an exact science. There is a lot of debate over how to estimate environmental costs, regarding what, or who, is included and that value. The issue is compounded by the fact that there are numerous benefits provided by environmental protection, but they are both nonexcludable and nonrival so there is even less incentive for private groups to contribute to the costs (Conte 2013). As noted by environmental economist and professor Marc Conte, “those asked to forgo private returns in order to ensure increased social benefits will tend to challenge the implementation of such regulation” (Conte 2013). Therefore, in order to accurately quantify the welfare implications of environmental policies, one must have “an

understanding of how ecosystem function is affected by human activity, how these effects alter the provision of [ecosystem services], and how this change in provision affects social welfare” (Conte 2013).

To begin the process of quantification, one must determine the philosophical approach they wish to use. The anthropocentric approach assigns value to ecosystem services on the basis of bringing satisfaction to humans, and its total value is measured as a sum of use and nonuse values (Conte 2013). In the market for conserved habitats, government regulation is necessary to achieve the efficient outcome. This is because of the external costs previously mentioned. In the absence of regulation, private firms will solely consider their own costs and benefits. However, these externalities cause a gap between the private cost and total cost, which includes social costs (Conte 2013). In addition, the same piece of habitat can provide several ecosystem services, so one must consider all of these in a valuation of the land. For non-market goods, such as some ecosystem services, there are two methods to determine demand: revealed preference and stated preference. In revealed preference methods, observed behavior and information from other markets are used to estimate the demand for a non-market good. Two main methods of revealed-preference are the travel cost method and hedonic valuation. On the other hand, stated-preference methods rely on individuals stating their behavior in a hypothetical setting “to identify the value placed on the nonmarket good of interest” (Conte 2013). Specific types of stated-preference methods include conjoint analysis, choice experiments, and the most common, contingent valuation which employs a survey to determine an individual’s stated willingness to pay for a good or willingness to accept a reduction in the good (Conte 2013). These methods allow for economic models that bridge the gap between private cost and total cost, thus allowing for more socially efficient outcomes by promoting habitat conservation.

Several publications have advocated that aspects of green chemistry are economically beneficial. For example, catalysis is one of the foundational pillars of green chemistry, as discussed in chapter three. Researchers Anastas, Kirchoff, and Williamson found that “industry is adopting green chemistry methodologies because they improve the corporate bottom line” (Anastas et al. 2001). It accomplishes this by decreasing operating costs, including those associated with environmental compliance, materials, and energy (Anastas et al. 2001). Environmental compliance can be very costly, as discovered by one environmental services company when it was fined \$790,000 after failing to contain hazardous wastes (Espinoza 2020). A 2020 publication similarly found that green chemistry was “a way of the firm to increase efficiency and reduce the costs of production,” thus making it “an opportunity for businesses to lighten their environmental burdens and make money” (Adam et al. 2020). The implementation of green chemistry not only reduces investment in waste storage and treatment, but also presents the possibility of compensation payments for environmental damage (Adam et al. 2020). Although these publications focus on industry, it can be inferred that adopting green chemistry in scientific laboratories would have similar results since laboratories face many of the same costs. In fact, one scientist found that implementing ecological awareness saved up to 40% of his research funding in one year (Bistulfi 2013). Thus, green chemistry not only has beneficial environmental impacts, but also addresses environmental ethics and economics.

Chapter 5. Powerful Policymakers

The findings of this paper call for action through updated policy. Since the use of disposables and hazardous materials in laboratories is often justified by saving time and money, we must introduce new frameworks for cost analysis and provide incentives for greener

laboratory practices. There is clear anecdotal evidence that more sustainable laboratory practices can save money, but more substantial research and quantitative data would greatly benefit this cause. Implementation of green chemistry in laboratories, backed by a new outlook on hazardous chemical risk assessment, would pave the way for a greener future of scientific research. Overall, new policies should include a focus on three main areas: revised risk assessment strategy, education, and scientific research funding.

Risk Assessment Analysis. In chapter 2 I provided detail regarding the accumulation of synthetic chemicals in the human body and in the environment, focusing on Thornton's work. Part of Thornton's purpose is to critique the Risk Paradigm, which encompasses the dominant models of environmental science and policy. Since the 1970s, a plethora of laws and regulations regarding chemical waste have been implemented—all overwhelmingly based on chemical-by-chemical assessments, discharge limits, and pollution control technology as discussed in chapter 2. However, analysis of the effectiveness of these policies has demonstrated their incompetence. An analysis by the Center for the Biology of Natural Systems concluded that such laws have reduced discharges from individual facilities to individual environmental media, but ultimately “environmental levels of the major substances regulated by this approach have not declined substantially; some have actually increased” (Thornton 2000). Thus, Thornton argues that the previous paradigm failed in its facilitation of environmental harm, thus a new model for environmental policy is needed.

Thornton introduces the Ecological Paradigm as a new, competitive model built on the foundation that ecosystems, organisms, and societies are “complex and dynamic systems in which innumerable parts are connected in webs of interdependency, multiple causality, and feedback loops, all of which change over time” (Thornton 2000). The new, preventive paradigm

seeks to protect these complex systems from the harms of toxic chemicals. Such a paradigm would greatly encourage, and even facilitate, a nationwide implementation of the principles of green chemistry.

The Ecological Paradigm informs policy as guided by the *precautionary principle*, which states that in situations where the potential impacts of a mistake are “serious, widespread, irreversible, and incompletely understood,” we must err on the side of caution (Thornton 2000). Following this principle, the Ecological Paradigm introduces three policy suggestions: Reverse Onus, Zero Discharge, and Clean Production.

Reverse Onus is a policy suggestion that would shift the default state of environmental regulation from *permission* to *restriction*, which would also address many issues regarding the intersection of chemistry and environmental justice. (Thornton 2000). For example, this would include shifting the burden of proof. As discussed in the previous chapter, the burden of proof now rests within societies such that an impacted community must prove that they are being harmed by a certain chemical. Shifting the burden of proof is a policy advocated by Bullard and many others in the environmental justice community. Instead, they argue that the burden of proof should be shouldered by the producers of the hazardous waste. If enacted, these parties would have to “demonstrate in advance that their actions are not likely to pose a significant hazard” to the environment or human health (Thornton 2000). In addition, any current chemicals that do not meet such criteria would be required to be phased out with safer alternatives that do meet the criteria. Shifting the burden of proof has twofold beneficial outcomes. Firstly, it would achieve a greater degree of fairness. As highlighted in the environmental ethics section, current practices that put the burden of proof on affected communities are grossly unfair and unjust. By shifting the burden of proof, those responsible for the pollution would be responsible for proving that the

pollution has no harmful effects as they so claim. Secondly, shifting this burden would undoubtedly lead to a decrease in toxic pollution because producers of chemical waste would be required to comprehensively assess the toxicity of their products and processes. This would encourage a shift to practicing green chemistry.

In action, Zero Discharge would effectively eliminate, rather than permit, the release of synthetic chemicals into the environment. This policy would target manufacturers and users of synthetic substances that are persistent or bioaccumulative to further prevent issues related to their presence or biomagnification in ecosystems. The International Joint Commission defined zero discharge as “halting all inputs from all human sources and pathways to prevent any opportunity for persistent toxic substances to enter the environment as a result of human activity” (Thornton 2000). This idea was first articulated in the Great Lakes Water Quality Agreement of 1978 and later adopted in other international agreements. A zero discharge policy is founded on the fact that persistent substances are inherently incompatible with nature’s ecosystems. This is because they defy ecosystem services that facilitate natural degradation or recycling. Previous discussion regarding pollution focuses on chemicals that are persistent and bioaccumulative, but this policy targets chemicals that are either or both, recognizing that bioaccumulation is essentially a troublesome form of persistence.

Finally, Clean Production is a policy that would emphasize front-end solutions, like the principles of green chemistry describe. Examples of front-end solutions include the redesign of products and processes that cause hazardous waste, like the third and fourth principles of green chemistry. This way, hazardous waste is being eliminated from the source, not as an afterthought. This concept was first described in 1989 by the United Nations Environmental Program as “a conceptual and procedural approach to production that demands that all phases of the life-cycle

of a product or of a process should be addressed with the objective of prevention or minimization of short- and long-term risks to human health and to the environment” (Jackson 1993). There are a number of current laws that follow this idea. For example, the Massachusetts Toxics Use Reduction Act aims for a fifty percent reduction in toxic waste generation. It accomplishes this by requiring reduction plans from industry, providing technical assistance, and sponsoring research and development for less harmful alternatives. A stricter law that follows this policy is found in the Swedish Chemicals Action Program which requires, by law, the substitution principle—the least toxic available product or process must be used (Thornton 2000).

These three policy foundations—Reverse Onus, Zero Discharge, and Clean Production—reflect and encourage the principles of green chemistry in order to achieve a greener and more equitable world. Implementation of these principles in firm policies would by nature require the adoption of green chemistry in laboratories. Thornton’s policy foundations can, and should, be enacted through amendments to existing laws or the passing of new legislation.

Education. A second area for policy is in education. I suggest a new policy that requires an introduction to green chemistry in education. To begin, I believe that all chemistry majors and minors be introduced to the field in their undergraduate courses, whether that be a required course dedicated to green chemistry, or an incorporation of green chemistry in general chemistry and organic chemistry lecture and laboratory courses. Based on the success of this requirement I believe that green chemistry could eventually be integrated into secondary education curriculum.

The American Chemical Society’s *Journal of Chemical Education* has addressed the issue of harmful scientific research and potential solutions in a featured article called “Approaches to Incorporating Green Chemistry and Safety into Laboratory Culture” by authors O’Neil, Scott, Relph, and Ponnusamy. The authors postulate that chemists have an important role

in the future of sustainability because they work at the “molecular level of solutions to our global challenges” (O’Neil et al. 2021). Thus, they must be trained with the proper skills and culture by learning and adopting green chemistry “to intentionally solve problems with human health and the environment in mind and to examine their chemistry through the lens of safety and sustainability” (O’Neil et al. 2021).

Introducing scientists to this mindset early on in their careers has the potential to influence a new generation of green scientific thinkers. While traditional chemical education has focused primarily, if not entirely, on technical performance, green chemistry presents a unique opportunity to rethink our priorities. As described by lead thinker in the field of green chemistry Paul Anastas, “elegance in synthesis or chemical processes is rarely described in terms of atom economy, step economy, hazard, amount of waste generated, feedstock use, or other impacts of the chemistry beyond the effects on the yield and purity of the target product” (Anastas 2009). However, risks and hazards need not be accepted as being “simply part of the nature of the profession” of chemistry (Anastas 2009). Instead, if we shift our focus away from the end products and towards the processes that produce them, we find immense opportunity to make chemical education both safer and greener.

Many of the principles overlap with safety considerations, but the most notable is principle 12, safer chemistry for accident prevention, as discussed in chapter 3. Since this principle cannot be successfully achieved without the previous 11 principles, there is an intrinsic link between safety and green chemistry. Because of this, “the American Chemical Society Committee on Chemical Safety suggests that all undergraduate chemistry program students from first to fourth year students should be exposed to the topic” (O’Neil et al. 2021). One safety initiative that demonstrates this concept is the RAMP methodology, which advises individuals to

Recognize hazards, Assess the risks of the hazard, Minimize the risk of the hazard, and Prepare for emergencies (O’Neil et al. 2021).

A good starting place to introduce green chemistry to students is in the organic chemistry laboratory course in undergraduate studies. According to the ACS article, some schools have already incorporated this into their curriculum, and signed on to the Green Chemistry Commitment where they “pledged to implement Green Chemistry Student Learning Objectives in their curriculum” (O’Neil et al. 2021). Three organizations, Beyond Benign, My Green Lab, and MilliporeSigma, have partnered together and created a Guide to Green Chemistry Experiments for Undergraduate Organic Chemistry Laboratories for reference, which includes more sustainable renditions of common organic chemistry experiments (O’Neil et al. 2021). One critical aspect of this curriculum is that it introduces students to metrics that are used to characterize how “green” a chemical reagent or process is, including the e-factor and atom economy as well as DOZN 2.0, which addresses the recognition and assessment of the risks of hazards in chemical reactions (O’Neil et al. 2021). Overall, it would be greatly beneficial to the future of scientific research if the link between green chemistry and safety is recognized and policies are enacted to introduce students to green chemistry in their undergraduate curricula.

Furthermore, incorporating green chemistry into chemistry curricula facilitates opportunities to address equity and social justice through the lens of chemistry—making students explicitly aware of the connection between the two. As stated by Lasker and Brush, environmental justice “provides a framework for teaching and investigating chemistry as solutions to inequitable health and environmental impacts due to chemical exposure that can be mitigated through green chemistry principles that influence the design, manufacturing, and use of products with an emphasis in considering human and environmental health” (Lasker & Brush

2019). This type of interdisciplinary incorporation has also been shown to improve student engagement and retention, particularly for women and students of color, in addition to helping them develop leadership skills. When studying concepts of social justice and civic engagement in major level courses, students are able to frame such leadership skills within the context of their individual field, strengthening their educational experience (Lasker & Brush 2019).

Research Funding. A final suggestion is enacting a policy that requires some aspect of green chemistry in grant applications or introducing more funding opportunities for research in green chemistry. According to researchers Urbina, Watts, and Reardon, who quantified their production of plastic waste as discussed in chapter 1, the use of plastic waste is justified “on the grounds of costs and time saved” (Urbina et al. 2015). Because of this, they suggest that grant agencies introduce incentives to reduce plastic waste, which could be financial or help facilitate the transition to reusable materials. This could include lab washing-up facilities and recycling facilities (Urbina et al. 2015).

Similarly, much scientific research has been optimized with plastic materials, so switching to glass could pose logistical challenges. For example, research involving cell cultures uses broth reagents that were developed for plastic petri dishes. Cells, as researcher Kuntin describes, are aware of their environment and “can sense things like the roughness or stiffness of the surface they grow on” (Bell 2019). Thus, if a laboratory started using glass dishware in the middle of a long-term project, “unexpected changes in behavior could be misinterpreted as a consequence of an experiment,” instead of simply “the cells behaving differently on glass” (Bell 2019). This suggests that comprehensive research must be conducted on this transition, which could be costly, requiring outside funding.

Reusing glass also poses potential time and energy problems, which in turn costs universities money. It is unclear whether these costs would ultimately outweigh potential savings from new research methods, or end with a net gain. This is why updated, comprehensive economic analyses are needed, as discussed above. Furthermore, these analyses could prove the need for research subsidies. Researcher Lewis commented on this consideration, saying “We could do a whole-life costing exercise, and it may well be that plastics are so much cheaper... In which case, we would need subsidies” (Bell 2019). Ultimately, Lewis concludes that any real change toward improving the sustainability of scientific laboratories would require a change in how science is funded. He suggests that universities would likely need to demonstrate “some level of sustainability” in order to receive these specific grants (Bell 2019).

There are many sustainability research grants already in existence. For example, the EPA offers annual P3 awards, which is a national student design competition “focusing on people, prosperity, and the planet” (EPA¹¹). According to the program description, “P3 aims to foster progress towards environmental awareness by achieving the symbiotic goals of improved quality of life for all people, economic prosperity, and protection of the planet - people, prosperity and the planet” (EPA¹²).

One of the specific grant awards within this program in 2020 was conducted by students at the University of South Carolina at Columbia, and focused on “Green plasma technology for siloxane removal and landfill gas upgrade” (Hoque et al. 2020). Their project examined sustainable and cost-efficient methods of volatile methyl siloxane removal through the design of a non-thermal plasma system, CLnERG (Clean, Renewed, upgraded LFG) (Hoque et al. 2020). Another project, titled “Planet-friendly and scalable approach towards 100% recyclable water- and oil-resistant paper,” addressed the issue of widespread plastic use by developing water- and

grease-resistant paper. Generally water-resistant paper achieves its characteristics by being coated in fluorinated chemicals, which are toxic. The research group from Michigan State University used low-cost biobased materials with silicon oil, in particular blends of polyvinyl alcohol and chitosan-graft-polydimethylsiloxane copolymer (Nair et al. 2021). These are just two examples of sustainability projects that would likely not be possible without grant-funding. Taking previous chapters into consideration, it is important that grant agencies seek out and encourage sustainable projects in order to make scientific laboratories greener.

Bibliography

- Abraham, Martin. 2017. *Encyclopedia of Sustainable Technologies*. North Holland: Elsevier.
- Adam, Dini Hariyati, Elvina, Mila Nirmalasari Hasibuan, Rizki Syahputra, Laili Habibah Pasaribu, and Suriyani. 2020. "Green Chemistry: The Economic Impact Perspective." *International Journal of Scientific & Technology Research*. ijstr.org, April 2020.
<https://www.ijstr.org/final-print/apr2020/Green-Chemistry-The-Economic-Impact-Perspective.pdf>
- American Chemical Society. *ACS Vision & Mission*.
<https://www.acs.org/content/acs/en/sustainability/acsandsustainability/visionandmessages.html>
- American Chemical Society. n.d. "Green Chemistry History." American Chemical Society. American Chemical Society. Accessed October 4, 2021.
<https://www.acs.org/content/acs/en/greenchemistry/what-is-green-chemistry/history-of-green-chemistry.html>.
- Anastas, Paul T., Mary M. Kirchhoff, and Tracy C. Williamson. 2001. "Catalysis as a Foundational Pillar of Green Chemistry." *Applied Catalysis A: General* 221, no. 1-2 (November 30, 2001): 3–13.
[https://doi.org/10.1016/S0926-860X\(01\)00793-1](https://doi.org/10.1016/S0926-860X(01)00793-1).
- Ashbrook, P. C, and P. A. Reinhardt. 1985. "Hazardous Waste in Academia." *Environmental Science and Technology* 19:1150—1155.
- Barth, Edwin F. 1990. "An Overview of the History, Present Status, and Future Direction of Solidification/Stabilization Technologies for Hazardous Waste Treatment." *Journal of Hazardous Materials* 24, no. 2-3: 103–9. [https://doi.org/10.1016/0304-3894\(90\)87002-y](https://doi.org/10.1016/0304-3894(90)87002-y).
- "Basics of Green Chemistry." EPA⁶. Environmental Protection Agency. Accessed November 3, 2021.
<https://www.epa.gov/greenchemistry/basics-green-chemistry#definition>.
- Bell, Alice. 2019. "Can Laboratories Curb Their Addiction to Plastic?" *The Guardian*. Guardian News and Media, November 10, 2019.
<https://www.theguardian.com/environment/2019/nov/10/research-labs-plastic-waste>.
- Bell, Alice. 2019. "Can Laboratories Curb Their Addiction to Plastic?" *The Guardian*. Guardian News

- and Media, November 10, 2019.
<https://www.theguardian.com/environment/2019/nov/10/research-labs-plastic-waste>.
- Bistulfi, Gaia. 2013. "Reduce, Reuse and Recycle Lab Waste." *Nature News*. Nature Publishing Group, October 9, 2013. <https://www.nature.com/articles/502170a>.
- Bullard, Robert D. 1996. "Environmental Justice: It's More Than Waste Facility Siting." *Social Science Quarterly* 77, no. 3: 493–99. <http://www.jstor.org/stable/42863495>.
- Clark, James H., and Duncan J. Macquarrie. 2002. *Handbook of Green Chemistry and Technology*. Oxford etc.: Blackwell Science, 2002.
- Conte, Marc N. 2013. "Valuing Ecosystem Services." *Elsevier Inc*.
<https://drive.google.com/drive/folders/17Li5XSkUsz4ESBbBHKrBLPYo5-QE6YIZ>
- Culley, Marci R., and Joseph Hughey. 2007. "Power and Public Participation in a Hazardous WASTE DISPUTE: A Community Case Study." *American Journal of Community Psychology* 41, no. 1-2 (2007): 99–114. <https://doi.org/10.1007/s10464-007-9157-5>.
- de Marco, Bianca Aparecida, Bárbara Saú Rechelo, Eliane Gandolpho Tótolí, Ana Carolina Kogawa, and Hérica Regina Salgado. 2019. "Evolution of Green Chemistry and Its Multidimensional Impacts: A Review." *Saudi Pharmaceutical Journal* 27, no. 1 (January 2019): 1–8.
<https://doi.org/10.1016/j.jsps.2018.07.011>.
- Denchak, Melissa. 2018. "Water Pollution: Everything You Need to Know." *NRDC*,
<https://www.nrdc.org/stories/water-pollution-everything-you-need-know#:~:text=Water%20pollution%20occurs%20when%20harmful,to%20humans%20or%20the%20environment>.
- "DuPont: Influence." Powerbase, September 2, 2008.
https://powerbase.info/index.php/Dupont:_Influence#endnote_30.
- "Ecosystems and Human Well-Being: General Synthesis." 2005. Millennium Ecosystem Assessment. Island Press, Washington D.C.
- "Environmental Remediation." Wikipedia. Wikimedia Foundation, August 16, 2021.
https://en.wikipedia.org/wiki/Environmental_remediation#cite_note-5.

Espinoza, Richard. 2020. "How Hazardous Waste Disposal Affects the Environment." IDR Hazardous Waste Disposal Blog, November 24, 2020.

<https://blog.idrenvironmental.com/how-hazardous-waste-disposal-affects-the-environment>.

Fazzo, L., et al. 2017. "Hazardous Waste and Health Impact: A Systematic Review of the Scientific Literature." *Environmental Health*, vol. 16, no. 1, <https://doi.org/10.1186/s12940-017-0311-8>.

Fazzo, L., F. Minichilli, M. Santoro, A. Ceccarini, M. Della Seta, F. Bianchi, P. Comba, and M. Martuzzi. 2017. "Hazardous Waste and Health Impact: A Systematic Review of the Scientific Literature." *Environmental Health* 16, no. 1. <https://doi.org/10.1186/s12940-017-0311-8>.

"Frequent Questions About Managing Hazardous Waste at Academic Laboratories." EPA¹, Environmental Protection Agency, <https://www.epa.gov/hwgenerators/frequent-questions-about-managing-hazardous-waste-academic-laboratories>.

"Green Chemistry Challenge: 2021 Designing Greener Chemicals Award." EPA⁹. Environmental Protection Agency. <https://www.epa.gov/greenchemistry/green-chemistry-challenge-2021-designing-greener-chemicals-award>.

"Green Chemistry Challenge: 2021 Greener Synthetic Pathways Award." EPA¹⁰. Environmental Protection Agency. <https://www.epa.gov/greenchemistry/green-chemistry-challenge-2021-greener-synthetic-pathways-award>

"Green Chemistry Challenge: 2021 Small Business Award." EPA⁸. Environmental Protection Agency. <https://www.epa.gov/greenchemistry/green-chemistry-challenge-2021-small-business-award>

Harris, Paul G. 2013. "Environmental Justice: Pollution, Poverty, and Marginalized Communities." Essay. In *Routledge Handbook of Global Environmental Politics*. Abingdon, Oxon, NY: Routledge.

"Hazardous Waste Management Facilities and Units." EPA⁴. Environmental Protection Agency. Accessed December 16, 2021.

<https://www.epa.gov/hwpermitting/hazardous-waste-management-facilities-and-units>.

“Health and Ecological Hazards Caused by Hazardous Substances.” EPA³. Environmental Protection Agency. Accessed November 26, 2021.

<https://www.epa.gov/emergency-response/health-and-ecological-hazards-caused-hazardous-substances>.

“Health Effects of Chemical Exposure.” *ATSDR*, Agency for Toxic Substances and Disease Registry, <https://www.atsdr.cdc.gov/emes/public/docs/Health%20Effects%20of%20Chemical%20Exposure%20FS.pdf>.

“History of Chemistry.” Chemistry History. Accessed October 4, 2021.

<http://www.columbia.edu/itc/chemistry/chem-c2507/navbar/chemhist.html>.

Hjeresen, Dennis L., Janet M. Boese, and David L. Schutt. 2000. “Green Chemistry and Education.” *Journal of Chemical Education* 77, no. 12 (2000): 1543. <https://doi.org/10.1021/ed077p1543>.

Hjeresen, Dennis L., Janet M. Boese, and David L. Schutt. 2000. “Green Chemistry and Education.” *Journal of Chemical Education* 77, no. 12 (December 1, 2000): 1543.

<https://doi.org/10.1021/ed077p1543>.

Holifield, Ryan. 2004. “Neoliberalism and Environmental Justice in the United States Environmental Protection AGENCY: Translating Policy into MANAGERIAL Practice in Hazardous WASTE REMEDIATION.” *Geoforum* 35, no. 3 (2004): 285–97.

<https://doi.org/10.1016/j.geoforum.2003.11.003>.

Hoque, Shamia, Nicole D Berge, and Tanvir Farouk. “Green Plasma Technology for Siloxane Removal and Landfill Gas Upgrade.” EPA. Environmental Protection Agency, September 30, 2020.

https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract_id/11014/report/0.

HWH Environmental, 2021. “Facts and Statistics about Waste for 2021.” HWH Environmental, March 31, 2021. <https://www.hwhenvironmental.com/facts-and-statistics-about-waste/>.

“Information About the Green Chemistry Challenge.” EPA⁷. Environmental Protection Agency.

- <https://www.epa.gov/greenchemistry/information-about-green-chemistry-challenge>
- IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
- Jackson T. Preface. 1993. In: Jackson T, ed. *Clean Production Strategies: Developing Preventive Environmental Management in the Industrial Economy*. Boca Raton, FL: Lewis.
- Jessop, Philip. 2017. "Green/Alternative Solvents". In Abraham, M. A. (ed.). *Encyclopedia of Sustainable Technologies*. Elsevier. pp. 611–619.
- Keiser, Edward H. "An Outline of the Progress of Chemistry in the Nineteenth Century." *Scientific American*. *Scientific American*, July 13, 1901.
- <https://www.scientificamerican.com/article/an-outline-of-the-progress-of-chemi/>.
- Kizer, F. 1987. Telephone conversation of Shawn Sager of ICF-Clement Incorporated with Frank Kizer of the Council of State Science Supervisors, Lancaster, VA, May 12, 1987, concerning the use of commercial hazardous waste management facilities (From the Report to Congress).
- Koerth, Maggie. 2019. "Science Has a Sustainability Problem." *FiveThirtyEight*. *FiveThirtyEight*, June 19, 2019. <https://fivethirtyeight.com/features/when-trying-to-save-the-world-also-trashes-it/>.
- Korenaga, Takashi. 1994. *Hazardous Waste Control in Research and Education*. Boca Raton, MI: Lewis.
- Lankey, Rebecca L., and Paul T. Anastas. 2002. "Life-Cycle Approaches for Assessing Green Chemistry Technologies." *Industrial & Engineering Chemistry Research* 41, no. 18 (2002): 4498–4502.
- <https://doi.org/10.1021/ie0108191>.
- Lerner, Sharon. "Bad Chemistry." *The Intercept*. First Look Institute. Accessed December 20, 2021.
- <https://theintercept.com/collections/bad-chemistry/>.
- "Less Is Better: Guide to Minimizing Waste in Laboratories." ACS.org. American Chemical Society. Task Force on Laboratory Environment, Health, and Safety. 2002.
- <https://www.acs.org/content/dam/acsorg/about/governance/committees/chemicalsafety/publications/less-is-better.pdf>

- Miller, G. Tyler, and Scott Spoolman. 2015. *Living in the Environment: Principles, Connections, and Solutions*. 19th ed. Boston, MA: Cengage Learning.
- Mooney, Dana. 2004. "Effectively Minimizing Hazardous Waste in Academia: The Green Chemistry Approach." *Chemical Health & Safety* 11, no. 3 (2004): 24–28.
<https://doi.org/10.1016/j.chs.2004.02.004>.
- Morris, Peter J.T. 2016. *The Matter Factory: A History of the Chemistry Laboratory*. London, UK: Reaktion Books Ltd, in association with Science Museum, London.
- Nair A, Kansal D, Khan A, Rabnawaz M. 2021. Oil- and water-resistant paper substrate using blends of chitosan-graft-polydimethylsiloxane and poly(vinyl alcohol). *Journal of Applied Polymer Science*;138(21):50494.
- Nascimento, Elizabeth de, and Alfredo Tenuta Filho. 2010. "Chemical Waste Risk Reduction and Environmental Impact Generated by Laboratory Activities in Research and Teaching Institutions." *Brazilian Journal of Pharmaceutical Sciences* 46, no. 2: 187–98.
<https://doi.org/10.1590/s1984-82502010000200004>.
- National Research Council (US) Committee on Prudent Practices in the Laboratory. 2017. "Management of Waste." *Prudent Practices in the Laboratory: Handling and Management of Chemical Hazards: Updated Version*. U.S. National Library of Medicine.
<https://www.ncbi.nlm.nih.gov/books/NBK55885/>.
- O'Neil, Natalie J., Star Scott, Rachael Relph, and Ettigounder Ponnusamy. 2020. "Approaches to Incorporating Green Chemistry and Safety into Laboratory Culture." *Journal of Chemical Education* 98, no. 1: 84–91. <https://doi.org/10.1021/acs.jchemed.0c00134>.
- "People, Prosperity and the Planet (P3) Student Design Competition." EPA¹². Environmental Protection Agency. Accessed November 29, 2021. <https://www.epa.gov/P3>.
- Pogacar, Ziva. 2019. "After one short hour in the tissue culture lab I produced 400g of plastic waste! That would be more than 100kg per year! #LabWasteDay #eLifeAmbassadors." Twitter, September 17, 2019. https://twitter.com/z_pogacar/status/1174042544956555264.

- Ramírez Lara, Evangelina, Javier Rivera De la Rosa, Aldo Isaac Ramírez Castillo, Felipe de Cerino-Córdova, Ulrico Javier López Chuken, Sergio S. Fernández Delgadillo, and Pasiano Rivas-García. 2017. "A Comprehensive Hazardous Waste Management Program in a Chemistry School at a Mexican University." *Journal of Cleaner Production* 142 (January 20, 2017): 1486–91. <https://doi.org/10.1016/j.jclepro.2016.11.158>.
- Ren, Hong; Maloney, Kevin M.; Basu, Kallol; Di Maso, Michael J.; Humphrey, Guy R.; Peng, Feng; Desmond, Richard; Otte, Douglas A. L.; Alwedi, Embarek; Liu, Wenjun; Zhang, Si-Wei; Song, Siqing; Arvary, Rebecca A.; Zompa, Michael A.; Lehnherr, Dan; Martin, Gary E.; Chang, Hsieh Yao D.; Mohan, Anne E.; Guzman, Francisco J.; Jellett, Lisa; Lee, Alfred Y.; Spencer, Glenn; Fisher, Elizabeth S.; Naber, John R.; Gao, Hong; Lohani, Sachin; Ruck, Rebecca T.; Campeau, Louis-Charles. 2020. *Development of a Green and Sustainable Manufacturing Process for Gefapixant Citrate (MK-7264) Part 1: Introduction and Process Overview. Organic Process Research & Development*, acs.oprd.0c00248–. doi:10.1021/acs.oprd.0c00248
- Rich, Nathaniel. 2016. "The Lawyer Who Became Dupont's Worst Nightmare." *The New York Times*.
The New York Times.
<https://www.nytimes.com/2016/01/10/magazine/the-lawyer-who-became-duponts-worst-nightmare.html>.
- Salvin, Catherine. n.d. "The Science of Environmental Justice: Can Green Chemistry Change Our World?" *Yale National Initiative*, Yale-New Haven Teachers Institute,
https://teachers.yale.edu/curriculum/viewer/initiative_09.05.10_u.
- Sheldon, Roger A. 2016. "Green Chemistry and Resource Efficiency: Towards a Green Economy." *Green Chemistry* 18, no. 11 (2016): 3180–83. <https://doi.org/10.1039/c6gc90040b>.
- Shi, Lirong, and Manaswini Sarangi. 2021. "With Experiments, Comes Waste: Scientific Waste and Where It Ends Up." *misciwriters.com*.
<https://misciwriters.com/2021/01/05/with-experiments-comes-waste-scientific-waste-and-where-it-ends-up/>.

- Stanley, D. 1987. Telephone conversation of Shawn Sager of ICF-Clement Incorporated with David Stanley of the Center for Environmental Management, Tufts University, Medford, MA, May 20, 1987, to gather additional information on the Tufts report (From the Report to Congress).
- “Summary of the Pollution Prevention Act.” EPA⁵. Environmental Protection Agency. Accessed November 10, 2021. <https://www.epa.gov/laws-regulations/summary-pollution-prevention-act>.
- “Sustainability Research Grants.” EPA¹¹. Environmental Protection Agency. Accessed November 29, 2021. <https://www.epa.gov/research-grants/sustainability-research-grants>.
- The Nobel Prize Foundation. 2005. “The Nobel Prize in Chemistry 2005.” NobelPrize.org. The Nobel Prize Foundation. October 5, 2005. <https://www.nobelprize.org/prizes/chemistry/2005/press-release/>.
- The Nobel Prize Foundation. 2021. “The Nobel Prize in Chemistry 2021.” NobelPrize.org. The Nobel Prize Foundation, October 6, 2021. <https://www.nobelprize.org/prizes/chemistry/2021/press-release/>.
- Thornton, Joe. 2000. *Pandora's Poison: Chlorine, Health, and a New Environmental Strategy*. M.I.T. Press.
- “Toxics in the Food Web.” EPA², Environmental Protection Agency, 2021, <https://www.epa.gov/salish-sea/toxics-food-web>.
- Tufts University. 1987. *Hazardous Waste Management in Educational Institutions: A Report to the United States Environmental Protection Agency*. Prepared by the Center for Environmental Management, Tufts University, Medford, MA.
- U.S. Environmental Protection Agency Office of Solid Waste. 1989. *Report to Congress: Management of Hazardous Wastes from Educational Institutions*. <https://www.epa.gov/sites/default/files/2014-12/documents/1989rtc-labs.pdf>
- U.S. Environmental Protection Agency. 2008. “Laboratories for the 21st Century: An Introduction to Low-Energy Design.” NREL.gov. <https://www.nrel.gov/docs/fy08osti/29413.pdf>.
- U.S. EPA Office of Solid Waste. 1989. “Report to Congress: Management of Hazardous Wastes from

- Educational Institutions.” *EPA.gov*, U.S. Environmental Protection Agency, <https://beta.epa.gov/sites/default/files/2014-12/documents/1989rtc-labs.pdf>.
- Urbina, Mauricio A., Andrew J. Watts, and Erin E. Reardon. 2015. “Labs Should Cut Plastic Waste Too.” *Nature* 528, no. 7583: 479–79. <https://doi.org/10.1038/528479c>.
- USGCRP. 2018. “Fourth National Climate Assessment.” NCA4. U.S. Global Change Research Program. <https://nca2018.globalchange.gov/chapter/front-matter-guide/>.
- Walton, Wendy A. 1987. “Chemical Wastes in Academic Labs.” *Journal of Chemical Education* 64, no. 3 (March 1, 1987). <https://doi.org/10.1021/ed064pa69>.
- “Water, the Universal Solvent.” USGS: science for a changing world. U.S. Department of the Interior. Accessed November 15, 2021. https://www.usgs.gov/special-topic/water-science-school/science/water-universal-solvent?qt-science_center_objects=0#qt-science_center_objects.