The Theory And Practice Of Green Analytical Chemistry

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INTRODUCTION

The discipline of Analytical Chemistry has and continues to play an integral role in Environmental Law and Chemical Manufacturing. The reason Analytical Chemistry is so central to Environmental Law is due to Analytical Chemistry's capacity to identify and quantify environmental pollutants. In other words, quantitative analytical techniques can measure the concentration of environmental pollutants and confirm whether the concentration complies with the law. And, likewise, qualitative analytical techniques help elucidate new and previously unknown pollutants. Both qualitative and quantitative analytical techniques are central to environmental regulatory compliance.

Although compliance with environmental regulations continues to be an important aspect of Environmental Law, environmentalists, the chemical industry, and government agencies (such as the US EPA) started to realize in the 1980's and 1990's that measuring environmental pollutants once they were released into the environment might not be the optimal approach. Instead, some started to ask whether a better policy might be to eliminate pollution at the source? This very concept of pollution prevention was captured in the U.S. Pollution Prevention Act of 1990 which made it public policy within the United States to prevent industrial pollution before it escaped into the environment.

As a consequence of the shift from pollution release and monitoring to prevention, Analytical Chemistry expands its already important reach from measuring pollutants once they are released into the environment to becoming integrally involved in characterizing fine chemicals and materials before they leave the manufacturing value chain. Aspects of pollution prevention of chemicals before they reach other manufacturing streams (e.g., intermediates or end-products) are contained in both the Toxic Substance Control Act in the United States and the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) in the European Union. Both regulations require an analytical assessment of safety with regards to human health and environmental protection.

Regulations and environmental legislation are inherently political so it comes as no surprise that the discourses around safety, human health, and environmental protection can often take on a political nature as well. Analytical chemists working in the field of environmental law and regulations are often aware of the political nature of their work, but analytical chemists that only tangentially interact with Environmental Regulations may only have a vague sense of these political dimensions. Hence, while the main focus of this white paper will be on describing how practitioners can implement Green Analytical Chemistry in their own laboratories to support pollution prevention, a little public policy history will also be provided in order to provide the necessary context. To start the contextual discussion, I will first start with background on Sustainable Development before moving on to the Pollution Control Act of 1990 and Green Chemistry before ultimately arriving at Green Analytical Chemistry. Although Sustainable Development, Pollution Prevention, and Green Chemistry will be presented as distinct concepts, in reality they consist of many interlocking aspects.

SUSTAINABLE DEVELOPMENT

What do we mean exactly when we use the word sustainable? This eBook is first going to attempt to unpack the concept of sustainable or sustainability and link it with efforts in the chemical industry to become more sustainable. To be fair, sustainability is a rather nebulous concept, so we first need to look at terminology such as sustainable, sustainability, and sustainable development. While these terms often have varying definitions, this eBook will focus on sustainable development. The reason for focusing the on term sustainable development is to link with how the United Nations uses the terminology to connect economic, social, and environmental consequences of public policy. Further, by exploring sustainable development, the other two terms, sustainability and sustainable should become clearer. So, in the 1980's, the United Nations institutionalized these components (economic, social, and environmental) into the three pillars of sustainable development. By the 1990's, some corporations were starting to talk about sustainability or sustainable development and the chemical industry also started talking about a related concept called Green Chemistry to conduct fine chemistry development and production in a less polluting and more sustainable manner.

The pillars of economic, social, and environmental, partially tell the story of how the UN "institutionalized" sustainable development because these three pillars represent the three main interested parties in the negotiation for a more "sustainable" economic system. In the 1960's and 1970's, there were two main progressive discourses. One focused on social injustice and inequality and the second on environmental concerns due to several high-profile environmental catastrophes. Rachel Carson's 1962 "Silent Spring," is an example of one of the environmental discourses of the period. Counter to the progressive discourses was the business community's twin concerns about running out of natural resources (e.g., the 1973 OPEC oil embargo) and the costs of complying with environmental regulations, e.g., creation of the Environmental Protection Agency in 1970, 1970 Clean Air Act, 1972 Clean Water Act, 1976 Toxic Substance Control Act, etc. As a result of getting these three groups to sit down together and hammer out a consensus, the United Nations was able to formulate a conception of sustainable development where the economy would be able to continue growing, but at the same time not cause the environmental and social consequences that the progressive discourses had alleged. Further, in addition to mitigating potential consequences of economic development, sustainable development also took on the meaning of economic development for the present generation, but also leaving resources for the future generation's own economic development. Since, the initial UN's conception of sustainable development being comprised of three pillars, it has evolved with time to the UN 17 Sustainable Development Goals that were adopted by the United Nations General Assembly in September 2015 and sets 2030 as the year to achieve those goals.

POLLUTION PREVENTION

One of the fundamental premises of the UN's 17 Sustainable Development Goals is that an improving economy can help alleviate social conditions such as poverty and pollution in society provided that businesses follows sustainable best-practices. In the chemical industry, one of these sustainable best-practices is called Green Chemistry. The origin of Green Chemistry comes out of the U.S. Pollution Prevention Act of 1990. By the 1990's, environmentalists, the government, and businesses began to realize that pollution release limits were not achieving the desired goal of cleaner air and water. Further, the costs of complying were costing tens of billions of dollars according to the findings of Congress in the Pollution Prevent Act (42 USC Chapter 33 § 13101). So, the Pollution Prevention Act took a new approach, instead of setting pollution release limits, it instead encouraged businesses:

> [...] that pollution should be prevented or reduced at the source whenever feasible; pollution that cannot be prevented should be recycled in an environmentally safe manner, whenever feasible; pollution that cannot be prevented or recycled should be treated in an environmentally safe manner whenever feasible; and disposal or other release into the environment should be employed only as a last resort and should be conducted in an environmentally safe manner (42 USC Chapter 133 § 13101).

The clear language of the statute essentially says, don't pollute in the first place. But, how can a chemical company implement this? For example, when production of a fine chemical is scaled up to a tanker-car level, things that may not be complicated at the bench level now become monumental. Looking at this from a different perspective, at the bench level a scientist may use a rare earth catalyst that is highly toxic. Since, the scientist is only using a tiny amount in the laboratory, there really is not a problem if s/he follows laboratory safety best-practices. However, what happens if s/he scales that same reaction up to a tanker-car scale? How does large quantities of this toxic substance affect the workers? How does a company dispose of the toxic catalyst so that it doesn't get into the environment? Does it impact the local community? Looking at the issue from both perspectives starts to illustrate how big the issue can become. Taking into perspective laws such as the Pollution Control Act, it is no longer acceptable to let a chemical engineer try to "clean up" a reaction after initial discovery. It's now the responsibility of everybody – from the research chemists in initial discover to the chemicals engineers in production to think about pollution prevention.

GREEN CHEMISTRY

Starting a new way of doing things is always a challenge and it's usually easier if someone provides some guidance or check list to illustrate how to prevent pollution throughout the chemical development and production process. In 1998, two scientists developed a guidance for the industry in the form of a book called: "Green Chemistry: Theory and Practice." It was written by Paul T. Anastas, who was then Director of the Green Chemistry Program at the EPA, and John C. Warner, who was then a chemistry professor at the University of Massachusetts, Boston. The high-level concept of Green Chemistry is that there are two aspects of Green, first, Green refers to the environment or environmental protection and second, green is the color of money (at least in the US) and illustrates the economic benefit of waste reduction. So, Green Chemistry tries to balance the economic and environmental impacts of fine chemical production just as the UN's three pillars of sustainable development tries to balance the economic, social, and environmental. But, from a practical perspective, what "Green Chemistry: Theory and Practice" provides is a set of twelve principles that enable chemists to produce fine chemicals in a more environmentally benign way while reducing wastes. The twelve principles formulated by Anastas and Warner are summarized below:

(1) It's better to prevent waste than clean it up.

(2) Synthetic methods should incorporate all atoms into a reaction (e.g., don't forget the solvents).

(3) Chemicals should be designed that have no toxicity to humans or the environment.

(4) Molecular design should consider toxicity as well as function.

(5) Solvents should be eliminated whenever possible.

(6) Traditional reactions consume energy (e.g., hotplates). Reactions should be designed to run at ambient temperature and pressure.

(7) Feedstocks should be renewable whenever feasible.

(8) Chemical derivatization should be avoided.

(9) Catalysts should be used in favor of stoichiometric reactions.

(10) Molecules and materials should be designed such that they break down at the end of their useful life.

(11) Use Analytical Chemistry to aid molecular design and reduce waste.

(12) Chemical agents should be chosen to avoid accidents.

What the twelve principles of Green Chemistry represent is a paradigm shift if you will. A kind of new way of thinking on the part of chemists. For example, as was illustrated above, synthetic chemists can't just leave figuring out how to make a reaction more benign to the chemical engineer in production, it now must be done in research at the bench level. An analogy can be made with how medicinal chemists in the pharmaceutical industry design and make drug candidates at the bench. In the pharmaceutical industry, medicinal chemists design molecules that they hope will cure disease. For example, let's assume that the medicinal chemist wants to shut down an enzyme active site because the biologists say this is the mechanism of the disease. The medicinal chemist designs several molecules to fit and bind with the active site and then once a few candidates are found, the prospective molecules are tested for toxicity. Tests for function and toxicity can be performed *in silico* even before any wet chemistry is performed. Whether toxicity is evaluated *in silico* or experimentally, the medicinal chemist will often have to adjust the molecule to reduce toxicity. For example, by adding or subtracting a functional group here or there. Although this analogy brushes with wide strokes, it illustrates that chemists in the chemical industry who follow the principles of Green Chemistry not only have to think about molecular function, but also have to think about toxicology – just like their medicinal chemist counterparts. The ultimate goal with Green Chemistry is that if you want the chemical making process to be benign so that if someone happens to touch a fine chemical then it won't be any more harmful for you then washing your hands in water. And finally, if the chemical creation process becomes more benign then the chemical industry will play its part in sustainable development that balances the environment, social, and economic aspects of economic development.

GREEN ANALYTICAL CHEMISTRY

Although fine chemical synthesis receives most of the emphasis in the twelve principles of Green Chemistry, principle eleven does specifically call out analytical chemistry. Admittedly, analytical chemistry is probably not top-of-mind to most scientists in relation to pollution prevention in fine chemical development and production, but techniques such as mass spectrometry (MS), liquid/gas chromatography (LC, GC), thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), rheology, nuclear magnetic resonance (NMR), etc. are widely used to design molecules and Green Analytical Chemistry simply advocates that these techniques also become a component of pollution prevention.

How can analytical techniques be used to implement Green Analytical Chemistry? Primarily, analytical techniques can support Green Analytical Chemistry in two ways: by supporting sustainable applications and by the analytical techniques becoming operationally more efficient.

In the first instance, Green Analytical Chemistry calls on analytical techniques to facilitate development of more sustainable forms of fine chemicals and materials. For example, fine chemicals derived from petroleum are widely acknowledged to be the dominant source of fine chemical feedstocks due to their lower costs and deep inherent knowledge of working with petroleum to create feedstocks. However, it is also generally acknowledged that moving away from petroleum derived feedstocks and towards renewable sources of bio-derived feedstocks is a more sustainable path and aligns better with the UN Sustainable Development Goals and Green Chemistry.

What this might mean in practice is replacing existing petroleum derived plastic food packaging with biomass derived equivalents (e.g., from lignins). But, how do we know that the new biomass derived food package is as good as the existing package? For example, what if we wanted to create a new plastic soda bottle? Then an analytical chemist could deploy TGA to compare the thermal profile (e.g., glass transition, crystallization, and melting temperatures) of the existing plastic bottle versus the new prototypes. In order to further dial in the desired polymer material profile, s/he could then use size exclusion chromatography (SEC) techniques such as Advance Polymer Chromatography (APC) to identify the optimal molecular weight profile of the feedstock polymer from various lignin sources to achieve the appropriate plastic clarity, toughness, and durability. Additionally, s/he might use liquid chromatography combined with mass spectrometry to understand the polymer additive profile of the existing plastic soda bottle and compare it with the prototypes. Subsequent safety studies might also use liquid chromatography and mass spectrometry (LC-MS) to determine if any of the polymer additives that make up the plastic are migrating into the beverage product (also known as non-intentionally added substances (NIAS)). Admittedly, this example is just the tip-of-the-iceberg, but it does begin to illustrate how analytical techniques can help in efforts to move us towards more sustainably derived materials. Examples beyond plastic bottle development are virtually unlimited and could include lubricant reformulation for electric vehicles, more benign industrial catalysts (e.g., based on metal organic frameworks), reformulated cosmetics and personal care products, more efficient lithium ion batteries, and so on.

Moving beyond the almost unlimited number of sustainably derived products and applications, probably the biggest area where analytical chemistry can play a part in Green Analytical Chemistry is with analytical instruments that are more efficient and less polluting in their operation. Some of these possibilities are highlighted below:

- Savings in energy, materials, and waste
  - Instrument automation
  - Multi-detection
  - Miniaturization
  - Improved separation efficiency
  - Simpler instruments for routine tasks
  - Qualification of "optimal" instrument operation
  - Minimizing need for experimentation
    - Use of statistics, libraries, chemometrics for interpretation and method planning, AI, and Design-of-Experiment

- Solvent replacement
    - Replacing harmful solvents with benign solvents, e.g., MeOH for Acetonitrile, traditional solvents with supercritical fluids
    - Direct sampling
- Reducing paper and record storage costs
    - Automated data processing and reports
    - Electronic signatures
    - Electronic methods

First on the list above is energy, materials, and waste reduction. Some analytical techniques, such as liquid and gas chromatography, have already headed in the direction of energy, material, and waste reduction by using extensive sample automation. There are several benefits of sample automation. For example, automation means samples are loaded on a liquid or gas chromatography system in a highly accurate and precise manner so that less reworking is required. If there is less reworking, then that can often translate into less solvent usage in the case of a liquid chromatography system. Of course, both systems, GC and LC, benefit from less energy consumption due to automation. And in recent years, the LC technic has made large strides in the speed, sensitivity, and resolution of the technology due to smaller column particle sizes and higher pumping pressures as seen in the Waters™ ACQUITY™ UPLC™ line of liquid chromatography systems.

In addition to inherently higher performing LC systems, in some cases it may be possible to evaluate existing LC methods and switch solvent systems from something like acetonitrile to methanol. Other alternatives to solvent switching might include the consideration of supercritical fluid chromatography (SFC) in place of traditional LC, such as the Waters ACQUITY UPC^{2}™ line of separation systems that provide the benefits of GC and LC while entirely replacing the liquid solvent with gaseous carbon dioxide operated under supercritical fluid conditions. While carbon dioxide gets a bad reputation as a contributor to green house gases, the use of carbon dioxide in SFC technology is considered a green alternative to solvents because carbon dioxide from the environment can be captured and recycled in an SFC system.

Not only can analytical techniques be configured to reduce solvent consumption, but many either have or will transition to becoming paperless systems too due to advances in information technology. A chromatography data system (CDS) such as Waters Empower™ CDS uses a relational database to manage all data that is generated during an LC project. This can include the methods, calculations, and reports. In some workflows it may even be possible to make use of electronic signatures to approve test results before batch release. All this electronic data management not only minimizes paper, but also improves the efficiency of the overall laboratory workflow.

CONCLUSIONS

Efficiency of the laboratory assets in a contemporary analytical laboratory is probably the biggest contribution of Green Analytical Chemistry to Sustainable Development; although the contribution to developing sustainable new products should not be minimized. If analytical techniques can be used to reduce energy and material usage while minimizing waste, they can make a positive contribution to the twelve principles of Green Chemistry. And who knows maybe doing something good for the planet can end up saving on business costs – a win, win for everybody.

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