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Review article

Mainstreaming green chemistry: The need for metrics

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ABSTRACT

An ability to measure progress is consistently identified as a critical element in understanding if corporate and government policies and interventions are advancing green chemistry; if investment is occurring; and what must be done to accelerate progress in the future. In this commentary, we outline a rationale for improved green chemistry progress measures, identify some examples of the types of metrics needed for tracking green chemistry progress and outline future needs.

1. Introduction

The past decade has seen a significant growth in the demand for safer chemicals and products, from regulators and the marketplace. However, this demand has not been met with similar growth in green chemistry solutions and practices. While green chemistry, research, education, and adoption have certainly occurred and there are an increasing number of green chemistry success stories, it is still a niche consideration. Green Chemistry has yet to be integrated into the fabric of the chemical enterprise, educational systems, or government programs. Through extensive research the Green Chemistry and Commerce Council (GC3), a cross sectoral business to business network of firms working collaboratively to accelerate green chemistry, has identified a number of barriers to green chemistry adoption [1,2], including (1) the complexity of global supply chains and their established infrastructures, (2) the costs and time to scale to adopt new technologies, (3) the incumbency of existing technologies that are cost-effective, high performing and familiar (but may be problematic environmentally), (4) concerns about the risks involved in moving to green chemistry solutions (performance, process changes, material incompatibility or costs of recertification and potential for substitutes to be later designated chemicals of concern); and (5) limited investment, incentives, education, and metrics for green chemistry. Despite these barriers, ours and others' research has shown a clear economic and business case for scaling innovation in green chemistry [2,3].

Given the clear business case for green chemistry innovation, and very obvious barriers to its adoption, the GC3 developed its *Agenda to Mainstream Green Chemistry* to focus on concrete strategies and actions that can be taken in the coming years to accelerate green chemistry research, development, commercialization and adoption – to reach a point where all chemistry is green [4]. The Agenda identifies five broad strategies to accelerate green chemistry innovation, including:

- *Enhance Market Dynamics.* Building a comprehensive, ongoing understanding of green chemistry enablers, market drivers and obstacles allowing for more effective interventions that create market shifts to support green chemistry research, development and adoption.
- *Support Smart Policies.* Designing and advocating for innovative state and federal policies that can effectively support the supply of and demand for green chemistry solutions.
- *Foster Collaboration.* Facilitating the flow of information about green chemistry solutions among suppliers and product makers as well as assembling partnerships to tackle priority challenges can support the collaborations necessary to grow the marketplace for green chemistry solutions.
- *Inform the Marketplace.* Disseminating information about green chemistry business, economic, and health benefits, as well as opportunities and funding creates a clearer business and economic case for green chemistry

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- *Track Progress.* Improving green chemistry metrics and periodically gathering and reporting data on progress provides a way to demonstrate benefits and understand where interventions are necessary to accelerate green chemistry.

While all five strategies play an integral role in an effort to mainstream green chemistry, the last strategy listed above – tracking progress – is consistently identified as a critical element in understanding if corporate and government policies and interventions are advancing green chemistry; if investment is occurring; and what changes must be made to enhance progress in the future. In this commentary, we outline a rationale for improved green chemistry progress measures, identify some examples of the types of metrics needed for green chemistry and note future needs.

2. Why measure progress?

Simply put, you can't manage what you can't measure. While there is much discussion of the range of activities occurring to advance green chemistry, from academic programs, to U.S. Presidential Green Chemistry Awards [5], to research grants, to new academic journals, the impact of these actions in the growth of safer chemicals in the marketplace has not been quantitatively (and barely qualitatively) assessed. There are a number of reasons why progress measures matter, including:

- An ability to evaluate the effectiveness of interventions and identify where interventions are needed. Businesses and business units as well as government agencies are evaluated based on the impacts of their programs or investments. They can serve to measure impacts and identify gaps in practice. Well-designed metrics help direct resources more intentionally and effectively toward a desired outcome.
- Make a stronger business/economic/political case. Increasingly, investors (including company business financial officers) and politicians require some evidence of return on investment for programs. Green chemistry is still a niche consideration, in part because its advocates have failed to create a strong business and economic case for investments. Well-designed metrics can help make a stronger case for additional investment and attention that strengthens the green chemistry movement.
- Identify potential trade-offs. While at first a green chemistry solution may seem safer and more sustainable or high performing and cost-effective, as it is adopted in the market, problems may be identified or unforeseen benefits may be found. In either case, having clear metrics can improve the ability to identify early warnings and facilitate corrective interventions.
- Distinguish green chemistry from “green wash”. Research by the GC3 has found that lack of a clear definition and measures of green chemistry can lead to confusion in the marketplace where innovations that are not green may be misbranded as green chemistry. A search for good metrics can sharpen our focus on specific desired outcomes that enhance a bold vision for green chemistry.

3. Mainstreaming green chemistry – what do we mean?

A clear and consistent definition of green chemistry is critical to defining clear, replicable, and useable metrics. Clarity about what we mean and the future state we hope to achieve, helps to clarify the types of measures needed to understand if we are moving the right direction (e.g. towards a desired outcome). The GC3 uses a variation of the definition of green chemistry developed by Anastas and Warner [6]:

> Green chemistry is the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substance throughout their lifecycles: design, manufacture, use, and end of life.

This definition provides a direction for continuous improvement. But based on this definition, how do we know if we have mainstreamed green chemistry? Mainstreaming green chemistry goes far beyond simply development of molecules based on the definition above. Green chemistry will not be mainstream until it is embedded in all actions related to chemical design and production decisions, including government research and development policy, investment funding and chemicals management policy. To be mainstream, green chemistry will have to form part of chemistry and chemical engineering education and cost-effective, high performing green chemistry solutions will need to be available in the market place. Table 1 outlines some of the desired outcomes of efforts to mainstream green chemistry, as identified by the GC3.

4. Developing approaches to measure progress towards green chemistry

Progress toward mainstreaming green chemistry can be measured at four levels: the molecular level, the product/chemical level, the firm level, and the societal/policy level. Each of these requires a different set of benchmarks and indicators. Despite the existing metrics at the molecular, chemical/product, firm and societal levels, most are focused on impact avoidance (i.e., doing less bad) and few are focused on measuring growth in the supply of, education around, or culture of green chemistry. Research conducted for the GC3 found that metrics at the molecular level tend to be the most developed [7]. As an example, E-factor (a measure of process efficiency for the synthesis of specific molecules) and other lifecycle indicators (water and resource use) are widely used in industry [8]. A number of chemical/product level metrics also exist. These include chemical hazard assessment tools, such as Clean Production Action's GreenScreen® for Safer Chemicals [9] and SC Johnson's Green list™ [10]; product certifications, such as Cradle to Cradle Certification™ Product Standard [11], bluesign™ [12], or the European Union Ecolabel [13]; and product evaluation systems like the Higg Index [14]. Metrics at the molecular and chemical/product levels can be useful in determining if a particular chemistry, material, or product represents an improvement based on the definition and principles of green chemistry or if they present possible trade-offs that may deviate from the principles. Being able to track the growth of chemicals and products that are safer and more sustainable can demonstrate growth in green chemistry solutions. Alone, however, they can provide examples of successes but do not tell us whether green chemistry is becoming mainstream.

As such, firm and societal level measures are necessary to evaluate if investments, policies, and actions are creating the scientific, business, and cultural shifts that are critical to mainstreaming green chemistry. Firm and societal measures can become more complex because there are an expanded number of indicators that can be evaluated from investments, to education, to management systems, to product growth, to toxics reduction. At the firm level, there are measures that have been developed by firms themselves, such as Sigma Aldrich's effort to benchmark its chemistries against the 12 principles of Green Chemistry [15] and SC Johnson's aggregated reporting of its Greenlist™ scores across products [10]. Other measures have been developed by sectors and nonprofits. Most of these types of measures have been developed to evaluate the broad sustainability profile of a firm, such as the Global