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Implementing Green Chemistry in Chemical Manufacturing: A Survey Report

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ABSTRACT: Green chemistry is being implemented in chemical manufacturing to advance sustainability. A scouting survey and recent industry-wide reports find that several green chemistry principles and related metrics are routinely being implemented in the chemical manufacturing sector. A cross-section of stakeholders surveyed agree that broader adoption of the principles of green chemistry can be promoted by collaboration among companies to identify best practices and define opportunities to increase green chemistry implementation in chemical manufacturing. Active collaborative efforts to improve implementation include identifying common attributes of effective process metrics, developing means of tracking sector-wide implementation, and defining industrial needs for translating promising green chemistry ideas into implementable, cost-effective, and low business risk technologies.

KEYWORDS: *Collaboration, Industrial adoption, Metrics, Roundtable, Sustainable*

Sustainable chemical manufacturing strategy has increasingly focused on designing safer chemicals, use of renewable feedstocks, and design for energy efficiency. These are also three of the 12 principles of green chemistry first published in 1998.[1] Implementing green chemistry principles is seen as fundamental to achieving the sustainability goals of chemical companies, for these principles can be used to guide the design of more efficient lower impact products and processes.[2] However, creation of a sustainable future also requires companies to work together differently than they have in the past.[3] The American Chemical Society Green Chemistry Institute (ACS GCI) does just this by convening companies to work together through industrial roundtables. The ACS GCI Chemical Manufacturer's Roundtable (hereinafter referred to as the Roundtable) provides a focus and a forum for chemical companies to collaboratively facilitate industrial adoption of green chemistry and thereby improve the sustainability of chemical manufacturing.

The study of navigation teaches that to map out where you are going, first you need to know where you are. With that in mind, a scouting survey was conducted to gain a better understanding of the current implementation of green chemistry in the chemical manufacturing sector as the basis for charting the direction of the Roundtable's efforts. The survey explored three key topics: (1) current application of green chemistry principles, (2) green chemistry-related metrics in use, and (3) priorities for collaborative efforts to foster broader green chemistry implementation.

Learning about the current implementation level of green chemistry principles indicates which principles are commonly used and which might require further evaluation. Seeing what metrics are currently in use lays the foundation for benchmarking and the design of refined metrics. Understanding stakeholder views on proposed strategic priorities helps focus the concerted action of Roundtable members on industry-wide matters of significant importance. Common challenges can be addressed cost-effectively and efficiently by working collaboratively with peer companies in a precompetitive environment.

Prior studies indicate that green chemistry is being implemented in chemical manufacturing. The compilation of winners of and nominees for the Presidential Green Chemistry Challenge Award[4] shows the large number of green chemistry success stories in U.S. chemical manufacturing. A review of industry applications of green chemistry focused on Europe demonstrated that industrial green chemistry is a reality through a number of relevant chemical manufacturing case studies and observed that profitability is "a prime driver for sustainability".[5] Examinations of patents in the United States[6] and globally[7] indicate growth in the adoption of green and sustainable chemistry. Review of venture investment and partnerships indicates an upward trend among biobased chemical developers over the past decade.[8] Market research

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forecasts substantial expansion of green chemical markets.[9] OECD (Organisation for Economic Cooperation and Development)[10] commissioned a survey of chemists (n = 146) concerning perceptions and practices in green and sustainable innovation among chemical industry firms, finding the following: (1) Green and sustainable chemistry approaches are pursued where they "produce competitive and therefore potentially profitable products". (2) Significant increases in market potential for "green/sustainable chemistry products" are predicted. (3) Of the various types of R&D collaborations in support of "green/sustainable chemistry products", over 50% of firms surveyed have collaborated with other companies in the same sector.

The ACS GCI Chemical Manufacturer's Roundtable is an example of chemical companies collaborating in the area of green and sustainable innovation. Founded in 2010, the Roundtable is a partnership between the ACS GCI and member companies united by a shared commitment to integrate the principles of green chemistry into the business of chemical manufacturing. Membership is open to manufacturers producing chemicals and/or polymers from renewable, petroleum, natural gas, or other sources via chemical or biochemical processes. Member companies at the time of writing this paper were (in alphabetical order): Ajinomoto North America, Inc., Arizona Chemical, Corbion Purac, Dixie Chemical, DuPont, Penn A Kem, Sigma-Aldrich, and Solvay USA, Inc.

In the three sections that follow, this paper briefly describes the survey population, presents the results of the 2012 Roundtable survey and compares them to findings of recent chemical industry-wide sustainability surveys, and concludes with an outline of what the Roundtable is focused on going forward.

■ SURVEY POPULATION

Though the intended target for the survey was chemical manufacturers, the request to participate in the survey was widely communicated via electronic mail (direct and forwarded), social media (i.e., LinkedIn), the May–June 2012 ACS GCI electronic newsletter The Nexus, and the ACS weekly newsletter ACS Matters (weeks of June 5, 12, and 19) in an effort to reach the largest possible audience during the period May to June 2012. A total of 96 individuals responded to the survey questionnaire posted in an online survey tool (SurveyMonkey) during this time period. Survey respondents self-classified as follows: industry (41), academia (21), consulting (9), student (8), retired (5), government (4), other commercial (e.g., testing lab) (4), not for profit (2), trade organization (1), and unemployed (1). Of the 41 industry respondents, 26 indicated that they work in chemical manufacturing. (Other industry was largely made up of pharmaceutical manufacturers and chemical formulators, each of which is represented by its own sector-specific ACS GCI industrial roundtable.) The survey response rate among chemical manufacturers cannot be computed because the number of survey recipients in this sector was not tracked.

While respondent geographic region was not included in the survey, chemical manufacturing subsectors were accounted for in terms of the following five general types of chemicals manufactured: petroleum-based industrial chemicals, biobased industrial chemicals, petroleum-based specialty chemicals, biobased specialty chemicals, and other (e.g., polymers).

Except where noted below, review of data from the 2012 Roundtable survey concentrated on the responses from chemical manufacturers ($n \leq 26$).

■ SURVEY OF INDUSTRIAL IMPLEMENTATION OF GREEN CHEMISTRY

The Roundtable surveyed green chemistry practitioners in the chemical manufacturing sector about their use of green chemistry principles and related metrics. For the three key survey topics (principles, metrics, priorities), the 2012 Roundtable survey results are presented and discussed on a topic by topic basis. In each case, the survey question is listed, results are provided, and implications of these results are discussed in light of recent chemical industry-wide sustainability reports to better illustrate the current state of green chemistry implementation in the sector.

Current Application of Green Chemistry Principles. The 12 principles (summarized in Figure 1) define the field of

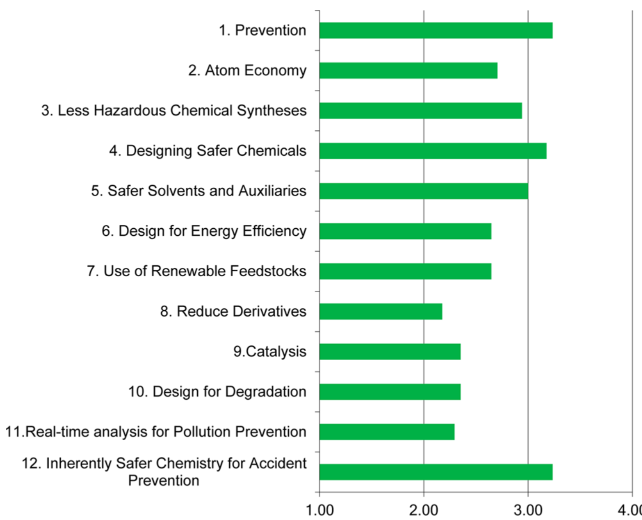

Figure 1. Frequency of the 12 principles of green chemistry implemented in chemical manufacturing. Average chemical manufacturer responses (n = 17) to the 2012 Roundtable survey question "In your opinion, how frequently does your company implement the following principles of green chemistry?" on a scale of 1 to 4, where 1 is never implemented (same value used for not applicable), 2 is rarely implemented, 3 is regularly implemented, and 4 is fully implemented. The magnitude of each bar is the average response calculated using the corresponding scale value (e.g., 3 for regularly implemented).

green chemistry. Practitioners were asked, "In your opinion, how frequently does your company implement the following principles of green chemistry?" on a scale of 1 to 4 (where 1 is never implemented and 4 is fully implemented).

As Figure 1 shows, chemical manufacturer respondents to this question (n = 17) report that several of these principles are routinely implemented in chemical manufacturing. Specifically, the figure indicates the following: (1) The implementation frequency across all the principles averages in the middle of the range (between 2 and 3 on the 1 to 4 scale), a moderate level of implementation for the 12 principles overall. (2) Five of the 12 principles of green chemistry are regularly or fully implemented: Principles # 1 (prevention), #3 (less hazardous chemical synthesis), #4 (designing safer chemicals), #5 (safer solvents and auxiliaries), and #12 (inherently safer chemistry for accident prevention). (3) The least frequently implemented principles reported in this survey are reduce derivatives (Principle #8), catalysis (Principle #9), design for degradation (Principle #10), and real-time analysis for pollution prevention (Principle #11).

These results signal that companies can be actively engaged in implementing the principles of green chemistry without addressing all 12 of the individual principles. Further examination of the survey responses points to a likely reason. Those who responded "never implemented" or "not applicable" for implementation of Principle #8 (the principle that received the largest number of "not applicable" responses) indicated their companies operated in one or two of the five chemical manufacturing subsectors noted in the Survey Population section. Furthermore, the chemical manufacturer respondents that reported regularly or fully implementing all 12 principles worked for companies operating in at least three of the five subsectors. This suggests that the breadth of operations across the entire chemical manufacturing sector affects the relevance and hence use of some of the green chemistry principles.

McKinsey & Company found similar trends in their survey of industry executives (n = 500) in the summer of 2011. They reported that "recyclability" and "low toxicity" were considered the most important green attributes for products globally.[11] These two attributes, which map to prevention (Principle #1) and designing safer chemicals (Principle #4), were among the most widely implemented principles of green chemistry reported in the 2012 Roundtable survey. Generally consistent with the results in Figure 1, the McKinsey survey found "bio-based" (related to Principle #7) and "biodegradable" (related to Principle #10) as the two least important green attributes for industry executives surveyed in the United States in contrast to Asia and Europe.[11] Among European respondents, McKinsey found "biodegradable" to be one of the top three green attributes, with equal importance to "low toxicity".

Results of the 2012 ICIS/Genomatica sustainability survey[12] of 702 chemical industry executives globally give insight into company plans for implementation of green chemistry principles in chemical manufacturing. When asked "What are the sustainable initiatives within your organization over the next 5 years?", 75% of respondents (n = 642) indicated that improving manufacturing processes by reducing energy (related to Principle #6) and reducing waste (related to Principle #1) is planned.[12] The next highest response (47%) indicated plans for reducing or eliminating toxic chemicals (related to Principles #3, #4, and #5). These results are in general agreement with the findings in Figure 1, for Principles #1, #3, #4, and #5 are among the most frequently implemented green chemistry principles in the 2012 Roundtable survey. The apparently dichotomous ICIS findings[12] that 28% of respondents to this question plan to "develop biodegradable products" while 27% of respondents plan to "develop new products that last longer" suggest a reason why design for degradation (Principle #10) was identified as one of the least frequently implemented principles reported in 2012 Roundtable survey. On the other hand, ICIS found that the third highest number of respondents (44%) reported "use/increase bio based/renewable content in materials" and that 40% of those responding to the ICIS/Genomatica survey were based in Europe.[12]

In summary, these results signal that industrial implementation of the principles of green chemistry is a significant component of advancing sustainability in chemical manufacturing. The principles of green chemistry are consistent with safer and more efficient process design and therefore make common sense to process chemists and engineers in chemical manufacturing. This alignment with core process design concepts has fostered widespread adoption of several of the principles of green chemistry in the sector.

Green Chemistry-Related Metrics in Use. The metrics that chemical companies choose to measure the "greenness" of a process or products gives insight into their implementation of green chemistry. The 2012 Roundtable survey asked, "What green chemistry and engineering related metrics does your company use? Select all that apply." The metrics in the survey are listed in Figure 2 and based on the metrics compiled in a recent review[13] of how pharmaceutical and fine chemical companies approach green chemistry.

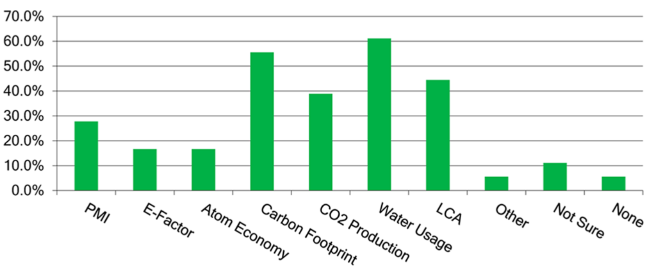

Figure 2. Green chemistry-related metrics used in chemical manufacturing. Chemical manufacturer responses (n = 18) to the 2012 Roundtable survey question "What green chemistry and engineering related metrics does your company use? Select all that apply." Percentage of respondents indicating one or more metrics surveyed in use computed as the ratio of [total responses − (not sure + none)]/(total responses). PMI = process mass intensity = (mass of raw materials)/(mass of final product).[14] E-factor = (mass of waste)/mass of final product).[14] LCA = life cycle assessment.

Over 80% of chemical manufacturer respondents (n = 18) indicated that one or more of the metrics surveyed are in use. Figure 2 shows a breakdown of which metrics are being used in chemical manufacturing. Of these, water usage (61% of respondents) and carbon footprint (56% of respondents) were reported as the most widely implemented, with lesser implementation seen for life cycle assessment (44% of respondents), CO_2 production (39% of respondents), and process mass intensity (28% of respondents). Process mass intensity (PMI), E-factor, and atom economy have been defined in a recent tutorial review by Dunn.[14] CO_2 production refers to the direct emissions associated with a process and is thereby a component of an overall carbon footprint. This explains why six of the seven individuals reporting use of CO_2 production as a metric also reported use of carbon footprint. In Figure 2, "Other" apparently relates to the use of company-specific approaches such as the Dow Chemical Sustainability Footprint Tool[15] or BASF eco-efficiency analysis.[16]

Comparison of these responses on use of metrics to those on implementation of green chemistry principles demonstrates internal consistency in the survey replies. For example, of the 10 respondents that use carbon footprint as a metric, eight report they regularly or fully implement both principles #6 (design for energy efficiency) and #7 (use of renewable feedstocks).

It should be noted that all of these metrics may not, and are very likely not, implemented on each product or process. For example, while life cycle assessment (LCA) is a valuable tool for evaluating impact across the supply chain, a fully burdened cradle-to-grave LCA is cost prohibitive to perform on every

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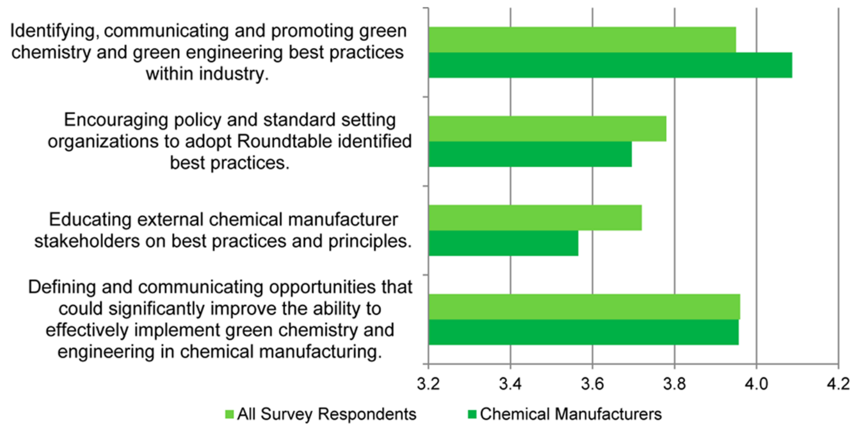

Figure 3. Priorities for collaborative efforts to foster broader green chemistry implementation. Average responses by all survey respondents (n = 81) and chemical manufacturers (n = 23) to the 2012 Roundtable survey question "How important are the following to you or your organization?" for each of the four priorities listed. Responses were provided on a scale of 1 to 5, where 1 is unimportant, 2 is slightly important, 3 is neutral, 4 is important, and 5 is very important, and weighted averages are shown.

product; market drivers generally determine where a fully burdened LCA is implemented.

While the 2012 Roundtable survey focused on metrics from a process perspective, the McKinsey survey addressed key performance indicators from a product perspective, concluding that to be a viable greener alternative to traditional chemicals, a chemical needs to also have comparable or better performance, quality, and cost.[11] Results of a 2013 survey of green chemistry professionals (n = 55) echoed the importance of cost, with "cost savings" perceived as one of the top two drivers for green chemistry adoption (along with "better training for chemists") in the coming years.[17]

The ICIS/Genomatica survey of chemical industry executives indirectly addressed green chemistry-related process metrics. In reply to a question about the importance of certain factors in how a company defines sustainability, 95% of respondents (n = 542) consider manufacturing process energy use and waste production and 85% of respondents (n = 569) consider the carbon footprint of raw material as "very important" or "moderately important".[12] Watson[13] reported that among pharmaceutical and fine chemical companies (n = 21) PMI is in use by 67% of companies, E-factor is in use by 48% of companies, and most companies use multiple metrics. The ICIS/Genomatica and Watson findings support the importance of waste intensity metrics (e.g., PMI and E-factor) and carbon footprint as key green chemistry-related process metrics.

While there is no shortage of proposed green chemistry-related metrics, there is no consensus on which metrics are the best ones. Two things that are clear about such metrics are that "one size does not fit all" and that each company has to consider its own unique set of needs.[18]

In concert with prior studies and the trends related to implementation of green chemistry principles described above, the metrics-related observations inform the authors' view that green chemistry is "an innovative, non-regulatory, economically driven approach toward sustainability".[19] Interestingly, on topics related to implementation of green chemistry principles and metrics, the relatively small sampling provided by the 2012 Roundtable survey yielded results indicative of large industry-wide sustainability surveys.

Priorities for Collaborative Efforts to Foster Broader Green Chemistry Implementation. The collaborative efforts of the Roundtable are built around four general strategic priorities. To help sharpen the future focus of these efforts, the 2012 Roundtable survey asked, "How important are the following to you or your organization?" and listed the following priorities for respondents to rate: (1) To identify, communicate, and consistently promote green chemistry and green engineering best practices within industry. (2) To encourage policy and standard setting organizations to adopt Roundtable identified best practices. (3) To educate external chemical manufacturer stakeholders on best practices and principles. (4) To define and communicate opportunities that could significantly improve the ability to effectively implement green chemistry and engineering in chemical manufacturing, recognizing any success could have a global impact on the sustainability of the chemical enterprise.

Feedback was collected from both the broader group of all respondents to this question (n = 81) to gauge the significance of these priorities with a cross-section of stakeholders and from chemical manufacturers (n = 23) to gather "voice of the customer". As Figure 3 indicates, both groups generally supported the strategic priorities above, with the first (identify, communicate, and promote best practices) and fourth (define and communicate opportunities to significantly improve green chemistry implementation) being the top two across the board. Hence, aligning the Roundtable's collaborative efforts with the first and fourth strategic priorities is expected to be the best course to chart for promoting wider industrial adoption of green chemistry in chemical manufacturing.

■ MOVING AHEAD

On the basis of survey results, the Roundtable is currently focused on identifying best practices and defining opportunities to improve green chemistry implementation in the sector. Consistent with the adage "What gets measured, gets improved", the Roundtable has initially steered work on best practices toward metrics for evaluating processes and for tracking sector-wide implementation. Analysis of the 2012 Roundtable survey findings on application of green chemistry principles suggests attention to catalysis (Principle #9), design for degradation (Principle #10), and real-time analysis for pollution prevention (Principle #11) for development of best practices. Considering the prominence of reducing energy in manufacturing processes in the ICIS findings, design for energy efficiency (Principle #6) is an important technology subject to address. As work progresses on these topics, training needs that may be unique to chemical manufacturing will be identified and communicated. The Roundtable has been developing these prospects into a number of actionable projects, three of which are summarized below.

Process Metrics. When it comes to process metrics, Roundtable members look for performance measures that (1) clearly link to company environment, health, and safety (EHS) and sustainability initiatives, (2) maintain the overall strength of the breadth of the 12 principles of green chemistry, (3) take a holistic approach to the range of EHS and sustainability factors associated with chemical manufacturing (e.g., water use, greenhouse gas emissions, process safety), (4) relate to key stages of manufacturing that make use of or could benefit from use of the principles of green chemistry, (5) make use of information typically gathered in chemical manufacturing, (6) are relatively easy for chemists and chemical engineers to use, and (7) fit with financial goals of chemical companies.

As a step toward the use of broader sustainability metrics that drive the adoption of green chemistry in chemical manufacturing, the Roundtable is evaluating how member companies can better highlight the economic and environmental aspects of the metrics they use.

Tracking Green Chemistry Implementation. Tracking the adoption of green chemistry in an industrial sector may be important for several reasons. First, it is an opportunity for companies to benchmark and identify best practices. Second, it is important for identifying gaps or areas where a small amount of effort could have a significant impact. Third, it could be used to identify areas where more research is needed to spur innovation and/or broader implementation. Fourth, it could provide governments with useful information to support tax changes or policy devices to facilitate adoption of more sustainable technology.

While green chemistry metrics are in place within a number of individual companies, effective means of tracking the overall implementation of green chemistry across a sector is not yet available. As evidenced by the survey reported on herein, the Roundtable sees this topic as a worthy challenge and has created a measurement focus area geared at measuring and tracking the adoption green chemistry in the chemical manufacturing sector. In addition to internal collaboration among member companies, this focus area is an opportunity to collaborate with other stakeholders.

Defining Research Needs for Industrial Application. Reducing the energy required to manufacture products is a fundamental and common goal of Roundtable members. Virtually all chemical processes include at least one unit operation to separate components. Separation by distillation accounts for over 30% of the energy used in the U.S. chemical manufacturing sector.[2] While process integration and other forms of energy conservation have helped reduce distillation energy consumption in the chemical process industries (CPI), the promise of new low energy separation methods in chemical manufacturing has not been realized. The National Research Council[2] identified "reducing the energy intensity of the CPI" as a "grand challenge for sustainability in the chemical industry". To this end, the Roundtable is actively working on a project to compile what it would take for companies to select less energy-intensive separation technology in place of conventional methods when the need to install new or replacement equipment arises. The key goal here is to jointly define research, development, and demonstration needs for translating promising relevant green chemistry and engineering ideas into implementable, cost-effective, low business risk technology options.

Further Collaboration. Collaboration is vital to assuring the sustainability of the chemical enterprise. It is the way that Roundtable members make progress on a mix of long-term and short-term projects of common interest. Guided by the survey results, members of the Roundtable are collaborating to navigate toward a common goal of sustainability. The Roundtable is open to mutually beneficial collaboration with companies and organizations with similar objectives for implementing green chemistry solutions. The ACS GCI roundtables provide a focus and a forum for companies to partner with each other and like-minded organizations to promote sustainability through broader adoption of the principles of green chemistry. Together, we can accomplish what no single company can do alone.

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Notes

The authors declare no competing financial interest.

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