Green Chemistry: Providing Value Through Sustainable Growth

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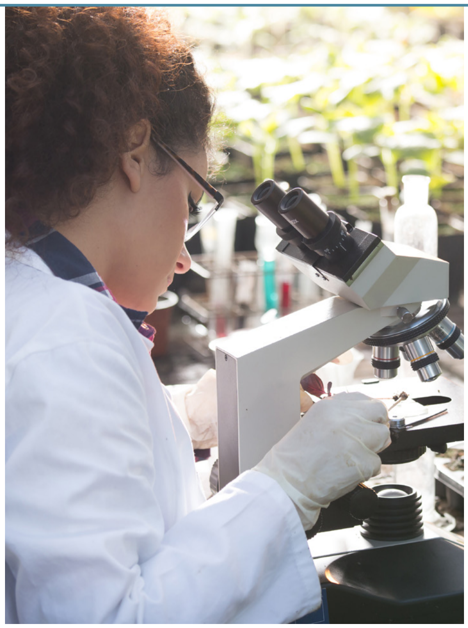

CHALLENGE

The chemical industry is currently ranked as the largest industrial energy consumer and third largest emitter of carbon dioxide.[1] And while it may not affect profitability in the short-term, it could directly impact credibility, value, and growth in the long-term if greener solutions are not considered and implemented.

SOLUTION

The chemical industry can provide immense value to the world and protect its global positioning by pursuing sustainable growth using cleaner, more earth-friendly chemical manufacturing practices and processes. Chemistry holds the key to finding sustainable ways to transform raw materials into products and finding alternative energy sources as our natural sources face depletion.

Green Chemistry

Defined as a framework to reduce the quantities of the chemicals that have a negative impact on human health and the environment

Sustainable Chemistry

The part of chemistry essential to a sustainable society, with a view to product design, manufacturing, consumption of resources, health and safety, economic success and technical innovation, extending far beyond the application of ecological principles in chemical production.

Overview

In 2019, the Chemical Industry reached $3.94 trillion in revenue worldwide ($5.7 trillion when pharmaceutical sales are included), making it the second largest manufacturing industry in the world.[2] After experiencing a decline in 2020 due to factors related to COVID-19, chemical sales are projected to not only recover, but also double until 2030.[3]

However, the continued decline of raw materials, increased pollution resulting from chemical processes and products, and other risks arising from hazardous chemicals demands is attracting a lot of attention from consumers and investors alike. With environmental, social, and governance (ESG) investments on track to become a $30 trillion dollar category by 2030, the increased scrutiny is not expected to wane.

Given this, the Chemical Industry is faced with a promising, albeit challenging, opportunity to innovate for cleaner practices and products, and contribute a unique and timely perspective to an eager and interested market.

The Spot on the Horizon

This paper will present both the progress in green chemistry, as well as the challenges that must be overcome to achieve widespread and universal implementation of green, sustainable practices.

Together, we must aim toward delivering any desired molecule to end-users using safe, economically viable, and sustainable processes.

To achieve that vision, the *Twelve Principles of Green Chemistry,* first outlined by Paul Anastos in his book, *Green Chemistry: Theory and Practice* (1998), are straight-forward objectives toward which all practices and operations should be aligned:

The Twelve Principles of Green Chemistry

1. *Prevent waste*
2. *Maximize atom economy*
3. *Design/use less hazardous chemical syntheses*
4. *Design safer chemicals and products*
5. *Use safer solvents, auxiliary substances and reaction conditions*
6. *Design for energy efficiency*
7. *Use renewable feedstocks*
8. *Reduce derivative reagents: avoid using blocking or protecting groups or any temporary modifications if possible, without generating waste*
9. *Use catalysts, not stoichiometric reagents: catalysts are used in small amounts and can carry out a single reaction many times. They are preferable to stoichiometric reagents, which are used in excess and work only once*
10. *Design chemicals and products to degrade after use*
11. *Analyze in real time to prevent pollution*
12. *Minimize the potential for accidents, by using safer chemicals*

The Path

The good news is the groundwork has already been laid, with several policy frameworks, initiatives, and practices already underway :[4]

1989

The Montreal protocol (1989) involves joint political action for prevention, reduction, remediation, minimization, and elimination of risks during the life cycle of chemicals.

2000

United Nations Member States unanimously adopted the Millennium Declaration at the Millennium Summit in September 2000 at UN Headquarters in New York. The Summit led to the elaboration of eight Millennium Development Goals (MDGs) to reduce extreme poverty by 2015.

2004

In 2004, Stockholm's Convention on Persistent Organic Pollutants (POPs) came into force: protect human health and the environment from POPs by restricting and ultimately eliminating their production, use, trade, release and storage.

2006

The Strategic Approach to International Chemicals Management (SAICM) adopted in 2006, created a policy framework to promote chemical safety around the world, an ambitious goal to achieve the sound management of chemicals in multi-stakeholder processes, so that by the year 2020 the objectives of SAICM were to be implemented.

2015

In 2015, the United Nations presented 17 Sustainable Development Goals (SDGs) to promote inclusive and sustainable industrial development by 2030 (The UN's 2030 Agenda for Sustainable Development).

And, in 2015, the European Commission, together with The Paris Agreement on Climate Change, released an action plan to stimulate Europe's transition toward a circular economy, boosting global competitiveness, fostering sustainable economic growth, and generating new jobs.

2019

In June 2019 Cefic launched its Mid-century Vision (MVC) — Molecule Managers — that sets out a realistic path towards a more sustainable, cleaner, healthier and inclusive Europe in 2050.

Also in 2019, the Inter-Organization Programme for the Sound Management of Chemicals (IOMC) provided an update on progress toward its 2020 goal of producing and using chemicals in ways that minimize adverse impacts on human health and the environment.

Steady Progress

The intentional integration of Green and Sustainable Chemistry practices into these frameworks and initiatives is an important next step, especially given the progress that's been made — and attention received — in chemical research and development, and education. For example, three scientists won the 2001 Nobel Prize in Chemistry for their research in catalyzed reactions (Knowles, Noyori, Sharpless); also the 2005 Nobel Prize in Chemistry was jointly awarded to Yves Chauvin, Robert H. Grubbs and Richard R. Schrock for discovering an organic, catalytic chemical process called "metathesis".

These awards helped crystallize and solidify the importance of research in green chemistry by creating a higher awareness among scientists that the future of chemistry should be greener.

***Metathesis** uses significantly less energy, has the potential to reduce greenhouse gas emissions for many key processes, is stable at normal temperatures and pressures, can be used in combination with greener solvents, and is likely to produce less hazardous waste.*

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And progress isn't just limited to laboratories. Several biotech and chemical companies have been innovating with Green Chemistry practices for nearly 25 years:

2021: **Bristol Myers Squibb** developed five mutually compatible reagents that can be used in solid phase synthesis. One key element of BMS' technology is the use of phosphorous reagents (in solid phase synthesis instead of the traditional non-strategic oxidation reaction) that reduce the amount of reagent and solvent required, as well as improve the stability of the reagent and intermediate products, leading to substantial environmental benefits. The enhanced air and moisture tolerance of the reagents eliminates the need for expensive technology, specialized shipping, and storage. Additionally, these reagents are derived from limonene, a sustainable waste product from discarded citrus peels.

2020: **Vestaron Corporation** developed a new class of biopesticides (SPEAR Insecticides) that show comparable efficacy with synthetic insecticides. The biopesticide is based on a naturally occurring component inspired by spider venom and controls pest management with no adverse effects on humans or the environment.

2019: **Merck & Co** developed a green and sustainable manufacturing process for the antibiotic Zerbaxa. This crystallization-based purification process reduces the mass index by 75%, reduces material costs by 50%, and increases the overall yield by more than 50%. It saves 3.7 million gallons of water annually, reduces the carbon footprint usage by 50%, and energy usage by 38%.

2017: **Dow Chemicals & Papierfabrik Augst Koehler** developed a sustainable thermal printing paper, which eliminates the need for chemicals used to create images, such as BPA or BFS that don't fade. This technology is compatible with thermal printers in commercial use around the world.

2012: **Elevance Renewable Sciences** won the Presidential Green Chemistry Challenge Award by using metathesis to break down natural oils and recombine the fragments into high-performance chemicals, all at advantageous costs.

2009: **Eastman Chem Company** introduced a gentle method for making esters using mobilized enzymes from delicate, natural raw materials never before available. This method saves energy and avoids strong acids and organic solvents.

2002: **Cargill Dow LLC** created bio based, compostable, recyclable PLA polymers using 20-50% less fossil fuel resources. This approach eliminates organic solvents and hazardous materials, is completely recyclable, and uses catalysts to reduce energy consumption and improve yields.

1996: **Donlar Corporation** developed thermal polyaspartate (TPA), a nontoxic, environmentally safe, biodegradable polymer for use in agriculture, water treatment, and other industries. Donlar manufactures TPA using a highly efficient process that eliminates use of organic solvents, cuts waste, and uses less energy. TPA has been used successfully in a variety of applications, such as improving fertilizer uptake in plants, and improving the efficiency of oil and gas production.

Acknowledging Concerns

As A.M. Noce points out, the key to the challenging transition towards a sustainable future and sustainable society, in balance with its environment, is the Green and Sustainable Chemistry. While there is great urgency and tremendous possibility for establishing wider and more standardized Green Chemistry practices, we must be prepared to address the concerns of companies as they shift toward the implementation of greener, more sustainable chemical processes and products:

- Profitability concerns due to compounding factors, including:
  - The current threat of global recession and slower economic growth due to the COVID-19 pandemic,
  - Supply-chain disruptions and with global trade negotiations,
  - Changing consumer demands, including ban on plastic products,
  - Weakened end-market demand in key industries such as aerospace, automotive, construction, etc.
- Reconfiguration of business and operating models to accommodate Green Chemistry practices, including integration of value chain partners.
- Concerns about energy price increases, scarcity of raw materials, and volatile commodity prices.
- Compatibility and integration with new technologies and digital operations.

The key to success will come as we help companies see how many of these challenges can be addressed through the solutions presented. It will require hard work, perseverance, and a great commitment to improve, but we must protect our global positioning through the pursuit of sustainable/ sustainability.

Toward Solutions

While progress is occurring, the entire chemical industry has a lot of work ahead to achieve the vision of delivering any desired molecule to end-users using "safe, economically viable, and sustainable processes," (Kilpin and Whitby Chemistry Central Journal (2015) 9 : 43).

>>> **And we all have a role.**

Chemists and chemical engineers *have enormous control over manufacturing processes by selecting the most sustainable synthetic routes and applying the Twelve Green Chemistry Principles. Specifically, they can aim toward:*

More efficient bond making reactions, targeting:

- Transformations that perform optimally under ambient conditions, which scale well, without requiring additional optimization (auto optimization of reactions),
- Cleaner profiles and higher yielding transformations, aiming 100% conversion,
- Development of systems designed to facilitate "self-separation" and no work up,
- Reactive fragments which can be 'clicked' together,
- Increased utilization of C-H activation, functionalization to improve atom, step economy and reduced reliance on pre-activation,
- Utilization of abundant feedstock precursors.

Employing faster, safer, cheaper methods, with less and greener solvent:

- Multi-step 'one pot' synthesis (Op) and process intensification (Pi),
- Holistic approaches to targets and avoidance of carcinogenic solvents and reagents,
- New developments in analytical purification/scavenger techniques,
- Modular reconfigurable/adaptable reaction systems and improved reaction specificity,
- Greater computing power, carrying out reactions repeatably with full capture of information (ELN integration) and structural data for in silico design,
- Modelling — integration of reaction and reactor design.

Catalytic paradigms for 100% efficient synthesis, that utilize:

- Highly selective catalyst/ligand systems that require lower loading, have higher turnover, are easily recovered and recycled,
- New approaches to selectivity and cross-compatibility for multi-catalyst processing,
- Multifunctional catalysts for sequential reactions,
- Abundant resources (Cu, Fe) and avoid the use of precious metals (Pt, Pd, Rh, Ir, Au),
- Knowledge-based approaches to increase chemo-catalysts discovery and optimization by combining experimental and theoretical approaches.

Chemical companies *can begin taking steps to:*

Develop sustainable, cost-effective alternative feedstocks, largely bio-based feedstocks.

Utilize carbon dioxide (as inexpensive, renewable C1 feedstock) in synthesis of chemicals and transforming the chemical industry.[6]

Establish more diversity, inclusion in the chemical industry, by yielding a greater innovation degree and superior performance.

Implement "Dial-a-molecule", a 100-percent efficient chemical synthesis that opens the door to:

- Designing smart, new, and powerful strategies for molecular assembly and reaction sequences,
- Providing sustainable synthetic routes to answer the need for a sustainable future,
- Achieving 100% efficient synthesis, which would be cost-effective, energy-efficient, and nearly waste-free,
- Modular, mutually compatible reactions that allow "one-pot" multi-step telescoping of reactions,
- Using catalysis and biocatalysis, important for new reactivities and selectivities.

Invest in Green Chemistry R&D through the lens of solution-finding for environmental concerns (e.g. reduction of toxic and hazardous substances, conservation of natural resources, waste management, climate change mitigation, air pollution abatement, water treatment, soil reclamation and bioremediation, sustainable processes).

The global chemical industry *can explore:*

Research and development funding and collaborations with potential partners, including:

- Conventional external sources (e.g. banks), government funding, venture capitalist funding, public offerings, and contractual relationships.

Government policies and programs to:

- Support research and development initiatives through public-private collaboration,
- Provide testimonials of positive impact of development and adoption of green, sustainable chemistry innovations.[7]

Partnerships and alliances between industry leaders, government leaders, policy makers, academia, and communities.

Establishment of metrics to create accountability and measure progress toward green, sustainable chemical practices.

Sustainable design of plastics and plastic projects, particularly how chemical selection considerations influence the overall environmental and health impacts at all stages of the manufacturing, user, and end-of-life stages.

Incorporating Green Chemistry practices along the entire supply chain, including API suppliers and generic drug companies that have not yet embraced Green Chemistry to the extent larger Research and Development companies have.

Changing the nature of the very definition of "performance" from function alone, to function and sustainability (products, feedstocks, and manufacturing processes will need to integrate the principles of Green Chemistry and Green Engineering, under an expanded definition of performance).[8]

Leveraging sustainable-minded customers to gain market share and accelerate adoption of Green Chemistry principles across the supply chain.

Adoption of simple, clear language for non-scientific community regarding the solutions Green Chemistry provides.

In Conclusion

>>> The benefits of Green Chemistry are numerous:

- Reduction/avoidance of toxic and hazardous chemicals, elimination of pollutant chemicals.
- Reliance on renewable resources, decreasing consumption of non-renewable resources.
- Minimization of negative environmental impacts of chemical processing and manufacturing through application of the Twelve Principles of Green Chemistry.
- Provision of clean technologies that are economically competitive for and advantageous to businesses, resulting in improved efficiencies and waste reduction.
- Improved environmental performance ratings that will elevate business brands and result in increased sales.
- Supports compliance with existing and future legal requirements and growing list of restricted substances and materials.

Green Chemistry is a continuously evolving frontier and the Chemical Industry has a tremendous opportunity to pioneer the world toward it. It will require both conviction, patience, and support as policy support, rules and regulations are enforced and research institutes, academia, and the industry align. This transformation will require the best of science, innovation and application of emerging design systems and thinking. Through the pursuit of sustainable growth, the Chemical Industry will not only increase the value it provides to the world, it will also protect its global positioning.

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