



Green Chemistry: A Framework for a Renewable Future

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How to Cite this Article:

Gan, A. (2026). Green Chemistry: A Framework for a Renewable Future. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(03).

<https://doi.org/10.55041/ijcope.v2i3.258>

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<https://doi.org/10.55041/ijcope.v2i3.258>

Abstract: Green Chemistry, guided by its 12 principles, serves as a framework for a renewable future by designing chemical products and processes to minimize or eliminate the use and generation of hazardous substances. It achieves this through a systematic, intentional approach that promotes the use of renewable feedstocks like bio-based materials, reduces waste, increases energy efficiency, and considers the entire life cycle of a chemical, moving towards a more sustainable, circular economy and aligning with global goals like the UN SDGs.

KEYWORDS: Sustainable Chemistry, Sustainable Development Goals (SDGs), Depolymerization, Waste Minimization, Life-Cycle Assessment (LCA) Methods, Life-Cycle Thinking (LCA)

How Green Chemistry Supports a Renewable Future

- **Renewable Feedstocks:** Green chemistry encourages the replacement of finite, non-renewable resources, such as fossil fuels, with renewable materials like plant-derived substances and waste materials.
- **Reduced Waste:** It prioritizes the reduction of waste generation during chemical processes, aiming for efficiency and minimizing the need for disposal or cleanup of hazardous byproducts.
- **Safer Chemicals and Products:** The framework focuses on designing chemicals and processes that are less hazardous to human health and the environment, promoting the use of safer alternatives and benign solvents.
- **Energy Efficiency:** It emphasizes the design of chemical processes that require less energy, ideally conducted at ambient temperatures and pressures, to lower the environmental impact and costs.
- **Life-Cycle Thinking:** Green chemistry promotes a systems approach that considers the entire life cycle of a chemical, from sourcing raw materials to manufacturing, use, and eventual reuse or recycling.
- **Innovation:** By providing a framework for intentional design, green chemistry drives innovation in developing eco-friendly alternatives and new technologies, such as bio-based synthesis using enzymes and microbes.



Impact and Applications

- **Circular Economy:** The principles of green chemistry support a circular economy by minimizing waste and promoting the reuse and recycling of materials, reducing reliance on finite resources.
- **Alignment with Sustainable Development Goals:** Green chemistry's focus on reducing pollution, conserving resources, and promoting health directly contributes to achieving the United Nations Sustainable Development Goals (SDGs).
- **Industrial Transformation:** It offers a pathway for transforming industries, making chemical processes more efficient, less polluting, and more cost-effective, benefiting both the economy and the environment.

For more than three decades, Green Chemistry has provided a framework for chemists and chemical engineers to do their part in contributing to the broad scope of global sustainability. American Chemical Society journals are a great venue for these scientists to share their latest results and provide a resource to the chemistry community and beyond for understanding current problems and envisioning solutions. We believe this is an opportune time to highlight some of the leading articles on the broad theme of Green Chemistry being published today through a Virtual Issue of selected works from nine ACS chemistry and engineering journals. The inception of this Virtual Issue is no coincidence. We have timed it to the 2021 Green Chemistry & Engineering Conference taking place virtually June 14–June 18. Now celebrating its 25th edition, we have seen progress toward more sustainable chemistries being showcased and celebrated at each GC&E conference.¹ The theme of this year's meeting, "Sustainable Production to Advance the Circular Economy", is particularly bold. It highlights the recognition that contributions must take into account a systems approach to reducing environmental impact through intentional design of chemical products, not just considering how raw materials are sourced and in the manufacture and use of industrial and consumer goods but also how these materials and goods may be reused, recycled, or upcycled. The embrace of life-cycle thinking as a goal among the Green Chemistry community comes at the backdrop of the realization of limited resources and a climate crisis the likes of which most of us still fail to fully comprehend. We believe these selected articles are stepping stones on the pathway to advance closed-loop economies while still serving as models for innovation at a fundamental level within their respective chemistry subdisciplines. The drive for efficiency in organic synthesis merges the best of the idealisms of the Enlightenment and the Renaissance. Certainly, there is a premium on rationalism, with an aspiration of mechanistically sound reaction design and process development. But at the same time, the aesthetic appeal of the new ideas that culminate in the advances we now see routinely is unmistakable. There is no constraint on curiosity when we consider the boundary conditions of efficient, environmentally benign processes. On the contrary, these considerations spawn new concepts and approaches, ranging from postmodern expansions of photochemistry, reconsideration of seminal thinking about solvation, importation of physical and mechanical phenomena, to reaction development—the creativity born of efficiency considerations now drives major technology innovation in chemistry. The Journal of Organic Chemistry and Organic Letters are delighted to participate in this Virtual Issue with a selection of perspectives, research articles, and letters that highlight just some of the most impactful science in this arena, across a very wide swath of chemical space. Organometallics, a journal with a long-standing history of reporting fundamental advances in organometallic chemistry, catalysis, and materials, has selected contributions to this Virtual Issue that best highlight the diverse nature of this type of organometallic chemistry and that are likely to impact development of more sustainable chemical processes and the transition to a circular economy. ACS Sustainable Chemistry & Engineering is a world leader in publishing groundbreaking research that addresses the challenges of sustainability, advancing the principles of Green Chemistry and Green Engineering with global reach and impact. Key coverage includes catalysis with emerging feedstocks and synthetic methods for preparing materials and chemicals in a sustainable way to help bring critical innovations from a research setting to commercialization. The journal takes pride in its central role in promoting innovations that will enable the implementation of a circular economy. Industrial & Engineering Chemistry Research publishes many, many papers in the Green Chemistry and sustainability space as these are core considerations in applied chemistry and chemical engineering. With a similar goal, Organic Process Research & Development has a tradition of bridging industrial and academic research. Its focus on process



chemistry as the science that enables the safe, environmentally benign, and economical manufacturing of chemicals is evident in the selected articles for this Virtual Issue, which highlight aspects of catalysis, synthetic methodology development, and synthetic strategy exploration that are needed to enable circular economies.

Sustainable chemistry reducing waste and pollution, inherently safer design, and process optimization.

Another key challenge in developing manufacturing infrastructure for a circular economy remains the minimization of the overall environmental footprint, which must minimize both the environmental impact of the manufacturing processes of chemicals as well as their potential hazard and persistence of the commodity chemicals produced. While the former has been a cornerstone of research in Green Chemistry from its inception in the early 1990s, it is still a fertile area of research, and we see evidence of that in this Virtual Issue. The latter will be addressed in further detail later in this Editorial. Sustainability in organic chemistry, especially in organic synthesis, has been driving innovation for decades. With the amount of waste generated in many synthetic chemistry routes, especially at scale in manufacturing, we are faced with not only an ethical imperative to develop more sustainable chemical processes and products but also a financial imperative. Metrics to gauge our progress, including process mass intensity (PMI), have been developed that allow all aspects of a process to be compared. For example, conducting a reaction in water may not necessarily be an improvement if several volumes of an organic solvent are needed to extract/purify the product. One could even argue that water can be problematic because its high boiling point makes recycling energy intensive, but we do not know these details without consciously thinking about them. A recent perspective highlights the need to explicitly include the assessment of sustainability using Green Chemistry metrics.³ A number of studies highlight advances in catalysis and reaction engineering that have led to waste and energy minimization for processes that still pose significant challenges. Four of the contributions from Organic Letters focus on use of less harmful reagents, catalysts, or routes. On the catalysis front, we see an increase in the scope of synthetic transformations facilitated by supported catalysts. In one example, Pei, Lu, and Cai et al. described the preparation of a reusable magnetic Ag-Fe₃O₄ catalyst supported on cellulose microspheres for reduction of nitrophenols. We also see increased exploration of the utility of base metals in catalysis and organocatalytic processes being performed under mild conditions and with low catalyst loading: for highly enantioselective epoxidation of α,β unsaturated ketones, Jarczak et al. employed an amide-based Cinchona alkaloid at loadings as low as 0.5 mol % as a hybrid phase-transfer organocatalyst. On the application front, the quest for reducing traditionally high E-factors in the pharmaceutical sector continues. In two critical perspectives, colleagues from major pharmaceutical companies highlight the need to develop less wasteful and toxic methods for peptide and oligonucleotide synthesis and purification methods, in light of the growing utility of biological peptide-based pharmaceuticals. In another perspective in The Journal of Organic Chemistry, Rossen highlights insights from process chemistry that can reduce the impact of synthetic chemistry at smaller scales. In Organometallics, Leahy and colleagues provide a perspective from the pharmaceutical industry on the role of catalysis with Earth-abundant metals. Catalysis with Earth-abundant rather than precious metals continues to be an active area of research and key component of sustainable chemistry research. Manuscripts in Organometallics focus on cobalt and iron catalysts for hydrosilylation and nickel precursors and heterogeneous catalysts for Suzuki-Miyaura coupling, one of the most widely used methods for C-C bond formation. Pidko et al. also report the role of manganese in mediating C-C bond formation from organoboranes. Waste reduction also continues to be tackled on the solvent front in the development of alternative solvents, such as less hazardous task-specific ionic liquids, deep eutectic solvents, and increasing the scope and efficiency of reactions in water, such as amidation, amine synthesis, and transfer hydrogenation. We also see the development of new biomass-derived solvents with greener profiles, such as glycerol-derived 1,2,3-triethoxypropane and systematic solvent selection protocols for “greener” solvents.



Safe and Sustainable by Design (SSbD)

Minimizing the environmental impact of chemicals through renewable resources and cleaner production technologies remains essential; however, increasing attention is now being given to the **toxicological profiles** of chemicals throughout their life cycle. Assessing the risks associated with thousands of existing and emerging chemicals at the design stage presents a significant challenge and requires strong interdisciplinary collaboration.

Many toxicological mechanisms are still poorly understood and remain insufficiently regulated. To address this, advanced *in silico* approaches, such as molecular dynamics simulations, are being developed to identify molecular initiation events and predict toxicological behavior. These tools enable faster and more efficient screening of large numbers of chemicals.

Rather than evaluating chemicals individually, researchers have proposed **class-based assessment approaches**, where groups of structurally or functionally similar chemicals are analyzed together. This method helps avoid “regrettable substitutions,” where harmful chemicals are replaced with alternatives that later prove equally or more toxic. For example, the replacement of polybrominated diphenyl ethers (PBDEs) with organophosphate ester flame retardants (OPFRs) has led to unintended adverse health and environmental effects. Similarly, perfluoroalkyl substances (PFAS) are increasingly being addressed as a chemical class due to their persistence and widespread impact.

Another critical area is the development of **sustainable and biodegradable plastics** derived from non-petrochemical sources. However, current research indicates that many so-called biodegradable plastics, such as those used in carrier bags, do not degrade as effectively as expected under natural conditions.

Innovative solutions are also emerging for environmental remediation. For instance, novel techniques using **hydrophobic iron nanoparticles** allow for the efficient magnetic extraction of microplastics from soil, sediments, and water. Such approaches offer promising, sustainable methods for reducing environmental pollution.

Sustainable Water Resources. The sustainable supply of potable drinking water is a global imperative and was identified as a United Nations Sustainable Development Goal in 2015. Just last month in ACS Omega, Gude et al. provided a critical evaluation and perspective of two major routes for developing more sustainable and circular-economy-based wastewater treatment and showed that integrating both concepts may result in superior energy and resource efficiency for wastewater treatment systems. Zodrow et al. report on the use of self-healing bacterially formed cellulose fiber networks creating sustainable biological membranes (Live Filtration Membranes) capable of filtering water for drinking water purposes. Alternative energy-efficient and sustainable remediation approaches include the application of UV/sulfite water treatments to offer effective degradation of persistent PFAS chemicals in raw water for onward drinking water use, reported by Li et al. in ES&T Letters. Environmentally sustainable and energy-efficient nanotechnology membranes also have water purification applications, often in combination with other environmental uses, including energy harvesting, environmental sensing, and remediation. Desalination technologies with superior high efficiency are based on selective desalination membranes and reduced graphene oxide membranes with minimal impact of nanowrinkles. In addition to desalination, the degradation of persistent organic pollutants is also a key priority for water purification. Li, Li, and Zhang report on the use of a porous, coral-like nanostructure photoelectrode for this purpose while simultaneously producing electricity. Luo et al. describe mechanisms of carbo-catalysis in carbon nanotubes with persulfate oxidation for water treatment applications.

De-reliance Dependence on Fossil Fuels.

De-reliance from fossil fuels involves shifting from coal, oil, and natural gas to renewable energy sources and increased energy efficiency to address climate change, reduce air pollution, and enhance energy security. Key strategies include investing in wind and solar power, expanding public transportation, promoting energy-efficient buildings, and implementing carbon pricing. This transition requires global cooperation, political will, and overcoming cultural and economic challenges rooted in historical fossil fuel dependence.



Why De-reliance is Necessary

- **Climate Change:**Fossil fuels are the primary drivers of anthropogenic climate change, leading to global warming and its associated risks like heat stress and increased disease, according to the National Institutes of Health (NIH).
- **Air Pollution:**Burning fossil fuels releases pollutants that cause air pollution, leading to millions of deaths annually from respiratory and cardiovascular diseases.
- **Energy Security:**Heavy reliance on imported fossil fuels makes countries vulnerable to geopolitical shocks, crises, and volatile energy markets.
- **Resource Depletion:**Fossil fuels are finite resources; continued consumption increases natural resource depletion and future energy security risks.

Strategies for De-reliance

- **Transition to Renewables:**Investing in and expanding variable renewable energy sources like wind and solar power is crucial to replace fossil fuels in electricity generation.
- **Improve Energy Efficiency:**Retrofitting buildings, promoting energy-efficient appliances, and improving insulation reduces overall energy demand.
- **Decarbonize Transportation:**Encouraging the use of electric vehicles, expanding public transportation networks, and developing sustainable agricultural practices can reduce reliance on oil.
- **Implement Policy Changes:**Governments can enact policies like carbon pricing, phasing out fossil fuel subsidies, and setting clear targets for renewable energy adoption.
- **Foster International Cooperation:**A global effort, exemplified by initiatives like the Fossil Fuel Non-Proliferation Treaty, is needed to coordinate phase-outs and support affected communities.

Challenges to the Transition

- **Economic and Cultural Roots:**Centuries of development have optimized global infrastructure and economies around fossil fuels, making the shift a complex cultural and technical challenge.
- **Infrastructure Overhaul:**Significant investment and transformation of existing energy infrastructure are required to support a fossil-free future.
- **Political Will:**Unwavering political commitment and international regulatory changes are essential to overcoming resistance and driving the transition forward.

Lifecycle and Systems Thinking. The ability to apply life-cycle thinking to prioritize research and propose truly longterm, sustainable solutions is critical for identifying feasible ways to address circularity. Two common life-cycle assessment (LCA) methods process LCA and economic input–output LCA both suffer from different shortcomings. As a result, many hybrid methods are used to improve the overall accuracy. Luo and Ierapetritou analyze different hybrid LCA methodologies through a case study of two biomass-based p-xylene production technologies and provide key insights applicable to future LCA analysis .LCA analyses of the synthesis of widely used titanium dioxide nanoparticles and butyl acetate provide theoretical guidance for more sustainable production of both. Parkinson and Hunt apply such an approach in proposing the conversion of agricultural land in groundwater-stressed areas from irrigated crop types to rain-fed crop types combined with diversification to solar harvesting, so-called “agrivoltaics”

Future Research Needs in Developing a Circular Economy. The selected publications in this Virtual Issue exemplify the diverse and interdisciplinary contributions surrounding the theme of this year’s conference. They also allow us to identify areas that will require further emphasis in order to strategically advance the field toward applications that facilitate circularity. Some of these areas include:



- Depolymerization and defunctionalization methods for existing chemicals that can allow circularity, especially for plastics;
- Design of circular systems with consideration of human health and ecotoxicity, ideally via rational design of benign commodity chemicals;
- Systematic application of life-cycle analysis, or thinking, and process metrics in developing new manufacturing/synthetic routes;
- Implementation of machine learning and other big-data methods to drive innovation toward new paradigms of circularity.

In order to allow future contributions to highlight the potential application to circular economies, authors may want to consider explicitly addressing some of following questions in their manuscripts. First, consider the source of the materials being used, and if it is fossil-fuel-derived, consider if there is a biobased alternative that could provide the same chemical insights. If elements are used that are facing limited supply, consider whether the synthetic routes and processes could help reduce the use of such materials. Second, discuss whether the method described could impact different stages of a chemical's life cycle. For example, is it a step that is potentially reversible based on kinetics and thermodynamics? If it produces byproducts, could those be a valuable resource? And finally, consider whether the method or product constitutes a safe product that can be either recycled, reused, or remanufactured. Addressing such questions forces the authors to apply life-cycle thinking and to broaden their discussion of the prior art most closely related to the advances presented. We look forward to future fruitful contributions to this field from the innovative authorship of the ACS family of journals.

Krishna N. Ganesh, Editor-in-Chief, ACS Omega, Indian Institute of Science Education Research

Deqing Zhang, Editor-in-Chief, ACS Omega, Chinese Academy of Sciences

Scott J. Miller, Editor-in-Chief, The Journal of Organic Chemistry, Yale University

Kai Rossen, Editor-in-Chief, Organic Process Research & Development, Sanofi

Paul J. Chirik, Editor-in-Chief, Organometallics, Princeton University

Marisa C. Kozlowski, Editor-in-Chief, Organic Letters, University of Pennsylvania

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