Sustainable Catalysis
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Editorial

Designing the Future of Sustainable Catalysis

Navneet Kumar Gupta [1,*] and Prashanth W. Menezes [2,*]

1 Centre for Sustainable Technologies, Indian Institute of Science, Gulmohar Marg, Bengaluru 560012, India
2 Department of Materials Chemistry for Catalysis, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Hahn-Meitner-Platz 1, 14109 Berlin, Germany
* Correspondence: nkgupta@iisc.ac.in (N.K.G.); prashanth.menezes@helmholtz-berlin.de (P.W.M.)
Received: 22 July 2026; Accepted: 27 July 2026; Published: 28 July 2026

How To Cite: Gupta, N.K.; Menezes, P.W. Designing the Future of Sustainable Catalysis. *Sustainable Catalysis* **2026**, *1*(1), 1.

More than 80% of the chemical industry employs catalysts because it effectively balances critical industrial parameters such as activity, selectivity, stability, etc. [1,2]. Catalysis enables the production of fuels, chemicals, and materials needed to sustain modern society. The current industrial catalysts have been developed through intensive research over many decades. At present, these catalytic systems are quite robust, offer high efficiency and economic viability, and have transformed chemical manufacturing into a sophisticated, automated, and globally accepted enterprise. However, most of these systems, especially the heterogeneous ones, remain fossil resource-based (crude oil, natural gas, coal, etc.). These processes have been fully optimized and integrated to operate highly efficiently with specific feedstocks, fulfilling particular industrial demands. Nevertheless, the extensive use of finite fossil resources has critical drawbacks, such as the increasing concentration of greenhouse gases in the atmosphere and a negative impact on climate change [3]. Consequently, there is a lot of interest in changing the existing catalytic processes to make them more sustainable. The chemical industry is shifting its focus to making both the energy and chemicals sustainable. The current evaluation matrix has moved beyond the traditional criteria of cost, yield, and productivity, and now focuses on carbon footprint, energy efficiency, green chemistry, feedstock renewability, and life-cycle assessment [4]. Consequently, renewable-based chemical industries are in demand and are being prioritized [5]. Despite their rapid expansion, these sectors are nascent and face challenges, including extreme price competition from dominant, established, optimized, and rationalized conventional processes, as well as supply chain inefficiencies. Since catalysis plays a central role in the chemical industry, the need for sustainable catalysis will accelerate. Sustainable catalysis is highly concerned about waste or low-carbon feedstocks—biomass, water, CO_2, and waste plastics—for chemical and fuel utilization to achieve carbon circularity. It will be central to the future of the chemical industry, providing favorable cost-benefit analyses and enhanced environmental performance and responsibility (Figure 1) through the minimization of waste and maximization of energy efficiency.

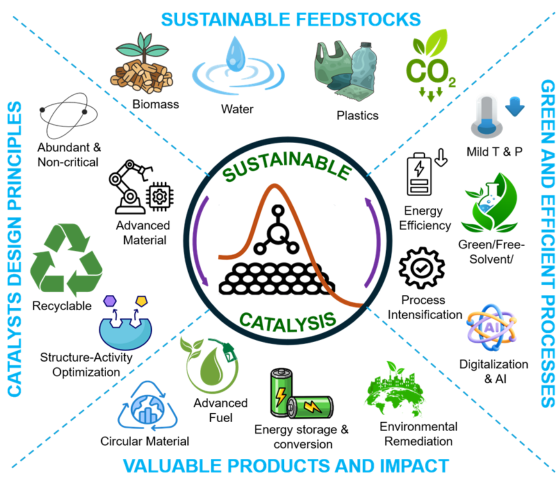

Figure 1. Framework for "Sustainable Catalysis" Design.

1. Outlook of Chemical Processes

The next generation of chemical manufacturing is expected to change dramatically due to the rapid advancement of environmentally friendly production technologies and the worldwide push to reduce carbon footprints. The change will include two notable paradigms: carbon-free energy systems (focused on hydrogen-based technologies) and circular carbon economies involving renewable, waste-derived carbon sources such as biomass, carbon dioxide, and plastic waste [6,7]. Hydrogen is likely to be considered a major clean energy carrier due to its ability to provide carbon-free fuel, chemicals, and electricity. At the same time, the utilization of waste carbon resources such as biomass, CO_2, and other waste streams will be the focus for minimizing the use of fossil resources [8,9].

There are two probable ways to shape the future industries:

i. Integration with Existing Infrastructure: The use of existing setups for renewable feedstocks or advanced carbon-neutral materials will be beneficial for economics and will save large CAPEX; this will also be helpful for the adaptability of new feedstocks at the industrial scale. The use of processing plants, supply networks, and reactor systems will significantly reduce cost and time. This allows industries to continue processing efficiently, while lowering their carbon footprint by changing their operations to use carbon-neutral feedstocks, intermediates or CO_2.

ii. Development of Disruptive Technologies and Materials: Concurrently, the new class of platform chemicals for the next generation of fuel and chemicals will be developed. These include new catalytic systems, advanced functional materials, and unconventional reaction pathways. These innovations could provide the route towards new classes of carbon-neutral chemicals, fuels, and materials with novel properties for new markets in energy storage, advanced fuels, and materials.

The chemical processing technology of the near future will be an integration of old processes and new feedstock and technologies. Sustainable feedstocks, advanced catalysis, and system-level optimization will be required for low-carbon and economically viable industrial processes. The future chemical industry will be largely based on the principles of carbon circularity for the utilization of feedstocks. The industry will move away from linear fossil resources and will increasingly employ renewable and recycled carbon sources, selecting feedstocks on the basis of availability, efficiency and overall sustainability. Water-based green hydrogen will be the major component of the switch. Hydrogen will also be an important reactant in chemical processes such as hydrogenation and hydrotreating, and a clean fuel. But cost optimization, efficient production, and solid storage and distribution systems will be key to large-scale deployment for widespread and reliable use. Biomass is going to be a major feedstock for next-generation fuels, polymers, and speciality chemicals. To make effective use of it, a good knowledge of the feedstock from the beginning to the end, including its variability, processing, upgrading, and final application, is needed. In order to ensure consistent and scalable production, challenges in the supply chain and feedstock heterogeneity need to be overcome. A key strategy will likely be decentralized, close to the biomass source, with efficient upgrading methodologies. The use of waste carbon will be increasingly important in enabling a circular carbon economy. Therefore, CO_2 and plastic waste will be abundant and valuable feedstocks for fuel and chemical production. Much attention will be paid to technologies that can transform plastics and CO_2 into fuels, chemicals, and recyclable materials. In particular, the development of recyclable products from these sources will be important for building carbon-neutral or even carbon-negative systems and thus help reduce the impacts of global warming.

Precision and control will be the most important consideration in the next generation of catalyst and materials design [10]. The focus is expected to shift from traditional nanoparticle-based systems to single-atom catalysis for wider and more effective applications. This transition will require careful engineering of catalyst structures that enable controlled adsorption, activation, and catalytic pathways with atomic-level precision [11]. Furthermore, bio-inspired materials are expected to be essential for the design of highly active catalysts that operate efficiently under mild, ambient conditions. Future catalytic systems will increasingly rely on integrated approaches involving multiple catalytic sites/domains, e.g., the coupling of biocatalysis and chemocatalysis, etc. The development of catalysts that can work under different conditions, including with solar light, would be a key focus area. Artificial intelligence and data-driven approaches will also accelerate the discovery and improvement of catalysts. Process development will rely heavily on an understanding of the basics from the molecular level to large-scale use. Understanding the active and reactive sites will help create new, improved catalysts that can be scaled up. Advanced in situ techniques that provide real-time insights into how catalysts operate will be crucial for understanding their behavior under real-world conditions. This will help close the gap between lab research and industrial use by elucidating the key role of multifunctional catalysts and providing insights into reactive sites, thereby enabling the rational design of next-generation catalysts suitable for scale-up.

Interest in artificial intelligence and machine learning is growing rapidly. These new technologies will play a role in designing new catalysts and also testing them quickly in AI-powered reactors under different conditions to accelerate material discovery [12,13]. AI-driven high-throughput catalysis will be the key to integrating various forms of catalysis, including electrocatalysis, photocatalysis, thermocatalysis, and biocatalysis, to achieve chemical reactions that are more efficient and selective. Combining these integrated catalysis approaches will enable specific reactions to occur under the specified conditions, to overcome the limitations of the process and the catalysts in sustainable chemicals and fuel production under energy-efficient and economically viable conditions. Future catalysis will go beyond laboratory-scale development and will assess viability in real-world applications, not only on cost but also on environmental impact, which will be the key parameter for process development.

2. Scope of the "Sustainable Catalysis" Journal

The Sustainable Catalysis journal is dedicated to moving research in sustainable catalytic science. The Sustainable Catalysis journal focuses on developing safer catalytic systems for the next generation of the chemical industry. This covers areas of catalysis, including homogeneous catalysis, heterogeneous catalysis, biocatalysis, electrocatalysis, photocatalysis, and biotechnology-driven approaches, as well as their integration. The main goal of the Sustainable Catalysis journal is to advance technologies that enable the transition from fossil-based materials to renewable feedstocks. This includes learning the basic principles of operation of catalytic systems and using sophisticated methods to design and optimize them. The journal is intended to bridge research and practice and to promote the development of efficient, sustainable, and scalable catalytic processes for future chemical and energy needs.

The field of Sustainable Catalysis is very broad. Includes many new and important areas, such as energy-related catalysis, circular-economy approaches, environmental catalysis, etc. Some key areas of focus for energy include water splitting, converting biomass to hydrogen/chemicals/fuels, carbon dioxide utilization, nitrogen fixation, and solar-driven fuels/chemicals production. The Sustainable Catalysis journal also examines how to efficiently use waste carbon resources and other waste streams. The main themes are CO_2 utilization, recycling and upcycling of plastics, waste to product conversion and recovery of critical raw materials by catalytic processes.

The journal also covers topics such as catalytic processes for degradation of pollutants, air and water purification. The journal Sustainable Catalysis is dedicated to making these processes work at scale by designing better reactors, creating new catalysts and developing strategies for scaling up these technologies. Sustainable Catalysis gathers experts from chemistry, materials science, chemical engineering and environmental science. The journal Sustainable Catalysis aims to capture the evolution of catalysis from a technology primarily used in fossil-based processes to a technology that is central to sustainable development. The journal Sustainable Catalysis aims to promote the development of catalysis technologies that are environmentally and socially beneficial through publication of rigorous research.

Author Contributions

N.K.G.: conceptualization; software; writing—original draft preparation; P.W.M.: conceptualization; visualization; validation; writing—reviewing and editing. Both authors have read and agreed to the published version of the manuscript.

Funding

N.K.G. thanks the Indian Institute of Science (IISc) for funding. P.W.M. greatly acknowledges support from the German Federal Ministry of Education and Research in the framework of the project Catlab (03EW0015A/B).

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

This article does not contain any new data.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were used in the writing.

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