

Recent Advances in Sustainable and Green Chemical Technologies

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Abstract

Sustainable and green chemistry seeks to redesign chemical products and processes so that they deliver useful functions while reducing hazardous substances, waste generation, resource consumption, and environmental impacts. Recent advances include renewable feedstocks, safer solvents, heterogeneous and biocatalysis, electrochemistry, photochemistry, carbon dioxide utilization, recyclable polymers, continuous-flow processing, and improved process monitoring. These technologies can reduce energy demand, increase selectivity, improve atom economy, and support circular use of materials. However, sustainability must be evaluated across the complete life cycle of a chemical product, including raw-material sourcing, manufacturing, use, and end-of-life management. This paper examines nine major areas of recent progress in sustainable and green chemical technologies and discusses their applications, benefits, challenges, and future prospects.

Keywords

Green Chemistry; Sustainable Chemistry; Green Solvents; Catalysis; Renewable Feedstocks; Biocatalysis; Circular Economy; Carbon Utilization; Green Manufacturing; Sustainable Technologies

Introduction

Chemical technologies support modern society through medicines, materials, agriculture, energy, food processing, electronics, and numerous industrial products. At the same time, conventional chemical production can consume substantial quantities of energy and raw materials and may generate hazardous substances and waste.

Green chemistry provides a framework for preventing pollution at the molecular and process level. Instead of relying primarily on waste treatment after production, it emphasizes designing chemical reactions and products that minimize hazards and waste from the beginning.

Recent technological progress has expanded the practical tools available to chemists and engineers. Renewable raw materials, advanced catalysts, electrochemical synthesis, photochemistry, biocatalysis, continuous processing, and circular material systems are increasingly being integrated into industrial chemistry.

The effectiveness of these approaches depends on chemical performance as well as energy use, feedstock origin, scalability, cost, safety, and complete life-cycle impacts.

1. 1. Renewable Feedstocks and Bio-Based Chemistry

Renewable feedstocks such as biomass, agricultural residues, sugars, oils, cellulose, and other biological resources can provide alternatives to selected fossil-derived chemical raw materials. Biorefineries seek to convert renewable resources into fuels, chemicals, polymers, and other useful products.

Advances in biotechnology and catalytic conversion have improved the ability to transform biomass into platform chemicals and functional materials. However, land use, water consumption, agricultural inputs, transportation, and competition with food production must be considered.

Sustainable feedstock selection therefore requires assessment of resource availability, processing efficiency, carbon balance, and environmental impacts.

2. 2. Green Solvents and Safer Reaction Media

Solvents can represent a major portion of the material input and environmental footprint of chemical processes. Green chemistry research has therefore explored water, ethanol, supercritical fluids, ionic liquids, deep eutectic solvents, and other alternatives to conventional hazardous solvents.

An environmentally preferable solvent should be evaluated for toxicity, volatility, persistence, recyclability, energy requirements, and compatibility with the desired reaction. A solvent with low volatility may still have environmental concerns if its production or recovery is energy-intensive.

Improved solvent selection guides and solvent-recovery technologies can reduce waste and occupational hazards while maintaining process performance.

3. 3. Advanced Catalysis and Biocatalysis

Catalysts increase reaction rates and can improve selectivity, allowing desired products to be formed under milder conditions. Heterogeneous catalysts, nanostructured catalysts, organocatalysts, and supported catalytic systems are being developed for cleaner synthesis.

Biocatalysts such as enzymes offer high selectivity and can operate under relatively mild temperatures and pressures. Protein engineering and directed evolution have expanded the range of reactions that enzymes can perform in industrial settings.

Future catalyst development increasingly emphasizes abundant elements, catalyst recovery, long service life, high selectivity, and reduced environmental impact.

4. 4. Photochemistry and Electrochemical Synthesis

Photochemical and electrochemical methods can replace or reduce the need for conventional reagents and harsh reaction conditions. Photochemistry uses light to activate molecules, while electrochemistry uses electrical potential to drive oxidation or reduction reactions.

These approaches can provide high selectivity and may be powered by renewable electricity or sunlight. Modern LED sources, improved photocatalysts, electrochemical reactors, and flow systems have expanded their potential for synthetic chemistry.

Challenges include scale-up, electrode and catalyst stability, mass transfer, light penetration, and integration with industrial process requirements.

5. 5. Energy-Efficient and Continuous Chemical Processing

Reducing energy consumption is a major objective of sustainable chemical manufacturing. Process intensification, microwave-assisted reactions, flow chemistry, membrane separation, heat integration, and improved catalysts can reduce energy demand in selected processes.

Continuous-flow chemistry can improve heat and mass transfer and provide precise control of reaction conditions. Smaller reaction volumes may also improve safety for certain highly reactive systems.

Energy efficiency should be assessed alongside productivity, equipment requirements, solvent recovery, waste generation, and the source of the electricity or heat used by the process.

6. 6. Carbon Capture, Utilization, and Sustainable Carbon Chemistry

Carbon dioxide is both a greenhouse gas and a potential carbon feedstock. Carbon capture and utilization research investigates ways to capture CO₂ and convert it into fuels, chemicals, polymers, carbonates, and other products.

Catalytic, electrochemical, photochemical, and biological approaches are being developed to activate the relatively stable CO₂ molecule. The sustainability of these pathways depends strongly on the energy source, capture requirements, conversion efficiency, product lifetime, and final carbon fate.

Carbon utilization is most beneficial when it forms part of a broader strategy for reducing emissions and avoiding fossil-carbon extraction.

7. 7. Circular Chemistry and Sustainable Polymers

Circular chemistry aims to keep chemical materials and their constituent atoms in productive use for longer periods. Polymer research is increasingly focused on recyclable-by-design materials, chemical recycling, depolymerizable polymers, biodegradable systems, and improved use of recycled feedstocks.

Designing materials for easier separation and recovery can improve end-of-life options. Chemical recycling can return selected polymers to monomers or useful chemical intermediates, while mechanical recycling can preserve polymer value when waste streams are sufficiently clean.

Material design should consider durability during use together with realistic recycling or degradation conditions after use.

8. 8. Green Analytical Chemistry and Digital Process Monitoring

Analytical chemistry supports sustainability by measuring reaction performance, contaminants, emissions, impurities, and resource use. Green analytical chemistry seeks to reduce sample size, solvent consumption, energy use, and hazardous reagents while maintaining reliable measurements.

Sensors, spectroscopy, process analytical technology, automation, and data-driven control can provide real-time information during manufacturing. Early detection of deviations can reduce rejected batches, energy waste, and unnecessary raw-material consumption.

Digital monitoring can therefore complement green reaction chemistry by improving process control and resource efficiency.

9. 9. Future Prospects and Challenges

The next generation of sustainable chemical technologies is likely to combine green chemistry with artificial intelligence, advanced materials, biotechnology, renewable energy, automation, and circular manufacturing. Machine learning can help predict molecular properties, reaction outcomes, catalyst performance, and process conditions.

Major challenges include scaling laboratory discoveries, ensuring consistent feedstock supply, reducing capital costs, validating life-cycle benefits, and developing infrastructure for recycling and resource recovery.

The future of sustainable chemistry will depend on integrating molecular design with process engineering and life-cycle thinking. Technologies should be evaluated not only by whether they use a renewable or safer input, but by their complete environmental and economic performance.

Diagram

The diagram below summarizes major areas of recent sustainable and green chemical technology, including renewable feedstocks, green solvents and catalysis, energy efficiency, and circular low-waste processes.

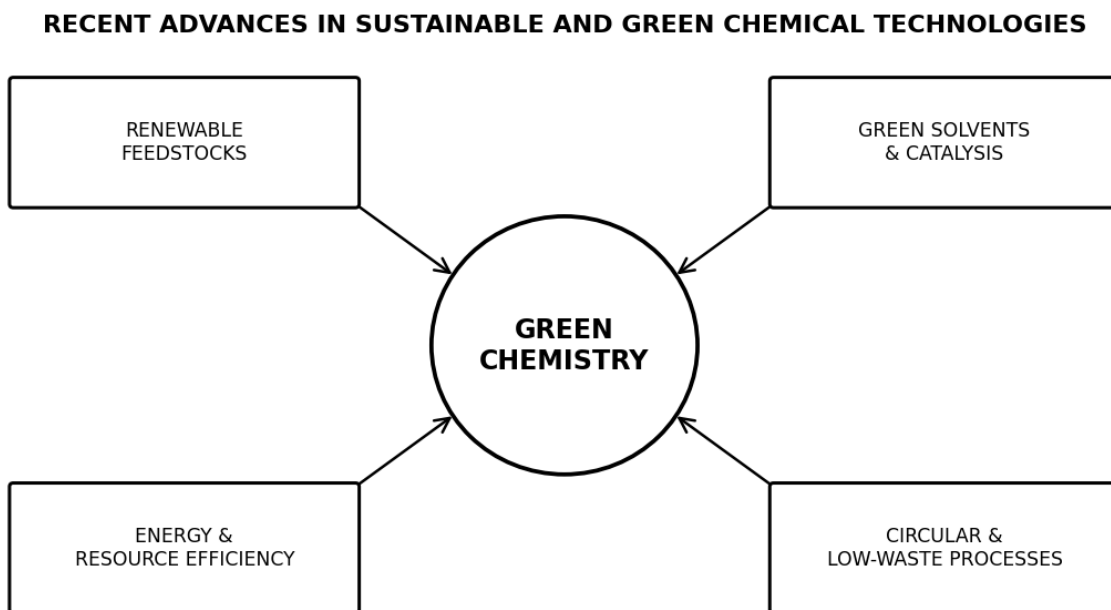


Figure 1. Simplified overview of sustainable and green chemical technologies.

Conclusion

Recent advances in green and sustainable chemistry are changing how chemical products and processes are designed. Renewable feedstocks, safer solvents, advanced catalysis, biocatalysis, photochemistry, electrochemistry, continuous processing, and circular materials can reduce waste and improve resource efficiency.

No individual technology is automatically sustainable. Energy requirements, raw-material sourcing, toxicity, catalyst recovery, process scale, product lifetime, and end-of-life pathways must all be considered. Life-cycle assessment is therefore important for distinguishing genuine environmental improvements from simple changes in input materials.

Continued integration of chemistry with biotechnology, renewable energy, digital technologies, and circular manufacturing can accelerate the development of safer and more resource-efficient chemical systems. The long-term goal is to maintain chemical functionality and economic value while minimizing environmental and health impacts.

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