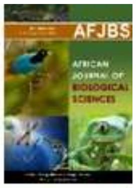
https://doi.org/10.48047/AFJBS.8.5.2026.105-120

African Journal of Biological Sciences

Journal homepage: http://www.afjbs.com



Research Paper Open Access

Advances in Green Chemistry for Sustainable Industrial Applications

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Volume 8, Issue 5, May 2026
Received: 25 March 2026
Accepted: 18 April 2026
Published: 22 May 2026
doi:10.48047/AFJBS.8.5.2026.105-120

Abstract

Green chemistry has emerged as a practical response to the environmental problems that conventional chemical processes have created over decades. This review covers recent developments in three interconnected areas: how industry is shifting to renewable raw materials, what cleaner chemical processes now look like in practice, and which waste-reduction strategies are proving most effective. We examine progress in sustainable feedstocks, including bio-based inputs and renewable energy, alongside catalytic innovations that cut dependence on hazardous reagents and solvents. The review also surveys atom-efficient reactions, waste valorization, and closed-loop industrial systems. We discuss what green chemistry adoption actually looks like at industrial scale, the real costs, the infrastructure headaches, and where technology transfer has worked and where it has stalled. Meaningful gaps remain in scaling these solutions, and we identify them directly. The review closes with directions for future work: better catalyst design, more energy-efficient processes, and the regulatory and policy frameworks that will determine how widely these approaches spread.

Keywords: Green Chemistry, Renewable Resources, Sustainable Processes, Waste Reduction, Industrial Applications, Clean Catalysis

Introduction

Green chemistry, sometimes called sustainable chemistry, is about designing chemical products and processes that eliminate or significantly reduce hazardous substances from the outset (Anastas & Zimmerman, 2018). The field is organized around twelve principles covering waste prevention, atom economy, safer solvents, energy efficiency, renewable feedstocks, and inherently safer process design (Tucker et al., 2020). Taken together, these principles push toward lower environmental impact, better process economics, and genuine innovation in the chemical sciences.

The case for this shift has become harder to ignore. Climate change, resource depletion, and growing industrial pollution have forced sustainability to the center of how we think about manufacturing. Traditional chemical production has long depended on energy-intensive methods and toxic reagents, with real costs to the environment and public health (Yousefi et al., 2021). Green chemistry offers a way to reduce contamination, improve economics, and meet tightening regulations, including those tied to the United Nations Sustainable Development Goals on responsible production, climate, and water quality (Glavič & Lukman, 2021).

This review was motivated by the growing urgency of moving industrial systems toward sustainable practice, and by how much has changed in recent years. Advances in catalysis, solvent design, biomass processing, and waste valorization are generating results that can actually scale (Kümmerer et al., 2020). The addition of machine learning and life cycle assessment tools is changing how we predict and measure sustainability outcomes at a systems level (Jeswani et al., 2022). Given how fast this field moves, a current review that names the real strategies, assesses scalability honestly, and identifies where knowledge is still thin seems worth doing.

The review is organized as follows. Section 2 covers novel green solvents and catalysts. Section 3 addresses waste minimization and valorization. Section 4 reviews synthesis advances, flow chemistry, photocatalysis, and biotransformations in particular. Section 5 presents industrial case studies. Section 6 discusses what challenges remain and where the field is likely to go.

Historical Context and Evolution of Green Chemistry

Green chemistry did not appear fully formed. It grew out of a specific moment in the early 1990s when the scale of chemical pollution was becoming impossible to manage after the fact. The field's clearest early landmark was 1998, when Anastas and Warner laid out the Twelve Principles, a framework that gave chemists a concrete way to design processes with environmental outcomes in mind from the start, not as an afterthought. What began as primarily academic work has since become central to both industrial practice and global sustainability policy (Bhandari et al., 2021).

Regulatory pressure has played a substantial role. The U.S. EPA launched its Green Chemistry Program in the 1990s to encourage safer, less polluting technologies (EPA, 2022). The EU's REACH regulation, introduced in 2007, pushed companies to demonstrate chemical safety and actively substitute hazardous substances (ECHA, 2020). These frameworks didn't just incentivize change, in many cases, they required it.

Early green chemistry focused mostly on cleaner lab-scale synthesis and waste reduction. The field has since expanded considerably, drawing on systems analysis, life cycle assessment, and artificial intelligence to design safer and more sustainable processes across entire value chains (Tulloch et al., 2020). It now extends well beyond synthesis into sustainable materials, renewable energy, circular economy models, and green engineering (Matos et al., 2022).

This shift, from niche concern to foundational industrial principle, reflects both scientific maturation and genuine alignment with environmental policy. Where the field goes next will depend on how well technological innovation, regulation, and interdisciplinary collaboration reinforce each other.

Emerging Sustainable Approaches

Recent progress in green chemistry spans several interconnected fronts. The areas seeing the most traction include renewable feedstocks, catalysis, alternative solvents, energy-efficient processing, and circular economy strategies.

Renewable Feedstocks and Biomass Utilization

One of the clearest trends in green chemistry is the shift away from fossil-based inputs toward renewable carbon sources. Lignocellulosic biomass, the complex of cellulose, hemicellulose, and lignin that makes up plant cell walls, has become a practical alternative feedstock for producing platform chemicals like levulinic acid, furfural, and 5-HMF from agricultural and forestry residues (Li et al., 2023). Better pre-treatment and catalytic conversion methods have made this increasingly cost-competitive.

Algae are attracting similar interest. Fast growth rates, minimal land requirements, and rich biochemical composition make algal biorefineries a credible route to biofuels, bioplastics, and specialty chemicals produced through green processing (Subramaniam et al., 2021).

A related approach, sometimes called waste-to-chemical, converts municipal solid waste, food waste, and industrial by-products into useful compounds. Anaerobic digestion, thermochemical conversion, and microbial fermentation are the main techniques here, and they address greenhouse gas reduction alongside resource recovery (Mahmoodi et al., 2022).

Green Catalysis

Catalysis sits at the center of most advances in green chemical processing. Both heterogeneous and homogeneous catalysts are being redesigned for better selectivity, stability, and reusability, reducing the need for toxic reagents and solvents. Nanostructured catalysts, in particular, show real potential for improving catalytic efficiency without the environmental costs of conventional approaches (Pérez-Ramírez & López, 2019).

Biocatalysis, using enzymes and whole-cell systems, offers high selectivity at mild conditions, cutting both energy use and waste. Directed evolution and machine learning-guided enzyme design have widened the industrial applicability of this approach considerably (Sheldon & Woodley, 2018).

Photocatalysis and electrocatalysis use light or electricity to drive reactions, making them attractive for applications like water splitting, CO_2 reduction, and selective oxidation (Wang et al., 2021). These methods tap renewable energy sources directly and avoid many of the reagent costs of conventional synthesis.

Replacing hazardous solvents remains a priority. Supercritical CO_2 provides a non-toxic, tunable medium for extraction, polymerization, and reactions like hydrogenation (Gogate & Pandit, 2019). Ionic liquids and deep eutectic solvents have moved from curiosity to practical tools, valued for their low volatility, thermal stability, and recyclability in catalysis, separations, and biomass processing (Paiva et al., 2021). Aqueous and solvent-free systems are also gaining ground, water, once considered unsuitable for most organic reactions, is now used routinely in multicomponent and enzymatic processes (Cintas & Mantegna, 2020).

Energy efficiency rounds out the picture. Microwave-assisted synthesis cuts reaction times and solvent use simultaneously (Kappe et al., 2022). Flow chemistry enables precise control over reaction conditions, better scalability, and improved safety for hazardous or exothermic processes, it is reshaping pharmaceutical and fine chemical manufacturing (Plutschack et al., 2017). Mechanochemistry and ultrasound-assisted synthesis offer solid-state or low-solvent alternatives that improve atom economy without sacrificing yield (Do & Friščić, 2020).

Waste minimization and circular economy thinking are now woven into green chemistry from the design stage. Atom economy, maximizing how much of the starting material ends up in the final product, guides reaction design (Trost & Brindle, 2020). Process intensification, combining reaction and separation steps and enabling multi-step transformations, reduces both material and energy waste. By-product valorization is gaining traction as well: glycerol from biodiesel production, for example, can be converted into solvents, polymers, or value-added chemicals rather than discarded (Zhou et al., 2022). Closed-loop systems that recycle solvents, catalysts, and by-products are becoming standard in industries pursuing zero-waste targets (Kümmerer et al., 2020).

Green chemistry principles are being applied across industry, pharmaceuticals, agrochemicals, polymers, textiles, and food, with concrete results in both environmental and economic terms.

In the pharmaceutical sector, adoption has been driven partly by regulatory pressure and partly by genuine cost savings. Companies including Pfizer and GlaxoSmithKline use Process Mass Intensity (PMI) as a standard metric for evaluating and improving green process development (Sherman et al., 2021). The synthesis of oseltamivir (Tamiflu®) was redesigned around shikimic acid from renewable sources and biocatalysis, replacing a hazardous reagent-heavy process (Lin et al., 2022). Merck's synthesis of sitagliptin using a transaminase enzyme cut waste by 19% and removed the need for metal catalysts entirely (Sheldon & Woodley, 2018).

Agrochemicals and fine chemicals have seen a shift toward pesticides with lower toxicity and higher biodegradability. New herbicides and fungicides draw on natural product frameworks, flavonoids and terpenoids, that break down more cleanly in the environment (Patra et al., 2020). Manufacturing processes have moved toward solvent-free synthesis, solid-supported catalysis, and flow chemistry, particularly for insect pheromones and plant growth regulators (Kümmerer et al., 2020).

Figure 1 shows a sustainable processing pathway for converting plant-derived terpenoids into bioactive agrochemicals using green chemistry methods. The process begins with biomass preparation, then extracts terpenoids using Deep Eutectic Solvents (DES), chosen for low toxicity, biodegradability, and high extraction yields (Nguyen et al., 2024). After separation, the terpenoids undergo mild oxidation in a DES medium to introduce functional groups or modify structure, improving biological activity while keeping the process aligned with green chemistry protocols. The oxidized terpenoids are then formulated with stabilizers and carriers for agricultural use.

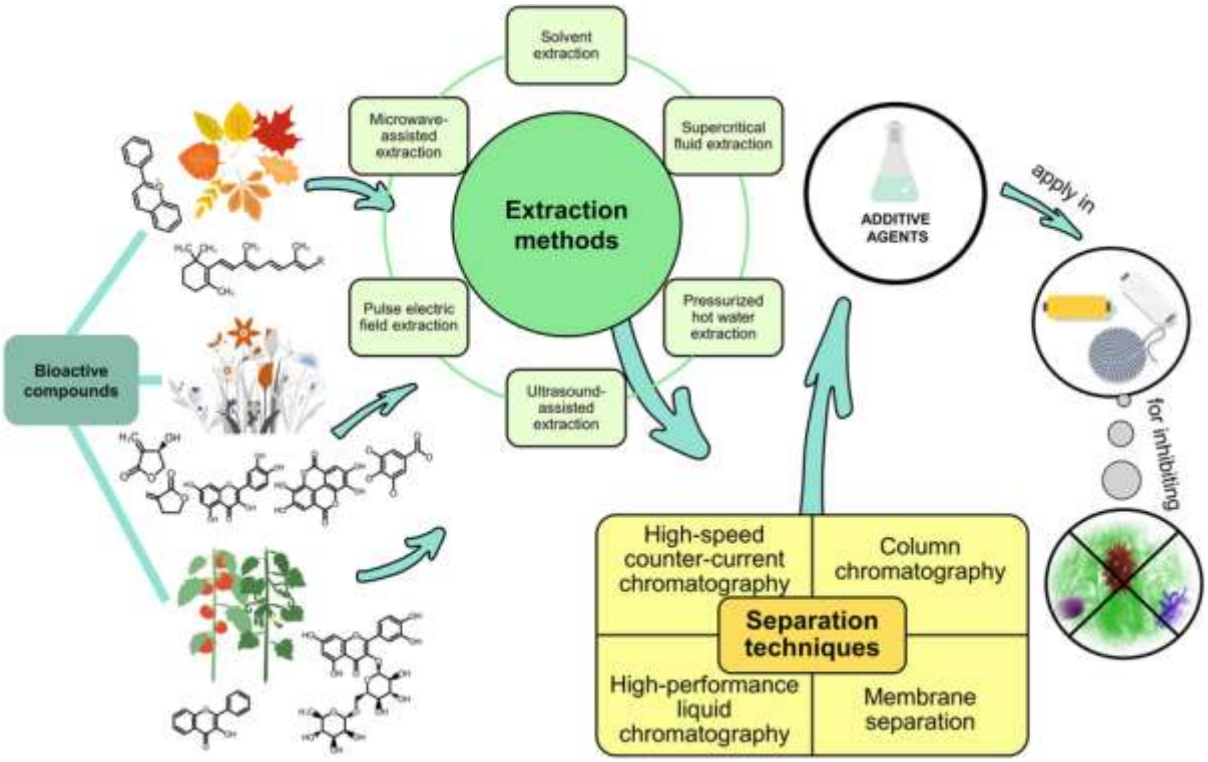

Figure 1. Green Bioconversion Pathway for Terpenoid-Based Agrochemical Formulation from Plant Biomass Using Deep Eutectic Solvents (DES) (Nguyen et al., 2024).

Polymer and Material Science

Bio-based polymers have moved from laboratory novelty to commercial reality. Polylactic acid (PLA) and polyhydroxyalkanoates (PHA), derived from starch or produced through bacterial fermentation, are now available at scale, compostable, renewable, and with a lower carbon footprint than conventional plastics (Chen et al., 2021). Alongside these, recyclable and degradable materials, CO_2-based polycarbonates, dynamic covalent polymers, and enzymatically recyclable plastics, are being developed for high-value packaging and electronics applications (Zhu et al., 2022).

Figure 2 illustrates the PLA production pathway. Starting from corn starch, the process runs through enzymatic hydrolysis, microbial fermentation to lactic acid, chemical conversion to lactide, and ring-opening polymerization to form high molecular weight PLA. The resulting polymer can be molded into biodegradable packaging. This is a circular alternative to petroleum-based plastics that degrades under composting conditions, directly addressing the plastic accumulation problem (EuP Egypt, 2025).

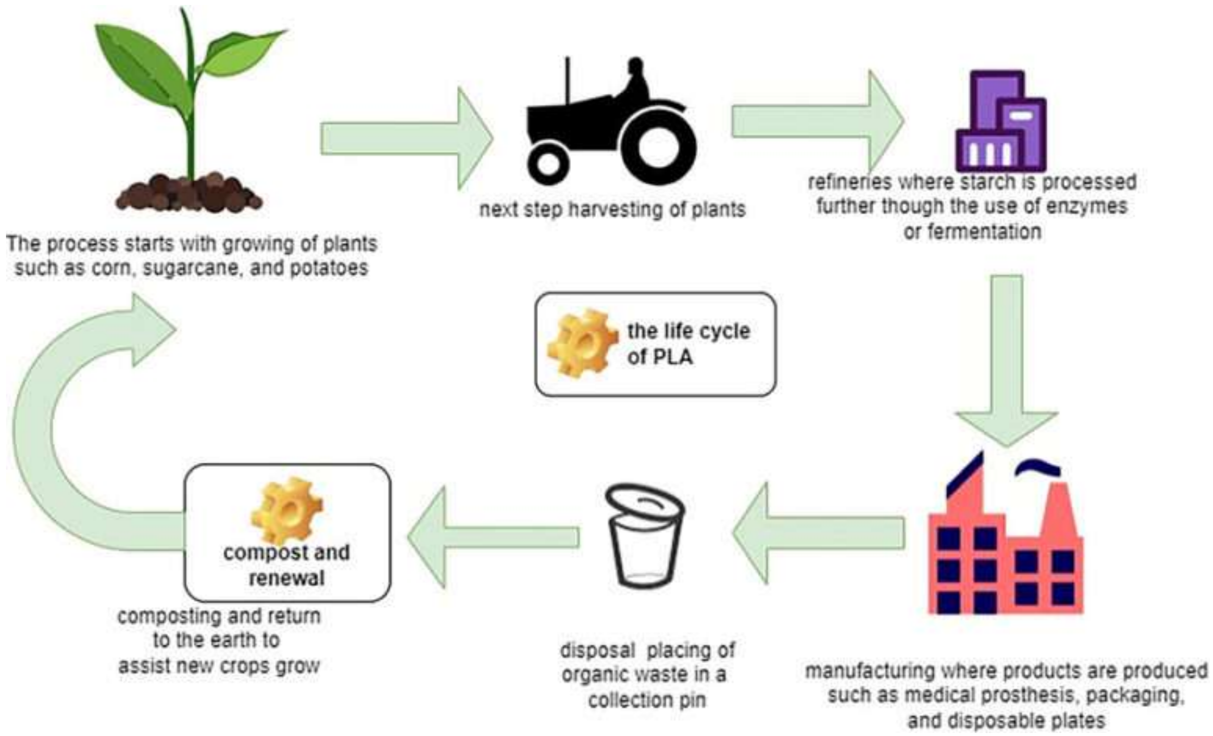

Figure 2. Sustainable pathway for converting corn-based biomass into compostable packaging through PLA synthesis (EuP Egypt, 2025).

Textile, Cosmetics, and Food Industry

Consumer-facing industries have been slower to shift, but the direction is clear. In textiles, hazardous azo dyes and heavy metal mordants are being replaced by plant-based indigo, enzymatic dyeing, and ultrasound-assisted dye fixation, reducing environmental toxicity while maintaining color quality (Rai et al., 2020). Cosmetics companies are reformulating away from parabens and petrochemicals toward bio-based emollients and natural antioxidants, responding to both health data and consumer pressure. In food processing, supercritical CO_2 and microwave-assisted extraction are displacing conventional chemical methods for producing natural colorants and preservatives (Galanakis et al., 2019).

Microalgae represent a particularly interesting case where environmental remediation and resource generation happen in the same system. By integrating microalgae cultivation into industrial operations, wastewater treatment plants, power stations, industries can use CO_2 emissions and nutrient-rich effluents as inputs. As Figure 3 shows, microalgae in photobioreactors absorb CO_2 from flue gas, nutrients from tertiary-treated wastewater, and light to produce biomass. That biomass yields biofuels, fertilizers, and food products (Shaikh Abdur Razzak et al., 2024).

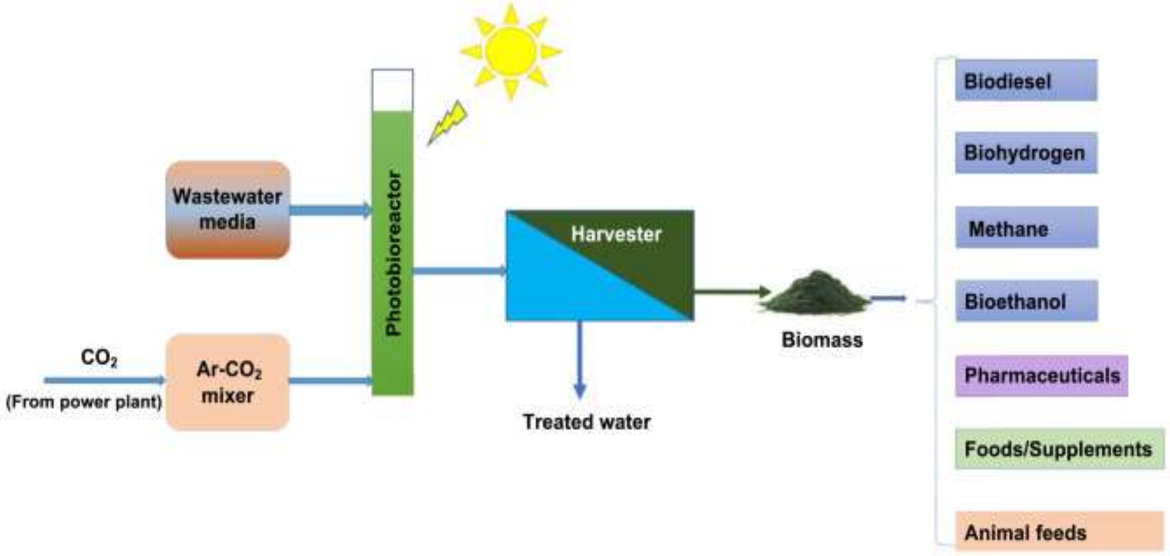

Figure 3. Integrated system for CO_2 capture, biomass harvesting, and production of fuel and non-fuel products through microalgae cultivation in a photobioreactor (Shaikh et al., 2024).

Green chemistry has also become the foundation for converting renewable biological feedstocks into industrial products at biorefinery scale. Microalgae, lignocellulosic biomass, and other bio-based inputs move through biochemical, thermochemical, or catalytic conversion to produce biofuels, biopolymers, and carbon materials like biochar and hydrochar. Co-products from these processes support carbon sequestration and wastewater treatment (Plotka-Wasylka et al., 2020; Choi & Verpoorte, 2019). The guiding principles are visible throughout: minimize waste, use renewable inputs, and favor cleaner transformations (Anastas & Warner, 1998). These frameworks align well with circular economy models, where cascading valorization means nothing goes to waste (Ferreira et al., 2023).

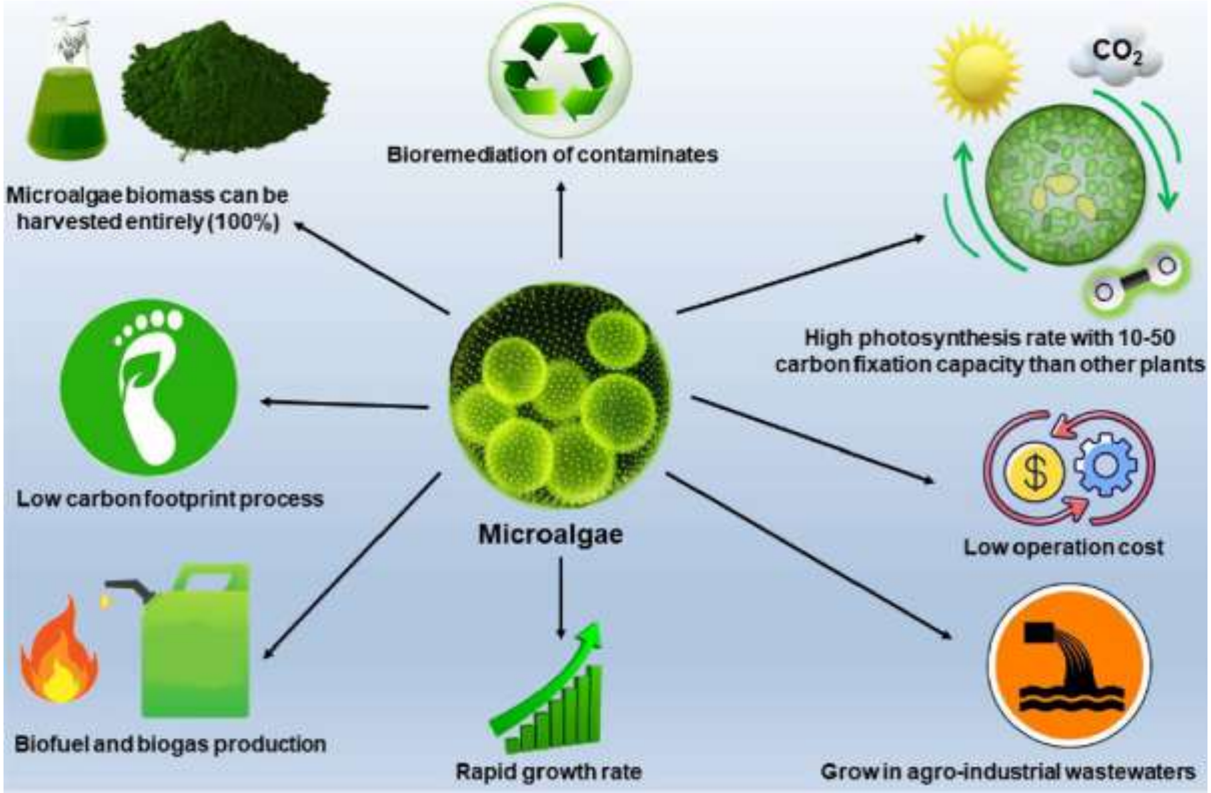

Figure 4. Integrated Green Chemistry Pathways for the Valorization of Microalgae into Sustainable Industrial Products (Katiyar et al., 2023).

Challenges and Limitations

The potential of green chemistry is real, but so are the obstacles to its wider adoption. Economic barriers, technical constraints, and regulatory complexity all slow the transition from laboratory results to industrial practice.

Economic and Scalability Issues

Cost remains the most persistent barrier. Many green chemistry solutions are environmentally superior but require significant upfront investment, new infrastructure, specialized equipment, or novel feedstocks (Sheldon, 2020). Biomass-derived feedstocks are renewable, but converting them to high-value chemicals often requires complex pre-treatment that becomes prohibitively expensive at commercial scale (Tuck et al., 2012; Ragauskas et al., 2014). Supply and quality consistency also vary by geography, creating logistics problems that make scale-up harder than bench results suggest.

Technical and Regulatory Barriers

On the technical side, catalyst stability, reaction selectivity, and compatibility with existing industrial infrastructure remain stubborn problems. Biocatalysts are selective, but they operate within narrow windows and require strict process control (Arora & Sharma, 2021). Photocatalysis and electrocatalysis often depend on scarce or expensive materials and may need substantial energy inputs, which can undercut their sustainability case.

Regulatory frameworks designed to encourage green chemistry sometimes create friction of their own. Compliance with REACH or EPA Green Chemistry requirements involves complex, time-consuming transitions for industry (Anastas & Eghbali, 2010; ECHA, 2022). The regulatory demands are legitimate, but the transition burden can slow the very shift they are meant to accelerate.

Gaps in Current Research and Adoption

There are still real knowledge gaps. Many proposed green solutions have not demonstrated clear superiority over conventional approaches across both environmental and economic dimensions. Closing those gaps requires research that spans synthetic chemistry, systems engineering, life cycle assessment, and industrial ecology working together, not in separate silos. Industry adoption is also hampered by limited awareness and insufficient training among working chemists and engineers, and by weak incentives to walk away from established conventional processes (Dicks & Hent, 2015; IUPAC, 2023).

Future Perspectives

Several developments look likely to reshape green chemistry over the coming decade, driven by new technologies, more supportive policies, and wider interdisciplinary collaboration.

Integration of AI and Digital Chemistry

Artificial intelligence, machine learning, and digital chemistry tools are changing how fast chemical discovery and process optimization can happen. These tools enable predictive modeling, real-time monitoring of green metrics like atom economy and E-factor, and faster identification of new catalysts (Schwaller et al., 2021). AI-driven retrosynthetic planning has already demonstrated its ability to design synthetic routes that reduce waste and energy use in alignment with green chemistry principles (Granda et al., 2018). High-throughput experimentation and autonomous laboratories are accelerating this further.

Green Chemistry in Emerging Economies

Africa, Asia, and Latin America are increasingly important in any realistic picture of global green chemistry adoption. These regions have local bio-based resources and are developing eco-friendly technologies that address environmental harm while supporting economic growth (Ameh et al., 2021; Bhaskar et al., 2020). But the barriers are real: limited infrastructure, weak policy enforcement, and low industry awareness. Targeted investment in capacity building and regional innovation hubs is needed, not just technology transfer from wealthier countries.

Policy, Education, and Global Collaboration

Policy frameworks will determine how far green chemistry spreads beyond early adopters. Government incentives for eco-innovation, requirements for greener alternatives in national regulations, and harmonized international chemical safety standards are critical priorities (OECD, 2022). Equally important is education: future chemists need to graduate with sustainability built into how they think about problems, not as an elective concern (Cacciatore et al., 2022). Global partnerships between governments, universities, and industry, supported by platforms like the UN Green Industry Initiative and the International Green Chemistry Institute, are necessary to enable the knowledge exchange that makes all of this scalable.

Potential for Interdisciplinary Innovation

Green chemistry has already crossed into biotechnology, nanotechnology, materials science, and engineering, and the results, biodegradable materials, green electronics, circular economy solutions, show what interdisciplinary work can produce (Kümmerer et al., 2020). Emerging research that integrates synthetic biology, data science, and systems-level life cycle analysis will expand these possibilities further, enabling the design of chemicals, products, and processes that are both high-performing and environmentally defensible.

Conclusion

This review has traced the real progress in green chemistry and what it means for industrial practice. Renewable feedstocks, innovative catalysis, alternative solvents, energy-efficient synthesis, and waste minimization are all reshaping how pharmaceuticals, agrochemicals, polymers, textiles, and food products are made with demonstrable results, not just promise.

The urgency of this transition should not be overstated for effect but it also should not be understated. Global pollution and resource depletion are accelerating, and conventional chemical manufacturing carries real, quantifiable costs. Green chemistry offers approaches that are scientifically sound, increasingly economically viable, and consistent with tightening regulatory requirements.

What it requires is coordinated effort. Researchers need to keep developing solutions that actually scale and that hold up under honest economic comparison. Industry needs to move beyond pilot projects and embed sustainability metrics into standard product development. Policymakers need to build incentive structures that make the transition easier, not harder, and to ensure green chemistry becomes part of standard chemistry education at every level.

The trajectory of this field will be shaped by whether academia, industry, and government can work together effectively not in isolation, and not at the pace of the slowest actor.

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