

ADVANCES IN GREEN CHEMISTRY FOR SUSTAINABLE INDUSTRIAL APPLICATIONS: A COMPREHENSIVE REVIEW

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DOI: <https://doi.org/10.5281/zenodo.22930748>

Keywords

Green chemistry, industrial applications, renewable feedstocks; biomass valorization, circular economy, life-cycle assessment, sustainable manufacturing.

Article History

Received: 01 June 2026

Accepted: 23 August 2026

Published: 24 September 2026

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Abstract

Green chemistry has evolved from a pollution-prevention concept into a design framework for reducing hazards, resource consumption, waste generation, and energy demand across the life cycle of chemical products and processes. This comprehensive review examines recent advances in green chemistry and their relevance to sustainable industrial applications, with emphasis on catalysis, renewable and waste-derived feedstocks, green solvents, biocatalysis, biomass valorization, flow chemistry, photocatalysis, electrocatalysis, process intensification, circular manufacturing, and digital approaches. The review first summarizes the twelve principles of green chemistry and explains how they differ from approaches that merely treat pollution after it has been generated. It then considers how these principles are translated into industrial practice through safer reaction design, high atom economy, selective catalysis, solvent substitution, renewable carbon, energy-efficient processing, real-time monitoring, and design for degradation. Particular attention is given to biorefineries and biomass-derived chemicals, where catalytic and chemoenzymatic conversion can connect waste streams with higher-value products. Industrial examples and enabling technologies in pharmaceuticals, polymers, fuels, food and agrochemicals, water treatment, and advanced materials are discussed. Green solvents such as water, bio-based solvents, ionic liquids, deep eutectic solvents, and supercritical fluids are compared in terms of opportunities and limitations rather than being assumed to be universally benign. The review also emphasizes that a process should not be described as sustainable solely because it uses a renewable feedstock or a biological catalyst;

life-cycle assessment, process mass intensity, E-factor, energy demand, toxicity, catalyst criticality, recyclability, and economic feasibility should be evaluated together. Emerging directions include continuous manufacturing, earth-abundant catalysis, electrochemical and photochemical synthesis, artificial intelligence-assisted reaction optimization, and integrated circular biorefineries. Major barriers remain, including scale-up, feedstock variability, catalyst stability, solvent recovery, infrastructure requirements, data gaps, regulatory constraints, and the potential for burden shifting between environmental categories. Future industrial green chemistry will therefore depend on systems-level design that combines molecular-level hazard prevention with process engineering, circularity, digital monitoring, and credible sustainability assessment.

1. INTRODUCTION

Industrial chemistry has delivered major advances in materials, medicines, agriculture, energy, food processing, electronics, and consumer products, but conventional production systems can also require large quantities of fossil-derived feedstocks, hazardous reagents, organic solvents, water, and energy. Waste streams may include volatile organic compounds, persistent substances, metal-containing residues, greenhouse-gas emissions, and aqueous effluents. Traditional environmental management frequently focuses on controlling or treating waste after it has been produced. Green chemistry shifts the emphasis upstream by designing chemical substances and processes so that hazardous substances and waste are avoided or minimized at the molecular and process-design stages. The U.S. Environmental Protection Agency defines green chemistry as the design of chemical products and processes that reduce or eliminate the generation of hazardous substances, and the framework applies across product design, manufacture, use, and disposal [1,2].

The twelve principles established by Anastas and Warner provide the conceptual foundation for this approach: prevention, atom economy, less hazardous synthesis, safer chemicals, safer solvents and auxiliaries, energy efficiency, renewable feedstocks, reduced derivatives, catalysis, design for degradation, real-time analysis for pollution prevention, and inherently safer chemistry for accident prevention [1,3]. These principles are

complementary rather than independent. For example, a highly selective catalyst can improve atom economy and reduce waste, while a solvent-free or aqueous process can reduce solvent emissions and downstream separation requirements. Similarly, a renewable feedstock is not automatically sustainable if its cultivation causes land-use change, high water consumption, biodiversity loss, or substantial fertilizer and energy inputs.

Industrial adoption has increased through improvements in catalysis, process intensification, solvent selection, biocatalysis, continuous processing, biomass conversion, and analytical technologies. The pharmaceutical sector provides a particularly visible example because active pharmaceutical ingredient synthesis often involves multiple reaction and purification steps and substantial solvent use. Recent reviews describe the integration of one-pot transformations, alternative reaction media, biocatalysis, continuous processing, and process intensification as important routes toward greener pharmaceutical synthesis [4,5]. In parallel, sustainable catalysis increasingly emphasizes earth-abundant metals, heterogeneous catalysts, catalyst recovery, and hybrid catalytic systems to reduce dependence on scarce or costly materials [6].

A central challenge is that 'green' and 'sustainable' are related but not interchangeable terms. Green chemistry primarily addresses chemical hazards and resource efficiency through molecular and process design, whereas sustainability also

encompasses environmental, economic, and social dimensions over the full life cycle. Green metrics such as atom economy, E-factor, process mass intensity (PMI), and reaction mass efficiency provide useful process-level information, but they do not fully capture toxicity, land use, water use, biodiversity, or upstream energy burdens. Life-cycle assessment (LCA) and broader sustainability assessment are therefore important complements to conventional green chemistry metrics [7–9].

2. Scope and Review Methodology

This article is a narrative comprehensive review focused on the development and industrial translation of green chemistry. Literature was identified from authoritative environmental and scientific sources, including the U.S. Environmental Protection Agency, American Chemical Society journals, Nature Portfolio, and major peer-reviewed chemistry and chemical-engineering literature. Emphasis was placed on foundational green chemistry literature and recent reviews and perspectives addressing industrial catalysis, sustainable solvents, biomass valorization, pharmaceuticals, biocatalysis, flow chemistry, and sustainability assessment. Publications were considered for conceptual importance, industrial relevance, methodological development, and evidence of practical implementation. The review is not a quantitative

meta-analysis and does not calculate a pooled effect size.

The synthesis was organized around five questions: (i) how the principles of green chemistry are translated into industrial process design; (ii) which enabling technologies have shown the greatest potential for reducing waste, hazard, energy demand, or dependence on non-renewable resources; (iii) which industrial sectors can benefit from these approaches; (iv) how green performance should be measured; and (v) which technological, economic, regulatory, and scale-up barriers remain. Recent literature published through 2026 was used where available to reflect current directions in biomass valorization, industrial biocatalysis, sustainable catalysis, and solar-driven biomanufacturing [6,10–13].

3. Foundations and Twelve Principles of Green Chemistry

Green chemistry is best understood as prevention by design. Instead of asking how to remove a contaminant from an effluent after synthesis, the green chemistry question is whether the contaminant can be avoided during synthesis. The twelve principles form a practical checklist for identifying opportunities to reduce material intensity, toxicity, energy consumption, and accident potential [1], as shown in Table 1.

Table 1. Twelve principles of green chemistry and their role in promoting safer, more sustainable chemical synthesis.

Principle	Industrial interpretation	Typical opportunity
1. Prevention	Avoid waste rather than treating it	Fewer by-products; integrated reaction and separation.
2. Atom economy	Maximize incorporation of reactant atoms into the product.	Addition/coupling reactions; avoid leaving groups.
3. Less hazardous synthesis	Reduce hazardous reagents, intermediates, and by-products.	Safer oxidants/reductants; catalytic routes.
4. Safer chemicals	Maintain function while reducing intrinsic hazard.	Design biodegradable and less toxic products.
5. Safer solvents	Minimize solvent use and select lower-hazard media.	Water, ethanol, selected bio-based solvents, solvent-free systems.

Principle	Industrial interpretation	Typical opportunity
6. Energy efficiency	Reduce heating, cooling, compression and separation energy.	Ambient conditions, flow, microwave/photochemical/electrochemical routes where justified.
7. Renewable feedstocks	Use replenishable carbon rather than depletable resources.	Biomass, wastes, CO ₂ -derived carbon where technically and environmentally appropriate.
8. Avoid derivatives	Reduce protecting groups and temporary modifications.	One-pot and direct transformations.
9. Catalysis	Use catalytic rather than stoichiometric transformations.	Enzymes, heterogeneous catalysts, organocatalysts, earth-abundant metals.
10. Design for degradation	Ensure products break down into benign substances after use.	Biodegradable polymers, degradable surfactants.
11. Real-time analysis	Monitor processes to prevent formation of hazardous substances.	PAT, online spectroscopy, sensors and automated control.
12. Inherently safer chemistry	Reduce accident potential from substances and operating conditions.	Lower pressure/temperature; less flammable/toxic materials.

4. Green Catalysis and Sustainable Reaction Engineering

4.1 Catalysis as a Core Enabler

Catalysis is one of the most powerful tools for implementing green chemistry because catalysts can lower activation barriers, improve selectivity, reduce reaction temperature and pressure, and suppress unwanted by-products. The industrial value of catalysis is therefore not limited to faster reactions; selectivity can reduce purification requirements and improve material efficiency. Modern sustainable catalysis includes homogeneous, heterogeneous, enzymatic, photocatalytic, electrocatalytic, and hybrid systems. Recent reviews identify catalyst deactivation, limited substrate scope, catalyst recovery, and scale-up as continuing barriers despite rapid progress [6].

4.2 Earth-Abundant and Recoverable Catalysts

Industrial catalyst selection increasingly considers availability, toxicity, recyclability, performance, and supply risk in addition to activity. Precious metals can be highly effective, but their scarcity, price volatility, and potential residue-control

requirements motivate research into iron, nickel, cobalt, manganese, copper, titanium, and other earth-abundant systems. In pharmaceutical manufacturing, non-platinum-group-metal catalysis is being investigated for transformations historically dominated by precious metals [14]. However, replacement should not be assumed to be greener simply because a metal is abundant. Catalyst loading, ligand requirements, toxicity, lifetime, separation, mining impacts, and end-of-life recovery must also be considered.

4.3 Biocatalysis

Enzymes can provide high chemo-, regio-, and stereoselectivity under comparatively mild conditions. Protein engineering has expanded the range of transformations accessible to industrial biocatalysis, and pharmaceutical and agrochemical companies increasingly use enzymes in route development and manufacturing [15]. Benefits can include fewer synthetic steps, reduced protection/deprotection chemistry, and lower energy requirements. Limitations include enzyme stability, substrate inhibition, cofactor requirements, aqueous-phase constraints, mass-

transfer limitations, and the need for efficient enzyme recovery or immobilization. Whole-cell systems can address some cofactor requirements but introduce additional downstream processing considerations.

Green and Sustainable Solvents

Solvents are central to reaction, extraction, crystallization, washing, and purification operations and can dominate the material footprint of chemical manufacturing (Table 2).

Recent solvent-sustainability research emphasizes that solvent choice should consider not only toxicity but also production route, volatility, energy required for recovery, persistence, biodegradability, and compatibility with the complete process [16]. Water, ethanol, selected esters and alcohols, bio-based solvents, supercritical fluids, ionic liquids, and deep eutectic solvents have all been investigated as alternatives to conventional solvent systems.

Table 2. Sustainable solvent alternatives and their key environmental and process-related advantages.

Solvent class	Potential advantages	Important limitations
Water	Low toxicity, nonflammable, inexpensive and widely available.	Poor solubility for many organic substrates; corrosion and separation can be issues.
Ethanol / selected bio-based solvents	Renewable routes possible; comparatively favorable safety profiles.	Flammability; upstream land/energy impacts depend on production route.
Ionic liquids	Very low vapor pressure; tunable properties; useful for catalysis and separations.	Some have persistence/toxicity concerns; synthesis and recovery can be energy/material intensive.
Deep eutectic solvents	Often simple preparation; tunable polarity; low volatility.	Viscosity, water sensitivity and incomplete toxicological datasets can limit adoption.
Supercritical CO ₂	Low solvent residue; tunable transport properties; useful for extraction.	High-pressure equipment and energy requirements.
Solvent-free / mechanochemical	Potentially very low solvent use and waste.	Heat/mass transfer, scale-up and equipment requirements vary by reaction.

6. Renewable Feedstocks and Biomass Valorization

Replacing fossil carbon with renewable carbon is a major direction in sustainable industrial chemistry. Agricultural residues, forestry residues, food-processing wastes, used oils, lignocellulosic biomass, and other organic wastes can provide carbohydrates, lignin, lipids, proteins, and platform molecules. The strongest green chemistry case arises when low-value residues are converted into higher-value chemicals and materials without creating competition with food production or causing substantial additional environmental burdens. Modern biorefineries aim to fractionate

biomass into multiple streams rather than converting the entire feedstock into a single low-value product. Cellulose can provide fermentable sugars and derivatives, hemicellulose can yield pentoses and platform chemicals, and lignin can provide aromatic compounds or materials. Catalysis is central to these transformations because it enables selective depolymerization and upgrading. Recent reviews emphasize the integration of physical, chemical, biological, photochemical, and electrochemical approaches and the importance of recovering solvents and catalysts to create closed-loop systems [10,18].

Chemoenzymatic cascades represent an emerging direction because chemical and biological catalysts can perform complementary steps in an integrated sequence. Recent work has reviewed their application to carbohydrates, lignin, triglycerides, proteins, and terpenes for production of fuels, furanics, aromatics, and materials [11]. The principal challenge is compatibility: chemical and enzymatic catalysts may require different pH, temperature, solvent, and redox conditions. Process integration, enzyme engineering, compartmentalization, and sequential operation can help address these constraints.

7. Green Chemistry in Pharmaceuticals and Fine Chemicals

Pharmaceutical synthesis presents distinctive green chemistry challenges because target molecules are often structurally complex and may require multiple synthetic and purification steps. Solvents can contribute substantially to manufacturing waste, while chromatographic purification, protecting groups, stoichiometric reagents, and precious-metal catalysts can increase material intensity [4,5,19]. Green approaches therefore prioritize route shortening, telescoping, catalytic transformations, selective biocatalysis, crystallization rather than chromatography where feasible, continuous processing, and solvent reduction. Continuous manufacturing can improve heat and mass transfer and provide better process control, while reducing the amount of material present at any one time. Flow systems can also facilitate hazardous reactions through improved containment and controlled residence time. However, continuous processing is not automatically green: pumps, reactors, pressure systems, solvent consumption, cleaning procedures, and equipment manufacture must be included in sustainability assessment [20].

Biocatalysis is increasingly integrated into pharmaceutical manufacturing. Enzymes can deliver stereoselective transformations that would otherwise require multiple steps or intensive chiral separation. Protein engineering, directed evolution, immobilization, and enzyme recycling

have expanded the industrial window for biocatalytic processes [15].

8. Green Polymers and Sustainable Materials

Polymer manufacturing presents opportunities and challenges across feedstock selection, polymerization, additives, processing energy, product lifetime, and end-of-life management. Bio-derived monomers such as lactic acid, succinic acid, furans, and other platform molecules can support production of partially or fully bio-based polymers. However, bio-based content alone does not establish environmental superiority. A polymer can be bio-based yet have high processing energy, difficult recycling, or adverse land-use impacts.

Design for circularity is therefore becoming as important as feedstock substitution. Chemical recycling can recover monomers or intermediates from selected polymers, while mechanical recycling is often more energy-efficient where material quality can be maintained. Designing polymers for controlled degradation, repair, reuse, or depolymerization can align product design with the green chemistry principle of design for degradation. The appropriate strategy depends on the product's required lifetime and contamination profile.

9. Photocatalysis and Solar-Driven Chemistry

Photocatalysis uses light to drive chemical transformations and can potentially reduce reliance on conventional thermal activation. Semiconductor photocatalysts, molecular photocatalysts, organic photocatalysts, and hybrid materials have been explored for oxidation, reduction, pollutant degradation, CO₂ conversion, and biomass upgrading. The sustainability of photocatalysis depends on the source of electricity or light, catalyst synthesis, catalyst lifetime, quantum efficiency, separation, and scale-up.

An emerging frontier combines renewable energy with biological synthesis. A 2026 review describes systems in which phototrophic bacteria use solar energy and renewable or inorganic carbon sources to support biochemical production, potentially

reducing dependence on refined organic carbon in some biomanufacturing systems [13]. These approaches remain at varying stages of development and require techno-economic and life-cycle evaluation before broad industrial deployment.

10. Electrocatalysis and CO₂-Based Chemistry

Electrochemical synthesis can replace some stoichiometric redox reagents with electrons supplied by an electrical circuit. When electricity is generated from low-carbon sources, electrosynthesis may reduce reagent waste and enable selective oxidation or reduction under milder conditions. Electrocatalysis is also being investigated for CO₂ conversion, water splitting, hydrogen production, and biomass upgrading. Key industrial challenges include electrode durability, mass transfer, current density, selectivity, electrolyte management, and electricity cost. CO₂ utilization is another important research area, but carbon utilization should not automatically be interpreted as carbon neutrality. The climate value depends on the source of CO₂, energy requirements, product lifetime, process emissions, and whether the carbon would otherwise remain in the atmosphere or be released from a fossil source. Green chemistry therefore requires an assessment of the complete carbon and energy balance rather than focusing only on the incorporation of CO₂ into a product.

11. Water and Environmental Applications

Green chemistry contributes to environmental protection not only by making industrial synthesis cleaner but also by enabling safer treatment technologies. Catalytic oxidation, adsorption, membrane processes, photocatalysis, electrochemical treatment, and biologically based remediation can reduce pollutant concentrations. The green chemistry perspective asks whether the treatment itself generates hazardous secondary products, consumes excessive energy, or requires difficult-to-recover materials. Advanced oxidation processes can transform persistent organic contaminants, but the energy requirement and formation of transformation products must be

considered. Adsorbents derived from agricultural residues can contribute to waste valorization, although their regeneration, contaminant disposal, and life-cycle impacts determine whether the overall system is preferable. Similarly, nanomaterials may provide high surface area and catalytic activity but require careful assessment of synthesis hazards, persistence, release, and end-of-life behavior.

12. Food, Agriculture and Agrochemical Industries

Green chemistry has applications across fertilizer, pesticide, food-additive, packaging, and agricultural-input manufacturing. Catalytic and biological processes can reduce energy and solvent demand, while controlled-release formulations can potentially reduce losses of active ingredients. Biopesticides and enzyme-based processes can provide alternatives for selected applications, but their production, formulation, field persistence, non-target effects, and scalability must be evaluated. Green synthesis of nanoparticles using plant or microbial extracts has received substantial research attention, particularly for agricultural and environmental applications. Such methods can reduce the use of certain synthetic reducing or stabilizing agents, but claims of 'green synthesis' require evidence on extract preparation, precursor toxicity, energy consumption, purification, nanoparticle stability, exposure, and environmental fate. The biological origin of a reducing agent alone does not establish overall sustainability.

13. Process Intensification and Continuous Manufacturing

Process intensification seeks to achieve greater production per unit volume or equipment footprint while reducing energy, material use, and waste. Flow chemistry, microreactors, membrane reactors, reactive distillation, intensified separations, microwave-assisted processes, and mechanochemistry are examples. Flow chemistry can improve heat and mass transfer and enable precise control of reaction time and temperature,

but sustainability must be evaluated beyond reaction-level yield [20]. Continuous processing also supports real-time process analytical technology (PAT). Online infrared, Raman, UV-visible, mass spectrometry, chromatography, and other sensors can identify deviations early and enable feedback control. This supports the eleventh principle of green chemistry by reducing off-specification material and preventing pollution before it occurs. Digital twins and machine-learning models may further support process optimization, but their computational energy demand and data requirements should be included where material.

14. Circular Economy and Industrial Symbiosis

Green chemistry and circular economy thinking are closely connected but operate at different levels. Green chemistry focuses strongly on the molecular and process design of chemical substances, whereas circular economy strategies address flows of materials across industrial systems. Together they can support cascading use of biomass, recovery of valuable chemicals, solvent recycling, catalyst regeneration, industrial symbiosis, and product reuse. A circular industrial

system attempts to keep materials at their highest practical value for as long as possible. Examples include using food-processing residues as biorefinery feedstocks, recovering solvents from pharmaceutical operations, regenerating catalysts, converting CO₂ or waste carbon into chemicals where energetically justified, and chemically recycling selected polymers. Successful circularity requires stable collection systems, material purity, economic incentives, compatible infrastructure, and credible measurement of environmental benefits.

15. Green Chemistry Metrics and Sustainability Assessment

Quantitative assessment is essential for distinguishing genuine improvement from superficial substitution (Table 3). Atom economy measures the theoretical incorporation of reactant atoms into the desired product. E-factor expresses waste mass per mass of product, while PMI accounts for the total mass of materials used per mass of product. Reaction mass efficiency combines conversion, selectivity, and stoichiometric efficiency. These indicators are useful but incomplete [7].

Table 3. Key quantitative metrics for assessing green chemistry performance and process efficiency.

Metric / tool	What it measures	Main limitation
Atom economy	Theoretical incorporation of reactants into product.	Does not capture solvent, energy, toxicity or yield losses.
E-factor	Waste generated per mass of product.	Depends strongly on system boundaries and waste definitions.
PMI	Total material input per mass of product.	Does not directly represent toxicity or environmental fate.
Reaction mass efficiency	Mass efficiency including yield and stoichiometry.	Limited life-cycle perspective.
Energy intensity	Energy required per functional unit/product.	Does not alone capture source or environmental consequences of energy.
Carbon footprint	Greenhouse-gas emissions over defined boundaries.	May omit toxicity, biodiversity and resource depletion.
LCA	Multi-stage environmental impacts across a life cycle.	Data-intensive; results depend on functional unit and system boundaries.

Metric / tool	What it measures	Main limitation
Techno-economic analysis	Cost, capital and economic feasibility.	Economic viability does not imply environmental sustainability.
Circularity indicators	Material recovery, reuse and loop closure.	Circularity can shift impacts if recovery is energy-intensive.

16. Artificial Intelligence, Automation and Digital Green Chemistry

Digital technologies are increasingly relevant to green chemistry because experimental optimization can be resource-intensive. Machine learning can assist catalyst discovery, solvent selection, reaction-condition optimization, and prediction of molecular properties. Automated experimentation can explore reaction spaces with lower manual intervention and generate standardized datasets. When linked with process sensors, digital systems can optimize yield and selectivity in near real time. Digital approaches should nevertheless be evaluated through the same sustainability principles as physical technologies. High-performance computing consumes energy and requires hardware and data infrastructure. Models can also reproduce bias from incomplete or low-quality experimental datasets. The most useful role for AI is therefore as an enabling technology that reduces experimental waste, accelerates discovery, and improves process control while remaining embedded within transparent chemical and sustainability criteria.

17. Industrial Implementation: Opportunities and Barriers

Table 5 highlights the major opportunities and challenges associated with emerging technologies in green chemistry. Catalysis and biocatalysis can improve reaction selectivity and reduce energy and reagent requirements, while green solvents and biomass offer opportunities to reduce hazardous chemicals and utilize renewable or waste-derived resources. Flow chemistry, photocatalysis, and electrochemistry can enhance process efficiency, improve reaction control, and reduce conventional reagent use. Circular processing promotes resource recovery and waste minimization, whereas digital chemistry can accelerate reaction optimization and enable real-time process control. However, each technology has limitations, including catalyst recovery and deactivation, enzyme stability, solvent recovery, biomass variability, scale-up costs, photon and electricity efficiency, infrastructure requirements, and data quality and validation. Thus, successful implementation requires a balanced assessment of both sustainability benefits and practical barriers.

Table 5. Major opportunities and key barriers associated with emerging technologies for sustainable green chemistry.

Area	Major opportunity	Key barrier / risk
Catalysis	Higher selectivity and lower energy/reagent demand.	Deactivation, critical materials, recovery, scale-up.
Biocatalysis	Selective reactions under mild conditions.	Enzyme stability, cofactors, substrate scope.
Green solvents	Lower hazard and emissions.	Performance, recovery energy, incomplete toxicity data.
Biomass	Renewable carbon and waste valorization.	Feedstock variability, logistics, land-use concerns.
Flow chemistry	Process intensification and improved control.	Capital cost, solids handling, scale-out requirements.
Photocatalysis	Light-driven selective chemistry.	Photon efficiency, catalyst recovery, scale-up.

Area	Major opportunity	Key barrier / risk
Electrochemistry	Reagent-free redox using electricity.	Electricity cost, electrodes, mass transfer.
Circular processing	Resource recovery and waste minimization.	Collection, contamination, infrastructure.
Digital chemistry	Faster optimization and real-time control.	Data quality, validation, computing requirements.

18. Detailed Industrial Translation of the Twelve Principles

The twelve principles are most effective when applied simultaneously during route selection, process development, plant design, product formulation, use, and end-of-life management. In industrial practice, the principles should not be treated as a checklist completed after a process has already been selected. Instead, they should guide early decisions about molecular structure, feedstock, reaction pathway, solvent, catalyst, equipment, energy source, and waste-management strategy. Early-stage decisions have a disproportionate influence on environmental performance because later modifications are often expensive and may be restricted by product specifications, regulatory requirements, and installed infrastructure. [1,7,8,9,37,38]

Prevention is the first principle because treatment and disposal generally require additional materials, energy, equipment, and monitoring. A process that produces a concentrated hazardous waste stream may be technically manageable, but a route that avoids that stream is usually more robust. Prevention can be achieved by improving selectivity, reducing excess reagents, increasing reaction concentration, replacing stoichiometric transformations with catalytic alternatives, and integrating reaction and separation. The principle of atom economy complements prevention by directing chemists toward transformations in which most atoms of the starting materials appear in the desired product. Addition, rearrangement, catalytic coupling, and direct functionalization reactions can be advantageous when compared with routes that require activating groups, protecting groups, or leaving groups.

The third and fourth principles distinguish safer synthesis from safer products. A reaction may use less hazardous reagents but still produce a product with significant toxicity, persistence, or bioaccumulation potential. Conversely, a product may have a favorable use profile but be manufactured through a hazardous route. Industrial development should therefore evaluate both the hazards of substances used during manufacture and the intrinsic properties of the final product. Toxicological screening, exposure assessment, degradation testing, and safer-by-design approaches can help identify trade-offs before commercialization.

The principles concerning solvents, energy, renewable feedstocks, derivatives, catalysis, degradation, real-time analysis, and accident prevention are closely connected. Solvent selection affects reaction rate, heat transfer, separation, worker exposure, and waste generation. Energy efficiency depends not only on reaction temperature but also on solvent evaporation, distillation, drying, compression, refrigeration, and wastewater treatment. Renewable feedstocks can reduce dependence on fossil carbon, but their sustainability depends on land use, agricultural inputs, transportation, seasonal availability, and conversion efficiency. Avoiding derivatives can reduce the number of operations and the quantity of reagents, while catalysis can improve selectivity and lower energy requirements. Real-time analysis and inherently safer design provide process-level safeguards that prevent deviations, runaway reactions, and off-specification batches.

19. Sustainable Catalytic Platforms**19.1 Homogeneous Catalysis**

Homogeneous catalysts are dissolved in the same phase as the reactants and often provide high activity and selectivity. Their molecular tunability allows chemists to adjust steric and electronic properties through ligand design. Homogeneous catalysis is important in hydrogenation, carbon-carbon bond formation, oxidation, carbonylation, hydroformylation, and pharmaceutical synthesis. Nevertheless, catalyst separation can be difficult, particularly when the catalyst is present at low concentration in a large solvent volume. Metal contamination may also be a critical issue for pharmaceutical products and food-related chemicals. [6,14,15,21,24]

Greener homogeneous catalysis focuses on lower catalyst loading, ligand simplification, earth-abundant metals, recyclable catalyst systems, aqueous or biphasic operation, and immobilization. Biphasic systems can allow the product to be separated from the catalyst-containing phase, enabling catalyst reuse. Thermomorphic solvents and switchable solvent systems have also been investigated for temperature-controlled phase separation. The industrial relevance of these approaches depends on whether the additional solvent, equipment, and separation requirements offset the benefits of catalyst recovery.

19.2 Heterogeneous Catalysis

Heterogeneous catalysts are commonly used in petroleum refining, ammonia production, methanol synthesis, hydrogenation, oxidation, environmental treatment, and biomass upgrading. Their major advantage is the possibility of separating the catalyst from the product by filtration, sedimentation, magnetic recovery, or fixed-bed operation. Catalyst supports can improve dispersion, stability, and accessibility of active sites. However, support manufacture, pore blockage, leaching, sintering, and regeneration can affect the overall environmental profile. Industrial catalyst development increasingly uses structured catalysts, monoliths, foams, membranes, and three-dimensional printed reactors to improve

transport and reduce pressure drop. Such structures can enhance contact between reactants and active sites and may permit smaller equipment. The design should consider not only initial activity but also catalyst lifetime, regeneration frequency, mechanical strength, and end-of-life recovery. A catalyst that performs exceptionally well for a few hours may be less sustainable than a slightly less active catalyst that remains stable for years.

19.3 Organocatalysis and Metal-Free Catalysis

Organocatalysis uses small organic molecules as catalysts and can avoid some metal-related concerns. Amines, N-heterocyclic carbenes, thioureas, Brønsted acids, and Lewis bases have been applied to asymmetric synthesis, condensation, oxidation, polymerization, and biomass conversion. Metal-free catalysis may simplify purification and reduce concerns about metal residues, but the catalyst itself may be toxic, expensive, or difficult to recover. A complete assessment must therefore consider catalyst synthesis, loading, solvent use, and recyclability.

19.4 Enzyme and Whole-Cell Catalysis

Enzymes operate through highly evolved active sites and can perform transformations with remarkable selectivity. Their use is particularly attractive when conventional chemical synthesis requires harsh conditions or multiple protection and deprotection steps. Enzymatic hydrolysis, oxidation, reduction, transesterification, amination, and acylation are relevant to pharmaceuticals, food ingredients, flavors, fragrances, polymers, and specialty chemicals. Immobilization can improve stability and facilitate reuse, but it may reduce apparent activity because of diffusion limitations or changes in enzyme conformation. Whole-cell biocatalysis can provide intracellular cofactors and metabolic regeneration systems. It is useful for redox reactions and for transformations requiring complex enzyme cascades. However, cell growth, nutrient supply, contamination control, cell separation, and downstream purification increase process

complexity. The best industrial choice depends on substrate toxicity, product value, reaction scale, oxygen transfer, and the feasibility of recycling the biocatalyst.

20. Green Solvent Selection in Industrial Practice

Solvent selection is one of the most consequential decisions in chemical manufacturing because solvents influence reaction kinetics, selectivity, crystallization, extraction, heat transfer, equipment compatibility, worker exposure, emissions, and waste treatment. A solvent should be evaluated using a hierarchy of criteria: health hazard, environmental persistence, flammability, reactivity, volatility, water demand, production route, recovery potential, and performance. The lowest-hazard solvent is not always the best choice if it requires very large volumes or energy-intensive recovery. [16,17,22].

Water is attractive because it is nonflammable, inexpensive, and generally low in toxicity. Its limitations include poor solubility for many nonpolar substrates, high heat capacity, corrosion, and energy-intensive evaporation. Aqueous systems may nevertheless be advantageous when reactions can be performed at high concentration or when products can be isolated by crystallization, extraction, or membrane separation. Ethanol and other selected alcohols are frequently used because they combine useful polarity with relatively favorable safety profiles, although flammability and upstream production impacts must be considered.

Ionic liquids have negligible vapor pressure and tunable physical properties, making them useful in catalysis, extraction, electrochemistry, and gas capture. Their sustainability depends strongly on cation and anion structure, synthesis route, purity, persistence, biodegradability, and recovery. Deep eutectic solvents are often prepared by mixing two or more components that form a low-melting liquid. They can be inexpensive and easy to prepare, but high viscosity and incomplete toxicological information may limit industrial adoption. Supercritical carbon dioxide offers tunable solvent properties and easy removal by

depressurization, but high-pressure equipment and compression energy can be significant. Solvent-free processing and mechanochemistry can reduce solvent waste dramatically. Mechanochemical reactions use milling, grinding, or related mechanical energy to promote chemical transformation. These methods are promising for selected reactions, polymerization, cocrystal formation, and materials synthesis. Scale-up requires attention to heat generation, mixing, wear of milling media, continuous feeding, and control of particle size. Solvent reduction should therefore be evaluated alongside equipment energy and product quality.

21. Biomass-Based Industrial Chemistry

Biomass is a chemically diverse resource rather than a single feedstock. Lignocellulosic biomass contains cellulose, hemicellulose, and lignin, while agricultural and food residues may also contain proteins, lipids, minerals, pigments, and extractives. The most sustainable conversion strategy uses fractionation and cascading valorization so that several products are obtained from one feedstock. This can improve economic resilience and reduce the pressure to cultivate dedicated energy crops. [10,11,18,23]. Pretreatment is often the most challenging stage in lignocellulosic conversion. It must disrupt the lignin-carbohydrate matrix while limiting sugar degradation and inhibitor formation. Physical milling, steam explosion, dilute-acid treatment, alkaline treatment, organosolv processing, ionic liquids, deep eutectic solvents, and biological pretreatment have been investigated. Each method has advantages and limitations related to chemical consumption, energy demand, solvent recovery, equipment corrosion, wastewater generation, and the quality of recovered lignin.

Cellulosic sugars can be converted into ethanol, lactic acid, succinic acid, levulinic acid, 5-hydroxymethylfurfural, and other platform molecules. Hemicellulose-derived sugars can provide furfural and xylitol, while lignin can be upgraded into aromatic chemicals, carbon materials, adhesives, and polymer precursors. Catalytic upgrading is difficult because biomass-

derived molecules contain multiple functional groups and can undergo competing reactions. Selectivity, catalyst poisoning, humin formation, and product separation are major research priorities. Waste oils and fats can be converted into biodiesel, renewable diesel, surfactants, lubricants, and oleochemicals. Enzymatic transesterification can operate under milder conditions and tolerate some feedstock variability, but enzyme cost and inhibition by impurities remain important. Used cooking oil collection and pretreatment are also decisive for the sustainability of the final product. A waste-derived feedstock should not be assumed to be environmentally preferable if collection requires long transport distances or extensive purification.

22. Sustainable Pharmaceutical Manufacturing

Pharmaceutical manufacturing requires high product purity, reproducibility, regulatory compliance, and control of residual solvents, metals, genotoxic impurities, and degradation products. These requirements can make green chemistry particularly challenging but also create strong incentives for process optimization. The most important opportunities include reducing the number of synthetic steps, increasing reaction concentration, replacing chromatography with crystallization, using catalytic and biocatalytic transformations, minimizing protecting groups, and developing continuous processes. [4,5,15,19,24]. Process mass intensity is useful in pharmaceutical development because it reveals the contribution of solvents, reagents, water, and purification materials to the overall material footprint. A reaction with a high isolated yield may still have poor PMI if it is conducted in dilute solution and followed by several extractions and chromatographic purifications. Telescoped processes, in which consecutive reactions are performed without isolating intermediates, can reduce solvent and handling requirements. However, telescoping requires compatibility between reaction conditions and careful control of impurity carryover.

Biocatalysis can reduce the need for chiral resolution and enable selective functionalization

of complex molecules. Directed evolution and computational protein design have expanded enzyme performance, while immobilization and continuous packed-bed reactors can improve operational stability. The adoption of biocatalysis also requires attention to enzyme production, fermentation media, downstream purification, and disposal. The environmental benefit is strongest when the complete route is compared with the conventional alternative. Continuous pharmaceutical manufacturing can reduce batch-to-batch variability and improve control of exothermic or hazardous reactions. Small reactor volumes reduce the inventory of hazardous material and may improve safety. Inline analytics can detect changes in concentration, impurity profile, and residence time. Challenges include equipment qualification, solids handling, fouling, cleaning validation, process flexibility, and regulatory acceptance. Hybrid systems that combine batch and continuous steps may provide a practical transition pathway.

23. Green Polymers, Packaging and Materials

Sustainable polymer design must address the entire life cycle, including monomer production, polymerization, additive use, processing, product lifetime, recycling, and disposal. Bio-based polymers may reduce fossil-resource demand, but their performance and environmental profile depend on feedstock production and conversion. Biodegradability is also context-dependent: a polymer may degrade under industrial composting but persist in soil, freshwater, or marine environments. [25,26,27]. Polymerization strategies relevant to green chemistry include ring-opening polymerization, catalytic condensation, enzymatic polymerization, reversible polymer networks, and controlled radical polymerization. Catalysts can improve molecular-weight control and reduce unwanted side reactions. Solvent-free polymerization and reactive extrusion can reduce solvent use, although high temperature and mechanical energy may be required. Additives should be selected with attention to migration, toxicity, recyclability, and compatibility with the intended end use.

Mechanical recycling is generally attractive when materials are clean and can retain adequate properties. Chemical recycling can be useful for selected polymers but may require high temperatures, catalysts, solvents, or separation steps. Design for recycling includes avoiding incompatible multilayer structures, reducing problematic additives, using identifiable polymer families, and improving collection systems. A circular polymer economy requires both molecular design and infrastructure for collection, sorting, cleaning, remanufacture, and quality assurance.

24. Photochemical, Electrochemical and Solar-Driven Processes

Photochemistry can access reaction pathways that are difficult to achieve thermally. Light-driven reactions may operate at lower bulk temperature and can use renewable electricity or sunlight. Photocatalysts include semiconductors, organic dyes, transition-metal complexes, carbon-based materials, and heterogeneous composites. Industrial implementation requires efficient light penetration, stable catalysts, effective heat management, and reactor geometries that provide uniform irradiation. [13,28,29]. Electrochemical synthesis replaces some stoichiometric oxidants and reductants with electrons. It can enable selective transformations, avoid hazardous reagents, and integrate directly with renewable electricity. The sustainability of an electrochemical process depends on current efficiency, cell voltage, electrode lifetime, electrolyte recovery, membrane performance, and electricity source. High current density and stable operation are essential for industrial competitiveness.

Solar-driven biological and chemical systems combine renewable energy with microbial metabolism, photocatalysis, or photoelectrochemical conversion. These systems may support carbon fixation, hydrogen production, CO₂ conversion, and synthesis of fuels or specialty chemicals. Their limitations include intermittent solar availability, low volumetric productivity, contamination, scale-up, and the need for efficient light distribution. Hybrid operation with grid electricity or stored

energy may be required for continuous manufacturing.

25. Environmental Treatment and Resource Recovery

Green chemistry in environmental applications should prioritize transformation of pollutants into less hazardous products while minimizing secondary waste. Adsorption, membrane separation, advanced oxidation, biological treatment, photocatalysis, electrochemical treatment, and constructed wetlands can be combined according to pollutant type and site conditions. The best treatment is not necessarily the one with the highest removal percentage; it should also have low energy demand, limited chemical consumption, manageable residues, and verifiable transformation products. [30]

Adsorbents derived from agricultural residues can support waste valorization, especially when the feedstock is locally available. Activation may improve surface area but can require acids, bases, high temperatures, or steam. Regeneration is essential because a single-use adsorbent transfers contaminants from water to a solid waste. Photocatalytic nanomaterials can degrade organic contaminants, but catalyst recovery and nanoparticle release must be addressed. Immobilized catalysts, magnetic recovery, membranes, and fixed-bed systems may reduce release risks. Resource recovery changes the treatment objective from simple pollutant removal to recovery of water, nutrients, metals, energy, or valuable chemicals. Electrochemical systems can recover metals from industrial effluents, while anaerobic digestion can convert organic waste into biogas. Nutrient recovery as struvite or ammonium salts may reduce dependence on mineral fertilizers. Such systems require assessment of contaminant accumulation and product quality before recovered materials can be safely reused.

26. Agriculture, Food and Agrochemical Applications

Agricultural chemistry can benefit from green synthesis, biological catalysis, controlled-release formulations, and waste-derived materials. Fertilizer production is energy intensive, and

improved catalysts, renewable hydrogen, and process integration may reduce its carbon footprint. Nitrogen-use efficiency can also be improved through formulation and application strategies that reduce volatilization, leaching, and denitrification losses. [31,36]. Biopesticides and botanical extracts provide alternatives for selected pest-management applications. Their development requires standardization of active constituents, stability testing, formulation, field efficacy, non-target assessment, and regulatory evaluation. Plant-derived products may vary with genotype, geography, season, extraction method, and storage. Green extraction methods such as water, ethanol, ultrasound, microwave, and supercritical-fluid extraction can reduce solvent hazards, but energy demand and extract concentration must be considered.

Nanomaterials are investigated for nutrient delivery, pathogen management, pollutant immobilization, and stress mitigation. Green synthesis using plant, microbial, or waste-derived extracts may reduce the use of conventional reducing agents. However, nanoparticle size, surface chemistry, dissolution, aggregation, mobility, and biological interactions determine environmental behavior. Agricultural application should therefore be guided by dose optimization, exposure assessment, persistence studies, and evaluation of effects on soil microorganisms, beneficial insects, aquatic systems, and food safety.

27. Lifecycle Thinking, Economics and Policy

Life-cycle assessment evaluates environmental impacts across defined system boundaries, from raw-material extraction to manufacturing, use, and end-of-life. It can identify burden shifting, such as a reduction in direct emissions accompanied by increased upstream energy use. The functional unit must be selected carefully. Comparing one kilogram of two chemicals may be misleading if they have different functions, concentrations, lifetimes, or performance requirements. [7,8,9,37]. Techno-economic analysis complements LCA by examining capital investment, operating cost, feedstock price, utility demand, labor, maintenance, product yield, and market value.

Green processes often face a 'valley of death' between laboratory demonstration and commercial scale. Pilot plants, reliable feedstock contracts, equipment compatibility, and product certification can reduce this gap. Policy instruments such as carbon pricing, extended producer responsibility, public procurement, grants, and safer-chemical regulations may improve the competitiveness of sustainable technologies.

Standards and transparent reporting are important because green claims can be overstated. A credible claim should identify the baseline process, system boundary, functional unit, data sources, uncertainty, and trade-offs. Terms such as renewable, biodegradable, non-toxic, carbon-neutral, and zero-waste should be used only when supported by appropriate evidence. Independent verification and standardized metrics can improve trust among regulators, industry, investors, and consumers.

28. Integrated Case-Study Framework for Industrial Evaluation

A practical industrial evaluation can be organized into six stages. First, define the product function and quality requirements. Second, map the complete material and energy flows, including upstream feedstocks, solvents, catalysts, water, utilities, packaging, and waste treatment. Third, identify molecular and process alternatives using the twelve principles. Fourth, compare alternatives using green metrics, LCA, safety assessment, and techno-economic analysis. Fifth, conduct pilot-scale validation under realistic concentration, residence time, impurity, and recovery conditions. Sixth, establish monitoring and continuous-improvement procedures after commercialization. [7,8,20].

29. Final Perspective

The future of industrial green chemistry will depend on integration rather than isolated innovations. Catalysts, renewable feedstocks, safer solvents, continuous reactors, digital analytics, renewable electricity, and circular recovery systems should be designed together. A highly efficient

reaction may lose its advantage if it requires a hazardous solvent that cannot be recovered. A renewable feedstock may provide limited benefit if it competes with food production or requires intensive irrigation. A biodegradable product may be inappropriate if its short lifetime causes excessive material consumption. These examples demonstrate why molecular design, process engineering, life-cycle assessment, and economic analysis must be connected. [7,8,38].

Industrial organizations can accelerate implementation by establishing green chemistry targets during research and development, training chemists and engineers in quantitative metrics, integrating safety and sustainability teams, and rewarding reductions in material and energy intensity. Universities and research institutes can improve translation by reporting complete mass balances, realistic process conditions, catalyst lifetime, solvent recovery, and uncertainty. Policymakers can support demonstration plants, infrastructure, standards, and markets for recycled and bio-based materials. Together, these measures can move green chemistry from a collection of promising laboratory methods toward a central operating principle of sustainable manufacturing.

30. Supplementary Discussion: Cross-Sector Integration

Cross-sector integration can improve sustainability because the waste of one industry may become the feedstock of another. Carbon dioxide from fermentation, biogas upgrading, or industrial exhaust can be considered for utilization when capture and conversion are technically and energetically justified. Heat from exothermic chemical processes can support nearby drying, distillation, or district heating. Wastewater containing nutrients may be treated and reused in industrial cooling or agriculture after appropriate safety assessment. Such integration requires compatible timing, quality specifications, logistics, and responsibility for contaminants. [23,32]. Industrial symbiosis is particularly promising in chemical parks where multiple facilities share utilities, treatment systems, storage, and transportation. Shared solvent-recovery plants can

improve economics and reduce emissions. Common analytical laboratories and digital monitoring platforms can improve quality assurance. However, shared systems may also spread contaminants or create dependence between facilities. Material exchange should therefore be supported by clear specifications, traceability, emergency planning, and contractual arrangements.

Education and workforce development are essential for implementation. Chemists need knowledge of reaction design, toxicology, solvent selection, catalysis, and analytical chemistry, while engineers need skills in process intensification, heat integration, life-cycle modeling, and risk assessment. Managers require the ability to evaluate capital investment, regulatory pathways, and supply-chain resilience. Interdisciplinary teams are more likely to identify solutions that are technically sound and commercially realistic. The credibility of green chemistry will depend on transparent communication. Publications should report negative results, limitations, and trade-offs rather than presenting only favorable outcomes. Industrial sustainability reports should distinguish absolute reductions from intensity reductions and should disclose the baseline, production volume, and system boundary. Independent review, standardized metrics, and open data can reduce greenwashing and improve comparability between technologies.

Ultimately, green chemistry is not a single technology or a guarantee of zero environmental impact. It is a design philosophy that encourages prevention, efficiency, safety, circularity, and continuous improvement. Its strongest contribution to sustainable industry is the ability to connect molecular decisions with process-level and system-level consequences. When applied rigorously, it can help industry produce essential chemicals and materials with less waste, lower hazard, reduced resource demand, and improved resilience.

31. Industrial Scale-Up and Technology Readiness

Scale-up is the stage at which many promising green chemistry concepts encounter their most difficult technical and economic barriers. A reaction that performs well in a small flask may behave differently in a pilot or commercial reactor because heat transfer, mixing, mass transfer, residence-time distribution, pressure drop, and impurity accumulation change with equipment size. Green process development should therefore begin with scale-relevant questions. Researchers should report concentration, volumetric productivity, catalyst productivity, solvent-to-product ratio, heat release, gas evolution, and isolation procedure rather than reporting yield alone. [20,33].

Technology readiness should be assessed through a staged program. Laboratory proof of concept establishes chemical feasibility. A process-development stage determines robustness, impurity control, catalyst lifetime, and separation requirements. Pilot-scale work examines equipment performance, safety, utilities, and material compatibility. Demonstration-scale operation tests reliability over extended periods and under realistic feedstock variability. Commercial implementation requires supply-chain security, quality systems, maintenance plans, regulatory approval, and a market for the product. At every stage, green metrics should be recalculated because the environmental profile may change with scale.

Scale-up can improve sustainability through economies of scale, heat integration, solvent recovery, and improved equipment utilization. It can also create new burdens, including larger inventories of hazardous materials, increased transportation, greater water demand, and more complex waste streams. Inherently safer design is therefore essential. Continuous reactors, smaller hold-up volumes, remote monitoring, passive cooling, and modular equipment may reduce accident consequences. However, safety improvements should be verified using hazard and operability studies, quantitative risk assessment, and emergency-response planning.

32. Green Chemistry in Energy and Fuel Systems

Energy systems are closely linked to green chemistry because fuels, batteries, electrolytes, catalysts, membranes, and energy-storage materials are produced through chemical processes. Sustainable fuel production includes biofuels, renewable hydrogen, synthetic fuels, and fuels derived from waste carbon. The environmental performance of each route depends on feedstock, electricity source, conversion efficiency, land use, water demand, and end-use emissions. A fuel should be evaluated over its complete life cycle rather than only at the point of combustion. [34,35]

Renewable hydrogen can support ammonia synthesis, hydrogenation, refining, and chemical production. Its sustainability depends on the electricity source and electrolyzer performance. Water electrolysis may be attractive where renewable electricity and water are available, but water purification, electrode materials, membrane durability, and hydrogen compression require assessment. Green ammonia production could reduce fossil dependence, yet the energy intensity of nitrogen fixation remains a major consideration. Improved catalysts and process integration may reduce pressure and temperature requirements. Battery and fuel-cell materials present additional green chemistry challenges. Cathode and anode materials may contain metals with supply, toxicity, or recycling concerns. Electrolytes must provide performance while limiting flammability, persistence, and hazardous decomposition products. Design for recycling should be considered before commercialization. Recovery of lithium, nickel, cobalt, manganese, copper, and graphite can reduce pressure on primary mining, but recycling processes must be evaluated for solvent use, energy demand, impurity management, and product quality.

33. Green Chemistry and Water-Efficient Manufacturing

Water is used as a reactant, solvent, coolant, cleaning medium, extraction phase, and waste-treatment medium. Industrial water sustainability

therefore requires more than reducing process-water volume. It requires attention to water quality, treatment energy, contaminant concentration, reuse, discharge, and competition with domestic and ecological needs. High-purity water can have a substantial energy footprint because of filtration, deionization, reverse osmosis, and sterilization. [30,39]. Water reuse is most effective when streams are segregated according to contamination and quality. Relatively clean cooling water may be recycled with limited treatment, while high-strength process effluent may require biological, chemical, or membrane treatment. Reuse can be supported by sensors that monitor conductivity, organic load, metals, pH, and microbial indicators. Closed-loop systems should not simply concentrate contaminants indefinitely; periodic purge and safe disposal may still be necessary.

Green chemistry can reduce water demand by increasing reaction concentration, using solvent-free processing, developing dry separation methods, and avoiding unnecessary washing. Membrane technology, crystallization, adsorption, and solvent recovery may reduce the need for repeated extraction. The selection of a water-saving technology should include the energy and chemical demand of treatment, because a reduction in water use may be accompanied by increased electricity or chemical consumption.

34. Regulatory, Ethical and Social Dimensions

Regulation is an important driver of green chemistry because chemical products must meet requirements for safety, environmental release, worker protection, food contact, pharmaceuticals, and waste management. Regulatory systems increasingly encourage substitution of substances of concern and improved information on chemical hazards. Nevertheless, regulatory compliance and green chemistry are not identical. A legally compliant process may still have high material intensity or significant climate impacts, while an innovative green process may require additional evidence before approval. [37,38]. Ethical considerations include the distribution of benefits and burdens across communities,

workers, consumers, and future generations. A process that reduces emissions at a manufacturing site may shift pollution to a mining region where catalyst metals are extracted. A bio-based product may create pressure on land or water resources in agricultural communities. Responsible innovation requires stakeholder engagement, transparent reporting, and assessment of environmental justice. Communities affected by industrial facilities should have access to understandable information about emissions, hazards, monitoring, and emergency procedures.

Social sustainability also includes decent work, occupational health, skills development, and equitable access to cleaner technologies. Automation can reduce exposure to hazardous operations but may alter employment patterns. New green industries can create jobs in recycling, biorefining, renewable energy, and environmental monitoring, yet training and transition support are needed. A complete sustainability strategy should therefore consider labor conditions, local economic development, affordability, and access to the benefits of innovation.

35. Research Gaps and Recommended Priorities

Several research gaps limit the reliable comparison of green chemistry technologies. First, many studies report reaction yield without complete mass and energy balances. Second, toxicity and environmental fate data are often unavailable for new solvents, catalysts, nanomaterials, and biomass-derived chemicals. Third, laboratory studies may use ideal feedstocks and purified reagents that do not represent industrial conditions. Fourth, the end-of-life stage is frequently ignored, especially for polymers, composites, and advanced materials. [7,8,37]. Future studies should report standardized information on substrate concentration, reagent excess, catalyst loading, solvent volume, reaction time, temperature, energy input, purification, yield, waste, and recovery. For biomass systems, researchers should report feedstock origin, moisture, composition, pretreatment chemicals, enzyme loading, inhibitor formation, and residual-solid management. For nanomaterials, synthesis

energy, precursor purity, washing, drying, particle release, and ecotoxicity should be considered. Such reporting would improve reproducibility and make life-cycle modeling more credible.

Interdisciplinary research is especially important. Chemists can design selective reactions, engineers can develop reactors and separations, toxicologists can evaluate hazards, data scientists can optimize conditions, and economists can assess commercial feasibility. Collaboration with industry can ensure that research addresses real constraints such as equipment availability, product specifications, quality control, and regulatory requirements. Funding programs should support pilot-scale demonstration and long-term performance, not only laboratory novelty.

36. Practical Checklist for Authors and Industrial Researchers

Before describing a process as green, researchers should ask whether the reaction prevents waste or merely treats it later; whether the route maximizes atom economy; whether hazardous reagents and products have been minimized; whether the solvent is necessary and recoverable; whether energy demand has been quantified; whether renewable feedstocks create land or water burdens; whether derivatives and protecting groups can be avoided; whether the catalyst is recoverable and made from responsible materials; whether the product is safe and appropriately degradable; whether real-time monitoring prevents deviations; and whether accident potential has been reduced by design. [7,20,21]. A strong green chemistry manuscript should clearly define the baseline process and explain why the proposed alternative is an improvement. It should report both benefits and limitations. If a new solvent reduces toxicity but increases energy use, that trade-off should be stated. If a catalyst improves yield but requires a scarce metal, the material-supply issue should be discussed. If biomass conversion produces a valuable chemical but requires intensive pretreatment, the energy and chemical requirements should be included. Balanced reporting strengthens scientific credibility.

For industrial decision-making, the checklist should be converted into measurable targets. Examples include reducing PMI by a defined percentage, lowering solvent use per kilogram of product, increasing catalyst turnover number, improving solvent-recovery rate, reducing water intensity, increasing recycled content, decreasing hazardous waste, and improving energy efficiency. Targets should be accompanied by a baseline, time frame, responsible team, measurement method, and verification procedure.

37. Integrated Discussion

Taken together, the evidence reviewed in this manuscript indicates that green chemistry is most effective when it is embedded in the earliest stages of product and process development. Molecular structure determines toxicity, biodegradability, volatility, and reactivity. Reaction selection determines atom economy, by-product formation, and the need for purification. Solvent choice affects worker exposure, emissions, energy demand, and separation. Catalyst choice affects selectivity, resource criticality, and recovery. Reactor design affects heat transfer, safety, productivity, and scale-up. Product design determines use-phase performance and end-of-life options. These decisions are interconnected, and optimization of one parameter can worsen another. [7,8,21]. Industrial sustainability should therefore be treated as a multi-objective problem. The objective is not simply to maximize yield or minimize cost, but to achieve acceptable performance across environmental, economic, safety, and social dimensions. Multi-criteria decision analysis can help compare alternatives when no single option is superior across all indicators. Stakeholders may assign different priorities to climate change, water scarcity, toxicity, resource criticality, and economic resilience. Transparent weighting and sensitivity analysis can reveal whether a decision depends strongly on uncertain assumptions.

The transition to green chemistry will also require changes in organizational culture. Research teams should be encouraged to question established routes and to consider waste and hazard at the

same time as yield and purity. Procurement departments should evaluate solvent and catalyst supply chains. Plant operators should be involved in process design because they understand equipment limitations and maintenance needs. Environmental, health, and safety professionals should participate before scale-up rather than only after incidents or regulatory concerns arise. Management should recognize that prevention can require early investment but may produce long-term savings through lower waste treatment, improved worker safety, reduced energy use, and stronger regulatory resilience. Green chemistry also offers opportunities for developing economies. Agricultural residues, food-processing wastes, and locally available biomass can become feedstocks for chemicals, materials, adsorbents, and energy products. Small and modular biorefineries may reduce transportation requirements and create rural employment. However, such systems require careful attention to feedstock seasonality, collection costs, local water availability, technical training, and product markets. Technology transfer should be adapted to local conditions rather than copying infrastructure designed for high-income industrial regions.

Finally, the success of green chemistry should be measured by real environmental improvement rather than by the use of fashionable terminology. A process is not necessarily green because it is biological, bio-based, nano-enabled, solvent-free, photocatalytic, or carbon-utilizing. These labels describe technologies, not complete environmental outcomes. The decisive question is whether the technology reduces hazard and resource demand over a defined life cycle while maintaining the required function and economic feasibility. This principle should guide future research, industrial investment, policy, and scientific communication.

38. Additional Sectoral Applications and Emerging Technologies

Textile manufacturing can benefit from green chemistry through low-impact dyes, enzymatic desizing, plasma treatment, supercritical-fluid processing, and improved wastewater treatment.

Conventional textile operations may consume large quantities of water, salts, alkalis, reducing agents, and synthetic dyes. Enzymes such as amylases, cellulases, laccases, and pectinases can operate under milder conditions and may reduce the need for harsh chemicals. The environmental benefit depends on enzyme production, dosage, reuse, water savings, and the fate of dye transformation products. Dye removal should not be evaluated only by color reduction because partially degraded aromatic compounds may remain biologically active. [10,13,25,28,30,34].

Leather processing is another sector where green chemistry can reduce chemical hazards and water use. Conventional tanning may involve chromium salts, sulfides, acids, and large wastewater loads. Alternative tanning agents, enzymatic dehairing, vegetable-derived tannins, and improved chromium recovery have been investigated. The choice of alternative must consider leather performance, durability, worker exposure, wastewater toxicity, and the environmental impact of producing the replacement chemical. Cleaner production is most effective when chemical substitution is combined with process control, water reuse, and recovery of valuable materials. Mining and metallurgical industries generate complex streams containing metals, acids, salts, and suspended solids. Green chemistry approaches include selective leaching, bioleaching, solvent extraction, membrane separation, adsorption, and electrochemical recovery. Bioleaching can use microorganisms to mobilize metals under comparatively mild conditions, but process rates may be slow and control of acidity and microbial activity is necessary. Selective recovery can reduce the volume of hazardous residue and create economic value from waste. The sustainability of metal recovery should include the energy and chemicals used for concentration, purification, and final metal production.

Food processing produces organic residues, wastewater, shells, peels, seeds, whey, and spent grains. These streams may contain carbohydrates, proteins, lipids, pigments, antioxidants, fibers, and minerals. Green extraction and fermentation

can convert them into food ingredients, enzymes, organic acids, animal-feed components, packaging materials, and bioenergy. Food-grade solvents and mild extraction conditions are important where products may enter the food chain. Safety assessment must include allergens, microbial contamination, pesticide residues, heavy metals, and process-derived contaminants. Cosmetic and personal-care industries are increasingly interested in plant-derived ingredients, biodegradable surfactants, safer preservatives, and low-water formulations. Green chemistry can support the development of surfactants from renewable oils, fermentation-derived ingredients, and encapsulation systems that improve stability and reduce excess active material. Botanical ingredients require chemical standardization because composition varies with plant source, cultivation, extraction, and storage. Claims concerning natural origin, biodegradability, or non-toxicity should be supported by analytical and toxicological evidence.

Electronics and semiconductor manufacturing requires high-purity chemicals, solvents, photoresists, etchants, cleaning agents, and specialty gases. Green chemistry opportunities include aqueous or semi-aqueous cleaning, less hazardous photoactive compounds, solvent recycling, low-global-warming-potential gases, and recovery of valuable metals from electronic waste. Because electronics manufacturing has stringent performance requirements, replacement chemicals must be evaluated for contamination, surface compatibility, yield, and reliability. E-waste recycling also requires careful control of brominated flame retardants, lead, mercury, and other hazardous substances. Construction materials can be improved through low-carbon cement chemistry, mineral carbonation, recycled aggregates, bio-based binders, and safer additives. Cement production is energy and carbon intensive because of limestone calcination and fuel use. Alternative binders and supplementary cementitious materials can reduce clinker demand, but their availability, durability, leaching behavior, and transport impacts must be assessed. Carbonation-based materials may store carbon

temporarily or permanently depending on product lifetime and processing energy. Green chemistry can contribute through mineral utilization, catalyst development, and design of materials for repair and recycling.

Packaging systems illustrate the importance of balancing function and end-of-life. Packaging must protect products from moisture, oxygen, contamination, and mechanical damage. Reducing material thickness may lower resource use but could increase food waste if protection is inadequate. Bio-based coatings, recyclable mono-materials, compostable polymers, and barrier films are being developed, but each requires appropriate collection and treatment infrastructure. Compostability is meaningful only where industrial composting systems exist and where the material does not introduce persistent additives or contaminants. Carbon capture and utilization is a developing field in which captured carbon dioxide is converted into fuels, carbonates, polymers, formic acid, methanol, or other products. The green chemistry value depends on capture energy, carbon source, hydrogen source, catalyst performance, product lifetime, and end-of-life emissions. Conversion of concentrated industrial CO₂ may be more practical than direct air capture, but direct air capture could become important if low-carbon energy and durable storage are available. Carbon utilization should be compared with permanent storage and with conventional production routes.

Green chemistry can also support disaster resilience and decentralized production. Modular water-treatment units, local biomass conversion, low-energy disinfection, and distributed chemical production may reduce dependence on long supply chains. Such systems are useful in remote or resource-constrained areas, but they require reliable maintenance, local training, spare parts, and safe management of residues. Technology design should account for intermittent electricity, variable water quality, limited laboratory facilities, and the need for simple monitoring.

39. Overall Synthesis and Research Outlook

The reviewed evidence shows that green chemistry is not limited to replacing one hazardous reagent with another. It involves redesigning the entire pathway from raw material to product and end-of-life. The most durable improvements usually combine several strategies: a selective catalyst, a safer solvent, a concentrated reaction, efficient separation, renewable or waste-derived feedstock, real-time monitoring, and recovery of water and materials. Such integration can produce benefits that are greater than the sum of individual changes. [7,8,9,21,23,37]. Future industrial systems are likely to become more interconnected. Biorefineries may combine fermentation, catalytic upgrading, extraction, and materials production. Chemical parks may exchange heat, water, solvents, and by-products. Digital platforms may connect laboratory data with pilot plants and commercial operations. Renewable electricity may power electrochemical synthesis, hydrogen production, and carbon conversion. These developments can reduce dependence on fossil resources, but they also increase the importance of systems modeling and infrastructure planning.

Scientific publications should provide enough information for independent evaluation. Complete material balances, solvent quantities, energy estimates, catalyst preparation, recovery procedures, uncertainty, and comparison with a realistic baseline are essential. Authors should avoid describing a process as sustainable when only one metric has improved. Journals and reviewers can encourage better reporting by requesting life-cycle boundaries, hazard information, and scale-up considerations. Such practices will help distinguish meaningful advances from laboratory demonstrations that are difficult to translate. Green chemistry is particularly relevant to the circular economy because it can prevent materials from becoming waste in the first place. Product design should consider repair, reuse, disassembly, remanufacture, and chemical recovery. Molecular structures that enable selective depolymerization or biological degradation can support circular systems. At the same time, durability remains

important for products that must function for many years. The appropriate design depends on the intended service life and the environmental conditions after use.

The central future challenge is to maintain chemical performance while reducing environmental and social burdens. This requires collaboration across chemistry, chemical engineering, materials science, biology, toxicology, environmental science, economics, data science, and public policy. Green chemistry will be most successful when sustainability is treated as a design requirement from the beginning rather than as a label applied after a process has been developed. Future Research Directions. Future green chemistry is likely to move from isolated 'green reactions' toward integrated sustainable process systems. Several priorities emerge. First, catalyst design should increasingly consider the complete life cycle of catalyst production, use, recovery, and disposal. Second, biomass conversion should progress toward integrated biorefineries that maximize the value of every major feedstock fraction rather than focusing on a single product. Third, solvent research should emphasize recovery, reuse, low-impact manufacture, and demonstrated toxicological performance. Fourth, electrochemical and photochemical technologies should be coupled with low-carbon electricity and efficient reactor designs. Fifth, continuous manufacturing and PAT should be integrated with digital control to minimize deviations, material loss, and energy consumption. Sixth, green chemistry education and industrial training should emphasize quantitative metrics and life-cycle thinking rather than treating individual technologies as inherently green. Seventh, regulatory frameworks can encourage safer-by-design products while preserving rigorous performance and safety requirements. Finally, sustainability claims should increasingly be supported by transparent data on mass balance, energy, emissions, toxicity, catalyst recovery, solvent recovery, and end-of-life behavior.

40. Conclusions

Green chemistry provides a practical framework for transforming industrial chemistry from a system that manages pollution after generation into one that prevents hazards and waste through molecular and process design. Advances in catalysis, biocatalysis, renewable feedstocks, biomass valorization, safer solvents, flow chemistry, photocatalysis, electrocatalysis, process analytical technology, and circular manufacturing are expanding the range of industrial processes that can be redesigned according to green chemistry principles. Pharmaceutical synthesis, polymers, fuels, agrochemicals, food processing, environmental treatment, and advanced materials all provide opportunities for implementation. The central lesson is that no single technology guarantees sustainability. Renewable feedstocks, biological catalysts, nanoparticles, ionic liquids, continuous reactors, or CO₂ utilization can provide important advantages under appropriate conditions, but each can also introduce new environmental or economic burdens. Robust industrial decision-making therefore requires integrated assessment using green chemistry metrics, life-cycle assessment, techno-economic analysis, safety considerations, and circularity indicators. The next phase of green chemistry should combine molecular-level prevention with process intensification, renewable energy, digital monitoring, resource recovery, and closed-loop manufacturing. Such systems-level integration can support chemical production that is more resource-efficient, less hazardous, and better aligned with long-term industrial and environmental objectives.

Funding

No specific funding information was provided for this review. This section should be revised to reflect the actual funding source, if applicable.

Conflict of Interest

The authors should declare any financial or non-financial competing interests.

Author Contributions

Asim Ullah: Conceptualization, methodology, investigation, data collection, data analysis, and writing—original draft. Khitab Ur Rahman: Methodology, investigation, experimental work, and data curation. Sehrish Javed: Literature review, data validation, visualization, and manuscript preparation. Rahman Ullah Khan: Statistical analysis, data interpretation, and critical revision of the manuscript. Rabail Urooj: Investigation, literature review, and manuscript editing. Rizwan Ullah: Supervision, project administration, critical review, and final approval of the manuscript. All authors contributed to the manuscript, reviewed and approved the final version, and agreed to be accountable for all aspects of the work.

Data Availability

Data is available upon request from corresponding author.

Ethics Approval

Not applicable.

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