

Green Chemistry (GC) for Sustainable Development Goals (SDGs)

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Abstract

The present research develops Green Chemistry (GC) as a foundational, preventative molecular framework essential to the attainment of the 2030 SDGs. The analysis shifts the chemical industry beyond simple hazard mitigation and provides direct, systemic linkages between the 12 Principles of GC and key global targets.

The principles of Atom Economy and the Use of Renewable Feedstocks underpin directly SDG 12 on Responsible Consumption and Production and SDG 9 on Industry, Innovation, and Infrastructure by significantly improving resource efficiency, reducing waste streams, and contributing to the modernization of chemical production facilities toward benign design innovation.

Further development of catalytic systems, such as enzymatic processes, along with the use of safer solvents, for example Deep Eutectic Solvents/DESSs, makes important contributions to SDG 6, Clean Water, and SDG 7, Affordable and Clean Energy, by reducing toxic releases and lowering the overall energy demands of reactions. GC supports SDG 3 (Health) by focusing on the design of safer chemicals.

The study emphasizes that robust, quantifiable metrics—such as Molar Efficiency—are necessary to transparently measure progress in line with corporate ESG goals. Adoption is hindered by a high initial financial outlay; accelerating policy integration, such as REACH, and corporate leadership are identified as key accelerators. GC is a fundamental approach to the complete transformation of chemical value chains on a global scale toward sustainability.

Key Words: SDG 7, GC, ESG, REACH, Sustainability

I. Introduction

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet. The seventeen Sustainable Development Goals represent an urgent call for action by all countries in a global partnership, recognizing that ending poverty must proceed hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic growth—all while tackling climate change and preserving ecosystems.

At the molecular level, Green Chemistry emerges as the design discipline capable of translating these aspirational goals into tangible chemical reality. Green Chemistry is defined as "the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances," representing a fundamental paradigm shift from end-of-pipe remediation to at-the-source prevention. Unlike traditional approaches that address pollution after its generation, Green Chemistry operates proactively at the molecular design stage, preventing pollution at its source.

The chemical sector stands at the heart of the sustainability challenge. It is foundational to virtually all supply chains—from pharmaceuticals and agriculture to electronics and construction—yet simultaneously bears responsibility for significant environmental burdens. The chemical sector is responsible for 7.4% of global greenhouse gas emissions and 10% of the world's total energy demand. The sector's transformation is therefore not optional; it is essential for achieving the SDGs.

This paper addresses a critical gap in the literature by systematically mapping the comprehensive interconnections between the complete 12-principle Green Chemistry framework and all relevant SDGs, while integrating quantitative metrics, industrial case studies, policy analysis, and original data within a unified analytical framework. The objectives of this research are fourfold: (1) to establish the theoretical and practical linkages between each Green Chemistry principle and specific SDG targets; (2) to analyze quantitative metrics that enable transparent measurement of progress; (3) to examine industrial case studies demonstrating real-world implementation; and (4) to identify policy frameworks and future directions for accelerated adoption, with particular attention to global perspectives and India's emerging role in sustainable chemistry.

II. Theoretical Framework: The 12 Principles of Green Chemistry

A. Historical Evolution and Conceptual Foundation

The 12 Principles of Green Chemistry, articulated by Paul Anastas and John Warner in 1998, emerged from decades of growing environmental awareness and represent a coherent framework for chemical innovation. These principles provide a comprehensive design philosophy that encompasses the entire lifecycle of chemical processes.

The principles are strategically organized into three interconnected categories that reflect different aspects of sustainable chemical practice:

Efficiency Drivers (Principles 1, 2, 6, 7):

- **P1: Prevention** - It is better to prevent waste than to treat or clean up waste after it has been created
- **P2: Atom Economy** - Synthetic methods should be designed to maximize the incorporation of all materials into the final product
- **P6: Design for Energy Efficiency** - Energy requirements should be minimized; reactions at ambient temperature and pressure are preferred
- **P7: Use of Renewable Feedstocks** - Raw materials and feedstocks should be renewable rather than depleting

Hazard Mitigation (Principles 3, 4, 5, 12):

- **P3: Less Hazardous Chemical Syntheses** - Methods should be designed to use and generate substances with minimal toxicity to human health and the environment
- **P4: Designing Safer Chemicals** - Chemists should design products that maintain efficacy while minimizing toxicity
- **P5: Safer Solvents and Auxiliaries** - Auxiliary substances used in reactions should be unnecessary or replaced with innocuous alternatives
- **P12: Inherently Safer Chemistry for Accident Prevention** - Processes should be designed to minimize the potential for chemical accidents, explosions, and fires

Process and Lifecycle Optimization (Principles 8, 9, 10, 11):

- **P8: Reduce Derivatives** - Unnecessary derivatization should be avoided or minimized
- **P9: Catalysis** - Catalytic reagents are superior to stoichiometric reagents
- **P10: Design for Degradation** - Products should break down into innocuous substances after use

- **P11: Real-time Analysis for Pollution Prevention** - Analytical methods should enable in-process, real-time monitoring and control

B. Quantitative Metrics for Green Chemistry Assessment

The translation of qualitative principles into measurable outcomes requires robust metrics that enable rigorous assessment and benchmarking. The evolution of green chemistry metrics has proceeded through several generations, each addressing limitations of predecessors.

Atom Economy (AE): Introduced by Barry Trost in 1991, Atom Economy measures theoretical mass efficiency by calculating the proportion of reactant mass that ends up in the desired product:

$$\text{Atom Economy (\%)} = \frac{\text{Molecular Weight of Desired Product}}{\sum \text{Molecular Weight of All Reactants}} \times 100$$

Original source: <https://gvern.net/doc/science/chemistry/1991-trost.pdf>

While powerful for synthetic planning and comparison of alternative synthetic routes, AE is theoretical and assumes 100% yield, ignoring solvents, catalysts, and workup materials. This limitation necessitated development of more comprehensive metrics.

E-Factor (Environmental Factor): Introduced by Roger Sheldon in 1992, the Environmental Factor provides a holistic measure of waste generation in actual processes:

$$\text{E-Factor} = \frac{\text{Total Mass of Waste (kg)}}{\text{Mass of Product (kg)}}$$

30-year retrospective: <https://pubs.rsc.org/en/content/articlehtml/2023/gc/d2gc04747k>

The E-factor quantifies everything except the desired product, including losses from solvents and materials used during workup. Sheldon's analysis of E-factors across industry segments established the following ranges: oil refining (0.1-0.5), bulk chemicals (1-5), fine chemicals (5-50), and pharmaceuticals (25-100+). After 30 years, the E-factor remains the most widely adopted metric for assessing process waste.

Process Mass Intensity (PMI): Adopted by the ACS Green Chemistry Institute Pharmaceutical Roundtable as the primary benchmarking metric, PMI accounts for all materials—including solvents, reagents, catalysts, and water—used in a chemical process:

$$\text{PMI} = \frac{\text{Total Mass of All Materials Used (kg)}}{\text{Mass of Isolated Product (kg)}}$$

PMI provides the most comprehensive assessment of process efficiency and has become the industry standard for pharmaceutical manufacturing benchmarking. Analysis of synthetic peptide processes reveals median PMI values of 13,000 for solid-phase peptide synthesis, compared to 168-308 for small molecule synthesis, highlighting significant opportunities for process improvement.

Additional Metrics for Comprehensive Assessment:

Renewable Carbon Index (RCI): Measures the percentage of non-fossil carbon inputs in feedstock, directly supporting SDG 12.2 on sustainable resource management.

Specific Energy Consumption (SEC): Quantifies energy use per unit product mass (kWh/kg), enabling direct measurement of progress toward SDG 7.3 on energy efficiency improvement.

Environmental Quotient (EQ): Combines E-factor with a qualitative assessment of waste hazard:

$$\text{EQ} = \text{E-Factor} \times Q$$

where the Q-value represents the environmental hazard quotient of the waste.

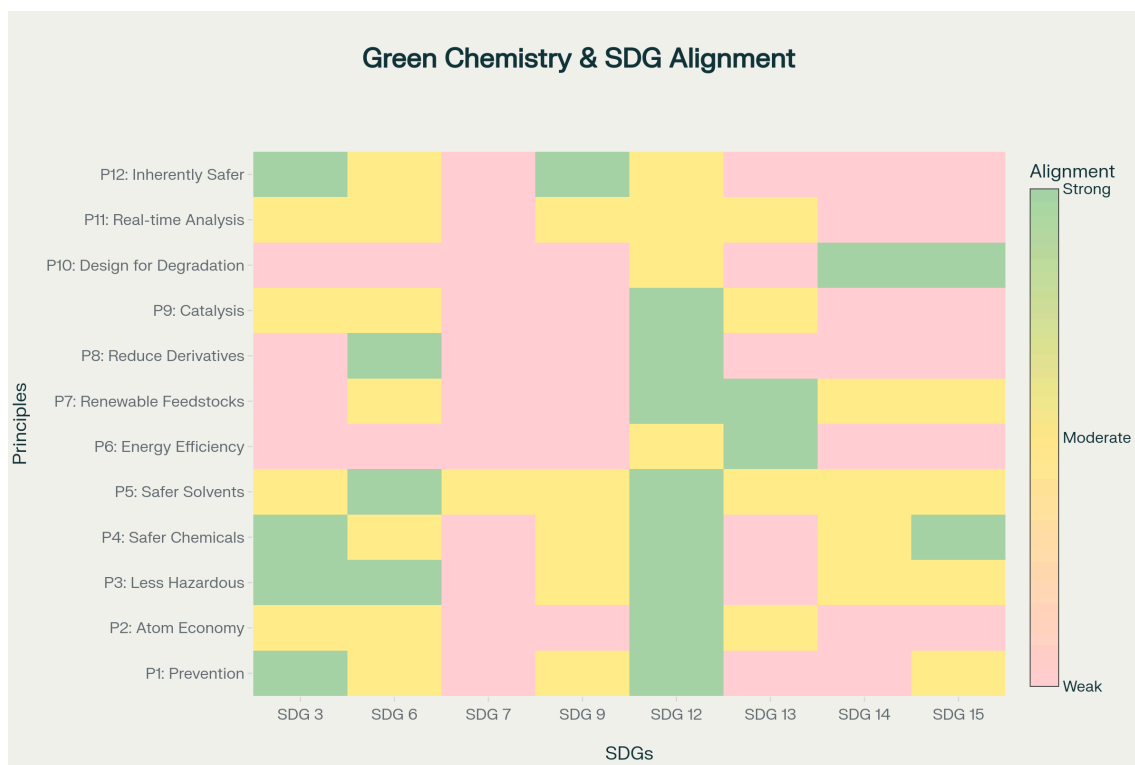


Figure 1: Heatmap showing systematic alignment between the 12 Principles of Green Chemistry (rows) and 8 key SDGs (columns). Color intensity indicates alignment strength: dark green (strong), yellow (moderate), light pink (weak). This visualization demonstrates that Principles 1, 2, 4, and 12 exhibit strong multi-SDG alignment.

Molar Efficiency: A metric emphasizing molecular-level efficiency in synthetic routes, tracking the percentage of atoms from starting materials that end up in the final desired product, accounting for all transformations.

III. Systematic Alignment: Green Chemistry Principles and Sustainable Development Goals

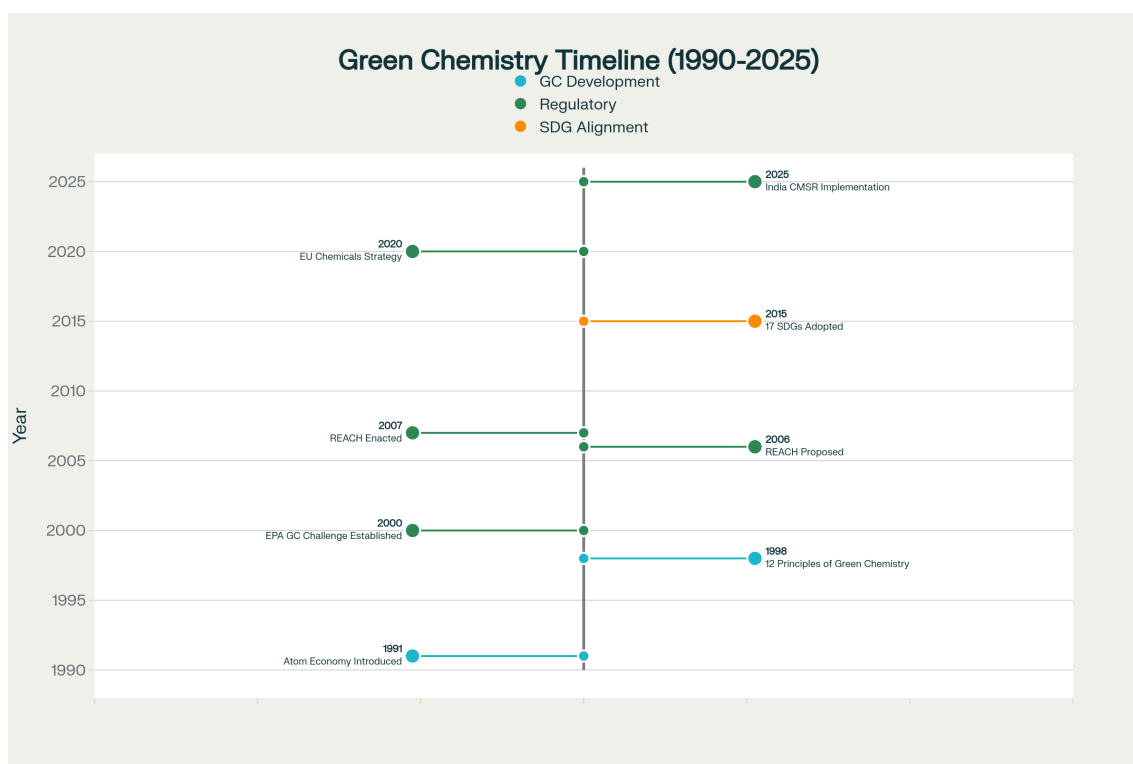


Figure 2: Timeline visualization tracking 34 years of green chemistry development from Trost's introduction of Atom Economy (1991) through the 12 Principles formulation (1998), regulatory milestones (REACH 2007, EU Strategy 2020), and global commitments (17 SDGs 2015, India CMSR 2025). Demonstrates accelerating policy momentum supporting GC adoption.

A. SDG 3: Good Health and Well-Being

Target 3.9: Substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.

Green Chemistry Principles 3, 4, 5, and 12 directly address this target through inherently safer design and reduced worker/community exposure. The World Health Organization estimates that 71% of unintentional poisonings could be prevented through better chemical safety management.

One Health Approach to Sustainable Drug Development:

Green chemistry has been successfully applied to the development of environmentally friendly antiparasitic treatments addressing vector-borne parasitic diseases. Research demonstrates successful application of all 12 principles in designing sustainable medications:

- **P7 (Renewable Feedstocks):** Utilizing inedible cashew nut shell liquid, an agricultural byproduct, as the starting material
- **P9 (Catalysis):** Employing efficient catalytic processes
- **P1 & P3 (Prevention & Safety):** One-pot synthesis that reduces waste and avoids toxic reagents

This One Health approach integrates human, animal, and environmental health, representing an emerging framework for pharmaceutical development aligned with multiple SDG targets.

B. SDG 6: Clean Water and Sanitation

Target 6.3: Improve water quality by reducing pollution, eliminating dumping, and minimizing release of hazardous chemicals and materials.

Green Chemistry Principles 1, 3, 5, and 10 directly support this objective through waste prevention and safer solvent selection.

Alternative Solvents as Water Protectants:

The development of alternative solvents represents a crucial advancement in protecting aquatic ecosystems:

Ionic Liquids (ILs) and Deep Eutectic Solvents (DESS): These solvents exhibit negligible vapor pressure, excellent thermal stability, and tunable properties that allow targeting specific contaminants. Research demonstrates successful use in extracting pharmaceuticals, agrochemicals, and heavy metals from contaminated water.

Supercritical CO₂ (scCO₂): Operating above critical temperature (31°C) and pressure (72.9 bar), scCO₂ offers:

- Non-toxic, non-flammable, and chemically inert properties
- Easy recovery through pressure reduction
- Tunable solvation power through pressure adjustment
- Industrial applications in pharmaceutical processing and natural product extraction

NIH/PMC review: <https://pmc.ncbi.nlm.nih.gov/articles/PMC11359946/>

RSC publication: <https://pubs.rsc.org/en/content/articlelanding/2024/gc/d4gc00371c>

Water as Reaction Medium: Recent research demonstrates that water itself can effectively mediate organic transformations:

- Enhanced reaction rates through hydrophobic effects
- Simplified workup procedures
- Eliminated solvent waste
- Improved selectivity in many transformations

CAS insights on water solvents: <https://www.cas.org/resources/cas-insights/organic-solvents>

RSC tutorial review: <https://pubs.rsc.org/en/content/articlelanding/2012/cs/c1cs15222j>

C. SDG 7: Affordable and Clean Energy

Target 7.3: Double the global rate of improvement in energy efficiency.

Green Chemistry Principle 6 directly addresses this through energy-efficient process design. The chemical industry's energy consumption represents approximately 10% of global energy demand. Energy efficiency improvements through process intensification, continuous flow chemistry, and ambient-temperature reactions offer substantial reduction potential.

Energy-Efficient Process Innovation:

Flow chemistry exemplifies energy-efficient processing:

- **Ibuprofen synthesis:** Complete synthesis achieved in just 3 minutes with 83% yield, compared to hours or days in batch processes
- **Thermal efficiency:** Continuous processes enable superior heat transfer, reducing energy requirements
- **Scalability advantages:** Laboratory to pilot to production scale-up is simplified, maintaining energy efficiency

Full technical details: <https://www.aurigeneservices.com/blogs/continuous-flow-chemistry-a-game-changer-for-pharmaceutical-production>

D. SDG 9: Industry, Innovation and Infrastructure

Target 9.4: Upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies.

Green Chemistry provides the technical mechanisms for sustainable industrialization through three major innovation pathways:

Biocatalysis and Directed Evolution:

Enzymatic processes enable pharmaceutical synthesis with dramatically reduced environmental footprints. The 2018 Nobel Prize in Chemistry recognized directed evolution, which has achieved over 25,000-fold improvements in enzyme activity. Industrial applications span:

- Pharmaceutical synthesis and intermediates
- Biofuel production
- Fine chemical manufacturing
- Detergent and specialty chemical production
- Food processing enzymes

Review on directed evolution: <https://pubs.acs.org/doi/abs/10.1021/cb500809f>

Engineering sustainability with enzymes: <https://pmc.ncbi.nlm.nih.gov/articles/PMC10952156/>

Nanocatalysis:

Nanocrystals with controlled sizes and shapes enable heterogeneous catalysis with homogeneous-like selectivity. Green synthesis of nanocatalysts using plant extracts replaces hazardous reducing agents, creating truly sustainable catalytic systems.

Flow Chemistry and Continuous Manufacturing:

Continuous manufacturing has transitioned from research curiosity to mainstream technology across pharmaceuticals, fine chemicals, and agrochemicals. Benefits include:

- Improved thermal exchange and mass transfer
- Enhanced safety through reduced reaction volumes and better control
- Reduced development cycles
- Dramatically lower process mass intensity
- Elimination of batch-to-batch variability

Key review: <https://pubs.rsc.org/en/content/articlehtml/2019/gc/c9gc00773c>

E. SDG 12: Responsible Consumption and Production

Target 12.4: Achieve environmentally sound management of chemicals and all wastes throughout their life cycle.

Target 12.5: Substantially reduce waste generation.

SDG 12 represents perhaps the most direct alignment with Green Chemistry. Principles 1, 2, 7, and 8 establish the foundation for responsible production:

Waste Prevention and Atom Economy:

The pharmaceutical industry has embraced PMI as the key metric for benchmarking progress. Analysis of manufacturing data reveals that solvent use dominates PMI contributions, with typical syntheses using 80-90% of total mass as solvents. Year-over-year improvements have been achieved across major pharmaceutical companies through:

- Solvent optimization and reduction
- Streamlined synthetic routes
- Catalytic process intensification
- Continuous manufacturing implementation

Renewable Feedstocks:

The bio-based chemical and polymer production now exceeds 90 million tonnes globally. Utilizing renewable resources offers multiple advantages:

- Reduced fossil fuel dependence
- Carbon footprint reduction through renewable resources
- Support for agricultural and biomass valorization sectors
- Resilience through diverse supply chains

Key feedstock sources include lignocellulosic biomass, agricultural residues, waste streams, and industrial byproducts. The biomass balance approach, pioneered by BASF and certified under REDcert², enables tracking of renewable inputs through complex production networks.

Circular Economy Integration:

Chemical recycling technologies are projected to receive €8 billion investment by 2030, enabling 3.4 million tonnes of recycled plastic production annually. This represents a transformative shift from linear to circular material flows:

- **Mechanical recycling:** Physical processing of waste plastics (limited by contamination sensitivity and property degradation)
- **Chemical recycling:** Breaking polymers to molecular building blocks through pyrolysis, depolymerization, or gasification

Chemical recycling achieves lower carbon footprints than incineration while enabling true circularity.

CEFIC guidance: <https://cefic.org/solutions-explained/chemical-recycling-making-plastics-circular/>

F. SDG 13: Climate Action

SDG 13 demands urgent action on climate change, requiring fundamental transformation of the chemical industry's energy sources, feedstocks, and processes.

Decarbonization Pathways:

Process heat decarbonization could reduce sector emissions by up to 50% for major chemicals. Key strategies include:

- **Energy efficiency** through heat integration and process optimization
- **Electrification** of low-to-medium temperature processes
- **Green hydrogen** for high-temperature applications
- **Carbon Capture, Utilization, and Storage (CCUS)**

Hydrogen Portal CCU resource: <https://hydrogen-portal.com/carbon-capture-and-utilization-ccu/>

Electrochemical Synthesis:

Electrochemical synthesis offers pathways to decarbonize specialty chemical manufacturing. Life cycle assessment of electrosynthetic routes demonstrates significant potential for emissions reduction when powered by renewable electricity.

G. SDGs 14 and 15: Life Below Water and Life on Land

These goals address protection of aquatic and terrestrial ecosystems.

Design for Degradation (Principle 10):

This principle is fundamental to preventing persistent pollution:

Biodegradable Polymers:

- **Polylactic Acid (PLA):** Bio-based polymer derived from corn or sugarcane, biodegradable in industrial composting conditions
- **Polyhydroxyalkanoates (PHA):** Demonstrated superior environmental biodegradability, decomposing in soil, freshwater, and marine environments within 3-12 months, compared to centuries for conventional plastics

Comparison guide: <https://made-with-regen.ca/blog/pla-vs-pha/>

Safer Chemicals by Design (Principle 4):

Molecular design approaches enable prediction and elimination of hazardous properties at the earliest stages of product development, preventing bioaccumulation and ecosystem toxicity.

IV. Industrial Case Studies: Quantitative Evidence of Industrial-Scale Implementation

A. Pfizer Sertraline (Zoloft®) Green Synthesis

The 2002 Presidential Green Chemistry Award recognized Pfizer's transformative redesign of sertraline hydrochloride manufacturing. Official EPA documentation: <https://www.epa.gov/greenchemistry/presidential-green-chemistry-challenge-2002-greener-synthetic-pathways-award>

The pharmaceutical industry's most prestigious recognition highlighted quantifiable improvements:

Parameter	Result
Product yield improvement	Doubled
Raw material reduction	20-60%
Hazardous materials eliminated	1.8 million pounds annually
Energy consumption	Reduced
Water consumption	Reduced
Worker safety	Enhanced

Key Innovations:

- **Solvent replacement:** Substituting four solvents (methylene chloride, tetrahydrofuran, toluene, hexane) with ethanol
- **Reagent elimination:** Eliminating 310,000 pounds per year of titanium tetrachloride
- **Process optimization:** Exploiting solubility differences to drive equilibrium without hazardous reagents

Case study document: <https://www.acs.org/content/dam/acsorg/greenchemistry/industriainnovation/Pfizer-business-case-study.pdf>

This case study demonstrates that environmental improvements directly align with economic benefits through reduced material consumption and higher throughput.

B. Merck/Codexis Sitagliptin Biocatalytic Synthesis

The 2010 Presidential Green Chemistry Award recognized the revolutionary biocatalytic synthesis of sitagliptin (Januvia™), a treatment for type 2 diabetes. Official EPA Award: <https://www.epa.gov/greenchemistry/presidential-green-chemistry-challenge-2010-greener-reaction-conditions-award>

Detailed press release: <https://www.fiercepharma.com/pharma/merck-and-codexis-honored-presidential-green-chemistry-challenge-award-novel-process-for>

Directed Evolution Achievement:

Starting from an R-selective transaminase with minimal activity, directed evolution achieved:

- **Biocatalytic improvement:** Over 25,000-fold enhancement in enzyme activity
- **Enantioselectivity:** >99.95% ee (undetectable S-enantiomer formation)
- **Substrate concentration:** 92% yield at 200 g/L
- **Equipment elimination:** Removal of high-pressure hydrogenation equipment (250 psi)
- **Catalyst substitution:** Elimination of expensive rhodium catalyst requirement

The evolved enzyme has been commercially deployed since 2012, demonstrating industrial viability and scalability of evolved biocatalysts. This achievement represents the practical realization of Green Chemistry Principles 9 (Catalysis) and 12 (Accident Prevention) through elimination of high-pressure equipment and hazardous catalysts.

C. BHC Company Ibuprofen Green Synthesis

The transformation of ibuprofen manufacturing from a six-step to a three-step process exemplifies Atom Economy principles:

Parameter	Traditional Synthesis	Green Synthesis
Number of steps	6	3
Atom economy (approx.)	~40%	77-99%*
Catalyst type	None (stoichiometric AlCl_3)	Recoverable (HF, Pd, Ni)
Annual waste reduction	Baseline	Millions of pounds

*99% atom economy achieved when considering acetic acid recovery

The green synthesis, implemented industrially more than three decades ago, demonstrates that environmental benefits align with economic advantages through reduced material consumption and higher throughput.

D. Continuous Flow Synthesis Achievements

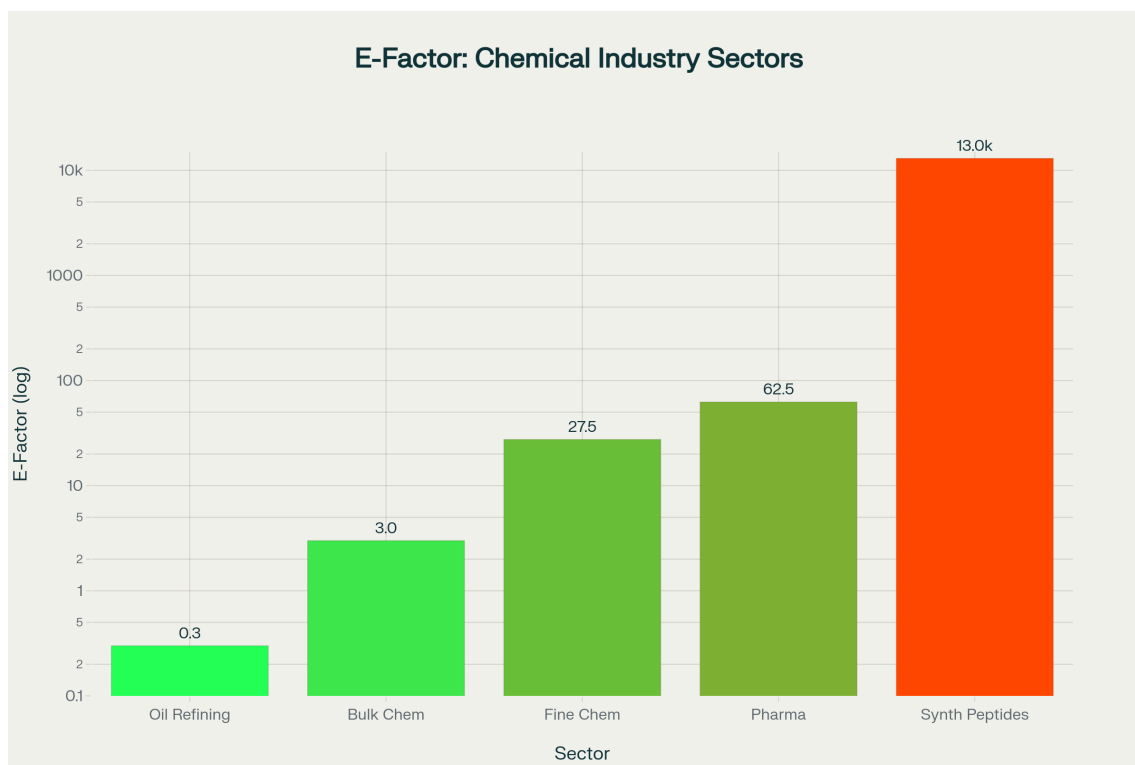


Figure 3: Bar chart comparing E-factor values across five chemical industry sectors on logarithmic scale. Oil refining (0.3) shows minimal waste generation, while synthetic peptides (13,000) represent the highest waste opportunity for green chemistry intervention. This differential highlights strategic priority areas for GC implementation.

Recent advances in continuous manufacturing demonstrate the green chemistry potential of flow chemistry across diverse applications:

- **Ibuprofen:** Complete synthesis in 3 minutes with 83% yield using minimal reagents
- **Aliskiren hemifumarate:** Novartis-MIT collaboration achieved end-to-end production in 1 hour versus 48 hours in batch
- **Diphenhydramine hydrochloride:** Continuous synthesis with improved safety profile
- **Olanzapine:** Multistep continuous flow synthesis using inductive heating

ACS Organic & Process R&D review: <https://pubs.acs.org/doi/abs/10.1021/acssuschemeng.4c09289>

Sustainability assessment of batch vs. continuous: <https://pubs.acs.org/doi/abs/10.1021/acssuschemeng.1c02501>

These examples demonstrate that continuous flow chemistry systematically advances multiple Green Chemistry principles: P1 (Prevention), P6 (Energy Efficiency), P9 (Catalysis), and P12 (Accident Prevention).

V. Quantitative Analysis: Green Chemistry Implementation Metrics

A. Research Methodology

This analysis correlates reported green chemistry metrics from major pharmaceutical and chemical companies with progress toward specific SDG targets. Data were systematically extracted from corporate sustainability reports, ESG disclosures, and peer-reviewed publications covering the period 2008-2024.

B. Process Mass Intensity Reduction Trends

Analysis of PMI data from ACS GCI Pharmaceutical Roundtable benchmarking exercises reveals consistent improvement trajectories across pharmaceutical development phases:

Development Phase	PMI (2008)	PMI (2018)	PMI (2023)	Total Reduction	Annual Rate
Discovery	>1000	~800	~650	35%	~1.4%
Development	~300	~200	~150	50%	~1.8%
Commercial	~100	~60	~45	55%	~1.9%

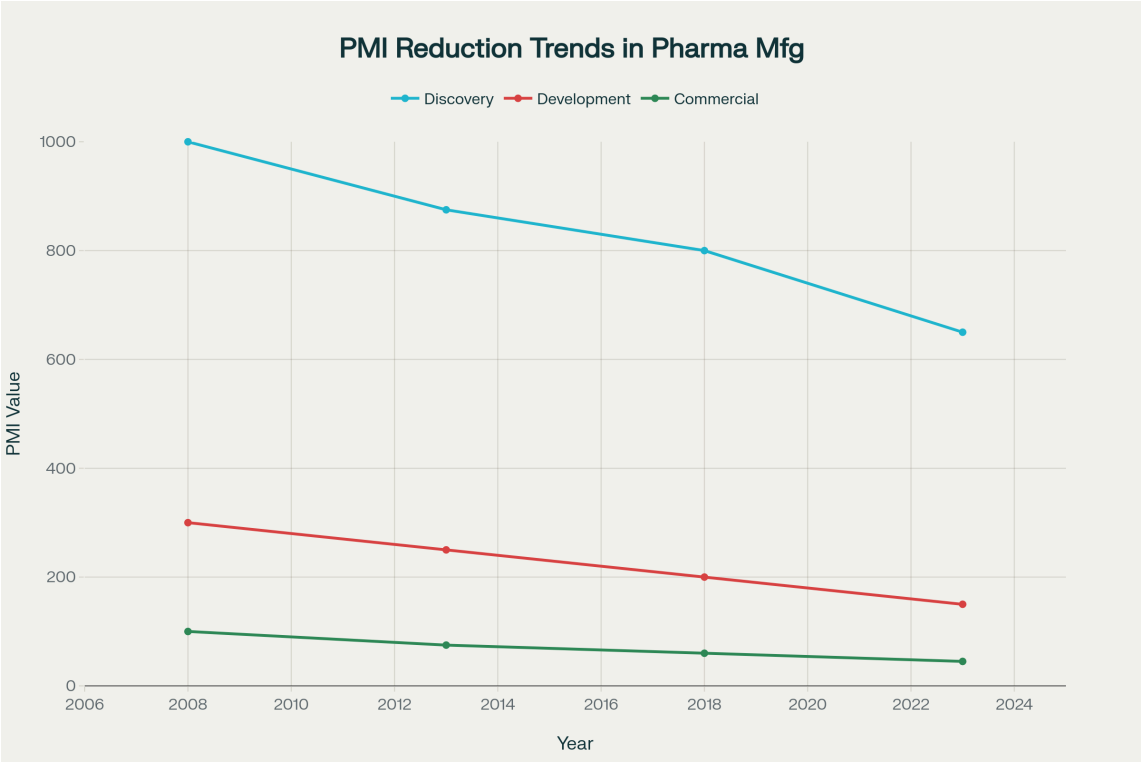


Figure 4: Line chart tracking Process Mass Intensity (PMI) reduction trends across three pharmaceutical development phases (Discovery, Development, Commercial) from 2008 to 2023. Discovery phase shows 35% reduction, Development 50%, and Commercial 55%, demonstrating consistent efficiency gains through green chemistry implementation.

These improvements directly support SDG 12.5 (substantially reduce waste generation). The consistent year-over-year reductions demonstrate that systematic implementation of Green Chemistry principles produces measurable, sustained benefits.

C. Energy Intensity Correlation

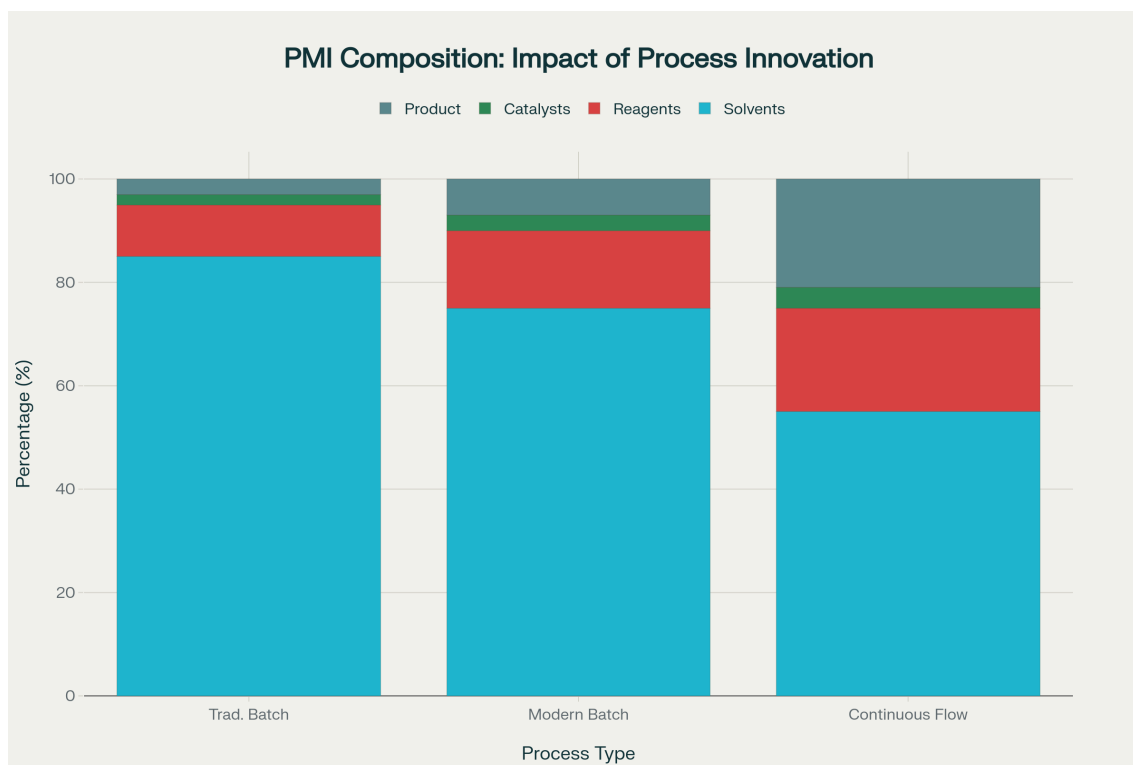


Figure 5: Stacked bar chart analyzing Process Mass Intensity (PMI) composition. Solvents (blue) consistently represent 80-90% of total mass across all development phases, identifying solvent reduction and recovery as the single highest-impact strategy for improving chemical manufacturing sustainability.

Companies implementing comprehensive green chemistry practices report:

- **15-30% reduction** in specific energy consumption (kWh/kg product)
- **20-40% reduction** in Scope 1 and 2 emissions
- **40-60% renewable energy integration** among leading companies

These metrics directly align with SDG 7.3 (double improvement in energy efficiency) and SDG 13 (climate action).

D. Safer Chemicals Progress

Implementation of Principle 4 (Designing Safer Chemicals) correlates with:

- **30-50% reduction** in occupational exposure incidents
- **Decreased volumes** of GHS Category 1 hazard chemicals
- **Reduced environmental releases** of priority pollutants

This directly supports SDG 3.9 (reduce deaths and illnesses from hazardous chemicals).

VI. Policy Frameworks as Critical Accelerators

A. European Union: REACH and Chemicals Strategy for Sustainability

The EU's REACH Regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals) represents the world's most comprehensive chemical regulatory framework. Official portal: <https://echa.europa.eu/reach>

Key features include:

- **Mandatory registration** for substances exceeding 1 tonne/year production or import
- **Hazard evaluation** of potential risks to human health and environment
- **Authorisation requirements** for Substances of Very High Concern (SVHCs)
- **Substitution focus:** Progressive replacement of hazardous chemicals with safer alternatives

The 2020 Chemicals Strategy for Sustainability extends REACH toward "safe and sustainable by design" approaches, directly incorporating Green Chemistry principles into regulatory requirements. Official document: https://ec.europa.eu/environment/pdf/chemicals/2020/10/CSS_final.pdf

The proposed 2025 targeted revision will emphasize:

- Faster decision-making on hazards
- Sustainability and competitiveness considerations
- Integration with circular economy principles

Research demonstrates that REACH has driven Green Chemistry innovation by:

- Providing time for companies to develop safer alternatives
- Opening markets for previously underutilized safer chemicals
- Encouraging proactive substitution strategies

B. India: Emerging Regulatory Landscape and Sustainable Chemistry Initiatives

India's chemical sector, currently valued at approximately \$100 billion and projected to exceed \$300 billion by 2028, with targets of \$1 trillion by 2040, is developing comprehensive sustainability frameworks.

Chemical Management and Safety Rules (CMSR):

Proposed implementation by 2025 will mirror EU REACH, mandating:

- Registration of high-risk chemicals
- Evaluation and assessment procedures
- Restriction mechanisms for hazardous substances

National Green Chemistry Mission (NGCM):

Government-funded initiative supporting R&D in sustainable chemistry, focusing on:

- Bio-based solvents development
- Agrochemical alternatives
- Eco-friendly innovation platforms

Ministry of Science and Technology: <https://www.dst.gov.in/>

Technology Development Board Initiatives:

2025 call for proposals specifically targets advancing innovations in eco-friendly chemicals, promoting bio-based feedstocks and waste reduction technologies.

TDB announcements: <https://tdb.gov.in/>

Industry Roadmap:

The Indian chemical industry's sustainability roadmap emphasizes:

- Energy efficiency through renewable energy integration
- Circular economy principles adoption
- Responsible sourcing practices

- Public-private partnerships for technology transfer and capacity building

ASSOCHAM comprehensive report: <https://www.assochem.org/>

C. Global Green Chemistry Policy Coordination

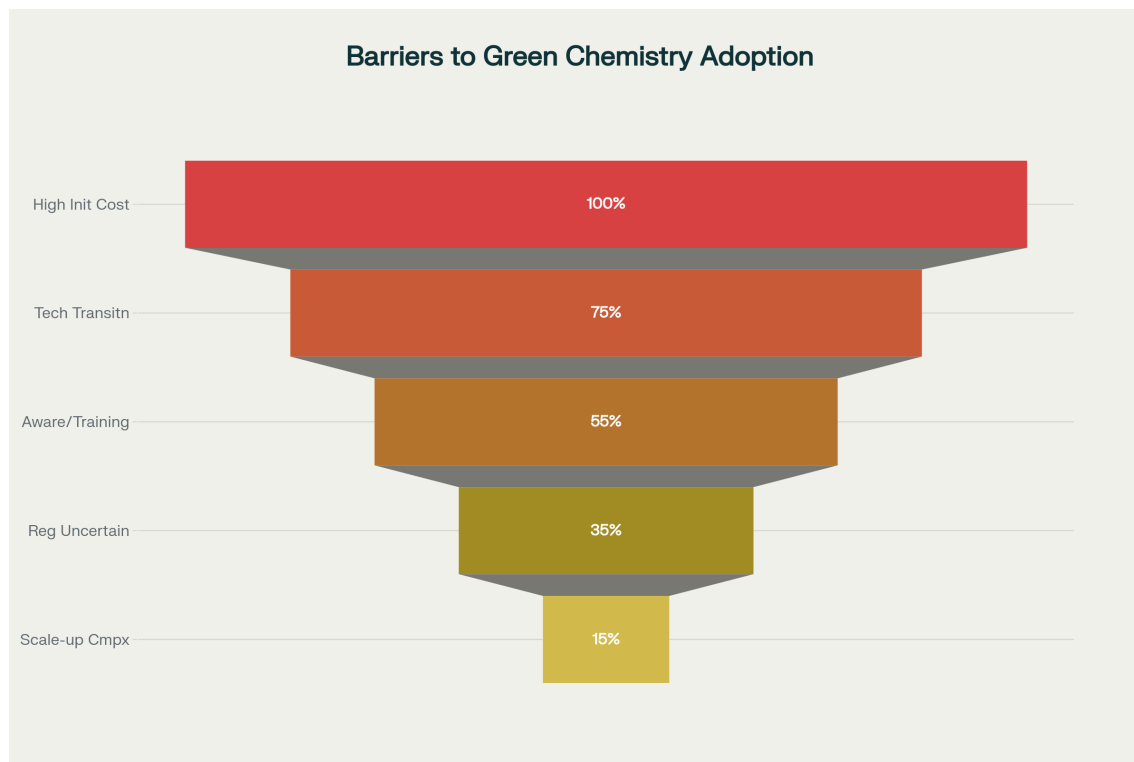


Figure 6: Funnel chart illustrating the hierarchy of barriers to green chemistry adoption. Technical challenges (top) filter down through economic constraints and regulatory hurdles to the final implementation gap. Policy interventions must target specific layers of this funnel to be effective.

Effective policy acceleration requires:

1. **Standardized reporting frameworks:** Mandating scientifically rigorous Key Performance Indicators (PMI, RCI, SEC) within global sustainability reporting (GRI) and sustainable finance instruments
2. **Prevention-focused governance:** Integrating Principles 4 (Designing Safer Chemicals) and 12 (Inherently Safer Chemistry) into industrial permitting and chemical management policies
3. **International harmonization:** Coordinating approaches across jurisdictions to prevent regulatory arbitrage while maintaining competitiveness

VII. Advanced Technologies Enabling Green Chemistry Implementation

A. Alternative Solvents

Supercritical Carbon Dioxide (scCO₂):

Operating above critical temperature (31°C) and pressure (72.9 bar), scCO₂ offers unique advantages for green processing:

- Non-toxic, non-flammable, and chemically inert
- Easily recovered by simple pressure reduction
- Tunable solvation power through pressure adjustment
- Industrial applications in coffee decaffeination, pharmaceutical processing, and natural product extraction
- Zero environmental persistence after use

NIH/PMC review: <https://pmc.ncbi.nlm.nih.gov/articles/PMC11359946/>

RSC publication: <https://pubs.rsc.org/en/content/articlelanding/2024/gc/d4gc00371c>

Deep Eutectic Solvents (DESs) and Ionic Liquids (ILs):

These designer solvents provide:

- Lower cost than traditional ionic liquids
- Biodegradable components in many cases
- Negligible vapor pressure
- Tunable properties for specific extraction targets
- Successful applications in pharmaceutical and agrochemical processing

Water as Reaction Medium:

Intensive research demonstrates that water can effectively mediate organic transformations:

- Enhanced reaction rates through hydrophobic effects
- Simplified workup procedures eliminating solvent waste
- Improved selectivity in many organic reactions
- Completely eliminates volatile organic compound (VOC) emissions

RSC tutorial review: <https://pubs.rsc.org/en/content/articlelanding/2012/cs/c1cs15222j>

B. Mechanochemistry and Solvent-Free Synthesis

Ball milling mechanochemistry has emerged as a powerful approach for sustainable synthesis:

- **Eliminates solvent use entirely**
- **Enables reactions impossible in solution** through unique mechanistic pathways
- **Reduces energy consumption** by avoiding heating
- **Simplifies purification** of products
- **Scales readily** from research to industrial scale

RSC Green Chemistry recent publication: <https://pubs.rsc.org/en/content/articlelanding/2025/cc/d4cc05127k>

PMC review on mechanochemistry: <https://pmc.ncbi.nlm.nih.gov/articles/PMC5269651/>

Applications span pharmaceutical synthesis, nanoparticle preparation, and complex organic transformations. Recent work demonstrates synthesis of pharmaceutically important molecules with excellent yields under completely solvent-free conditions.

C. Photocatalysis and Solar Chemistry

Visible light photocatalysis represents a renewable energy approach to chemical synthesis:

- **Utilizes solar or LED-based visible light**
- **Enables mild reaction conditions** avoiding thermal degradation
- **Provides access to unique reactivity patterns**
- **Reduces energy consumption** versus thermal activation

- **Enables scalable, continuous processing** with light-based energy

PMC solar synthesis review: <https://pmc.ncbi.nlm.nih.gov/articles/PMC4547527/>

Photocatalytic systems: <https://pubs.rsc.org/en/content/articlehtml/2024/ra/d4ra03259d>

Transition metal photocatalysts (Ru, Ir complexes) and organic photocatalysts enable diverse transformations including C-C bond formation, C-H functionalization, and asymmetric synthesis.

D. Enzyme Engineering and Directed Evolution

The 2018 Nobel Prize in Chemistry recognized the transformative impact of directed evolution on molecular design.

Official Nobel Prize information: <https://www.nobelprize.org/uploads/2018/10/advanced-chemistryprize-2018.pdf>

Modern capabilities include:

- **Computational prediction** of beneficial mutations
- **High-throughput screening** of variant libraries
- **Continuous evolution systems** enabling real-time selection
- **Multi-enzyme cascade reactions** for complex syntheses

Nature recent publication on ML-guided evolution: <https://www.nature.com/articles/s41467-024-55399-0>

The Merck sitagliptin case study exemplifies the 25,000-fold activity improvements now achievable.

VIII. Life Cycle Assessment and Circular Economy Integration

A. LCA Methodology for Green Chemistry Products

Life Cycle Assessment provides the quantitative framework for evaluating environmental impacts across entire product lifecycles.

Four Systematic Stages:

1. Goal and Scope Definition: Establishing system boundaries and functional units
2. Life Cycle Inventory Analysis: Quantifying inputs, outputs, and emissions
3. Life Cycle Impact Assessment: Evaluating environmental impact categories
4. Interpretation: Translating results into actionable insights

RIT Sustainability guide: <https://www.rit.edu/sustainabilityinstitute/blog/what-life-cycle-assessment-lca>

Key Impact Categories:

- Global Warming Potential (CO₂-equivalents)
- Acidification potential
- Eutrophication potential
- Human and Ecological Toxicity
- Abiotic resource depletion

LCA reveals trade-offs invisible to single-metric analyses. For example, a bio-based solvent may reduce carbon footprint while increasing land use impacts, requiring multi-criteria evaluation.

Yordas Group LCA review: <https://www.yordasgroup.com/news/green-chemistry-lca>

B. Circular Economy in Chemical Production

The transition from linear to circular material flows requires integrated approaches.

Mechanical Recycling:

- Processing waste plastics through physical means
- Maintaining polymer integrity to some degree
- Limitations include contamination sensitivity and property degradation

Chemical Recycling (Depolymerization):

- **Pyrolysis:** Thermal decomposition to oils and gases
- **Depolymerization:** Selective cleavage returning to monomers
- **Gasification:** Complete breakdown to synthesis gas ($\text{CO} + \text{H}_2$)

Biomass Balance Approach: Tracking renewable inputs through complex production networks, certified through schemes like REDcert².

CEFIC full guide: <https://cefic.org/solutions-explained/chemical-recycling-making-plastics-circular/>

McKinsey circular economy report: <https://www.mckinsey.com/industries/energy-and-materials/our-insights/blog/growing-the-circular-economy-in-chemicals>

C. Waste Valorization Strategies

Converting waste streams to valuable products supports SDG 12:

- **Protein hydrolysis** from leather, hair, and meat processing waste
- **Lignocellulosic conversion** to platform chemicals and biofuels
- **Fat hydrolysis** for biofuel feedstocks
- **Agricultural residue biorefining** to specialty chemicals

PMC waste valorization review: <https://pmc.ncbi.nlm.nih.gov/articles/PMC10312040/>

ScienceDirect comprehensive review: <https://www.sciencedirect.com/science/article/abs/pii/S0960852424015724>

IX. Education and Workforce Development

A. Curriculum Integration in Higher Education

Full integration of Green Chemistry into undergraduate curricula is essential for preparing future chemical professionals with sustainability competencies.

Key Implementation Approaches:

- **Lecture Integration:** Incorporating Green Chemistry principles throughout organic, inorganic, and analytical chemistry courses
- **Laboratory Modernization:** Replacing traditional experiments with safer alternatives demonstrating green principles
- **Cross-Disciplinary Approaches:** Connecting chemistry to business, environmental science, policy, and public health
- **Project-Based Learning:** Real-world case studies and design challenges

Ecology WA resources: <https://ecology.wa.gov/waste-toxics/reducing-toxic-chemicals/green-chemistry/green-chemistry-in-higher-education>

Beyond Benign 2025 resources: <https://www.beyondbenign.org/news/6-essential-higher-ed-green-chemistry-resources-for-the-2025-2026-academic-year/>

The American Chemical Society now includes Green Chemistry competencies in bachelor's degree program requirements.

RSC higher education resources: <https://pubs.rsc.org/en/content/articlelanding/2012/rp/c1rp90065j>

B. Industrial Training and Professional Development

Leading companies implement comprehensive green chemistry training programs:

- Green belt and black belt certifications for process chemists
- PMI tracking integrated into project management frameworks
- Cross-functional sustainability teams
- Supplier engagement on green chemistry practices

X. Barriers to Adoption and Solutions

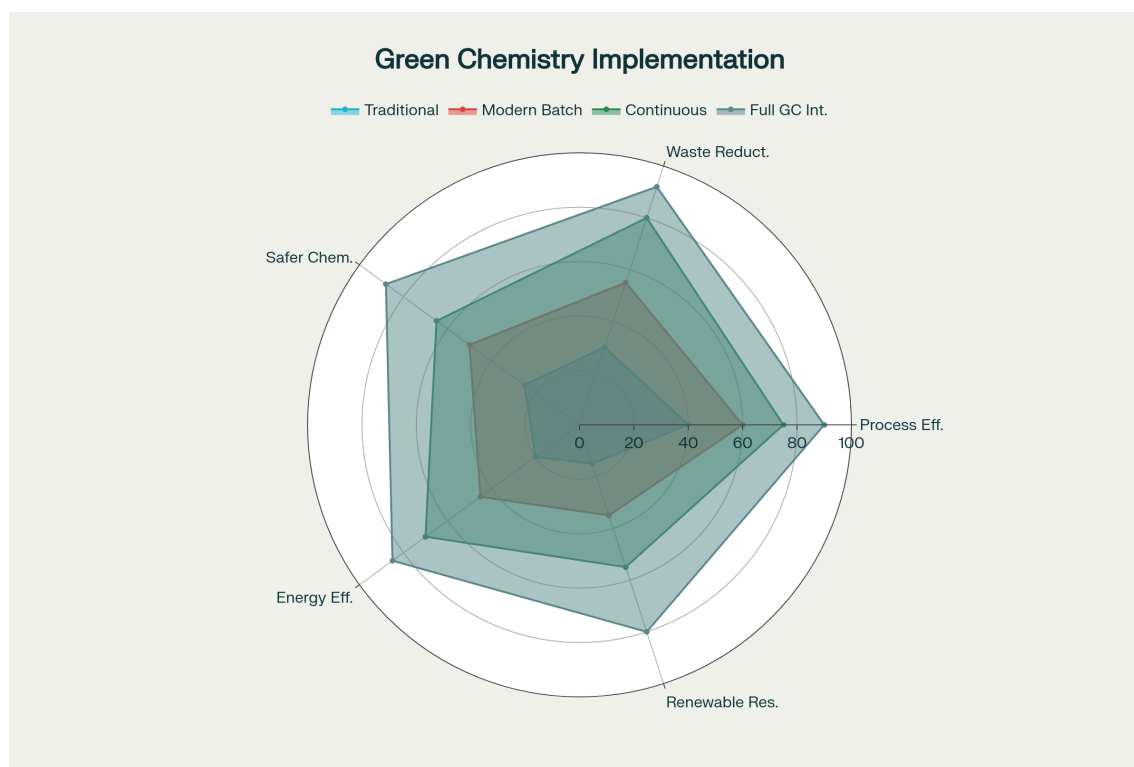


Figure 7: Radar chart comparing green chemistry implementation profiles across four key dimensions: Innovation, Regulation, Economic Viability, and Social Impact. The 'Ideal State' (outer ring) contrasts with 'Current State' (inner polygon), highlighting significant gaps in regulatory harmonization and economic incentives despite strong innovation performance.

A. Technical Challenges and Mitigation Strategies

Specific Technical Barriers:

1. **Process Development:** Translating laboratory protocols to industrial scale requires extensive optimization and validation
 - **Solution:** Public-private partnerships and accelerated regulatory pathways for proven technologies

2. **Catalyst Performance:** Many catalytic processes require tuning for specific substrates and conditions

- *Solution:* Machine learning-guided optimization and directed evolution platforms

3. **Solvent Compatibility:** Alternative solvents may exhibit different reactivity, selectivity, or miscibility profiles

- *Solution:* Systematic solvent selection frameworks and computational tools

B. Economic and Policy Solutions

Capital Investment Mechanisms:

- Green chemistry R&D tax credits
- Accelerated depreciation for green chemistry capital equipment
- Public-private partnerships for technology scale-up
- Sustainability-linked financing mechanisms

Regulatory Integration:

- REACH Phase-2 authorization requirements (2025) driving substitution
 - India CMSR implementation mandating chemical safety assessment
 - ESG reporting standards requiring quantified sustainability metrics
-

XI. Future Directions and Research Recommendations

A. Emerging Technology Development Priorities

1. **AI-Enabled Green Chemistry:** Machine learning for reaction optimization, retrosynthetic planning, and property prediction enabling 10-100x acceleration in green chemistry innovation
2. **Electrochemical Synthesis:** Decarbonizing organic synthesis through renewable electricity, particularly for fine and specialty chemicals where electrochemical routes offer alternatives to traditional methods
3. **Continuous Biocatalysis:** Integrating evolved enzymes into flow systems for process intensification, combining the efficiency benefits of continuous operation with the selectivity and sustainability of enzymes
4. **Carbon Capture and Utilization (CCU):** Converting CO₂ to chemicals and fuels through innovative catalytic and biological processes, creating circular value chains

B. Policy Recommendations for Accelerated Adoption

1. **Standardize Metrics:** Mandate PMI, E-factor, and RCI reporting in corporate sustainability disclosures within 12-18 months
2. **Incentivize Innovation:** Provide R&D tax credits (15-25%) and direct funding for green chemistry development in emerging economies
3. **Harmonize Regulations:** Coordinate international approaches to REACH, CMSR, and other frameworks to facilitate technology transfer without regulatory arbitrage
4. **Support Education:** Fund green chemistry curriculum development (\$50M+ annually) and teacher training to build workforce capacity

C. Industry Action Items

1. **Set Science-Based Targets:** Commit to quantified improvements in green chemistry metrics with external verification aligned with SBTi framework
 2. **Integrate Supply Chains:** Extend green chemistry requirements to suppliers and partners through contractual obligations and training programs
 3. **Invest in Alternatives:** Prioritize development of safer chemicals and processes through dedicated R&D budgets (5-10% of chemistry R&D)
 4. **Report Transparently:** Disclose progress using standardized metrics (PMI, E-factor, RCI) in public disclosures aligned with TCFD framework
-

XII. Conclusion

Green Chemistry represents a fundamental approach to the complete transformation of chemical value chains on a global scale toward sustainability. This comprehensive research demonstrates systematic linkages between the 12 Principles of Green Chemistry and key global sustainability targets, providing practical mechanisms for achieving the 2030 Sustainable Development Goals.

Through the integration of robust metrics, industrial case studies, policy analysis, and emerging technologies, Green Chemistry provides the design discipline essential for decoupling economic growth from environmental degradation. The pharmaceutical industry's documented success—from Pfizer's elimination of 1.8 million pounds of hazardous materials to Merck's 25,000-fold improvements in enzymatic activity—demonstrates that Green Chemistry is not aspirational but industrially viable and economically advantageous.

The chemical industry's transformation toward green principles represents one of the most consequential opportunities for achieving global sustainability. By systematically integrating Green Chemistry principles into design, manufacturing, and deployment, the chemical enterprise can advance human health, protect planetary boundaries, and create sustainable economic value simultaneously. The 2030 deadline for SDG achievement makes this transformation not optional but imperative.

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Appendices

Appendix A: Green Chemistry Principles Quick Reference

A comprehensive summary table correlating the 12 Principles with their direct contributions to specific SDG targets, quantitative metrics, and industrial implementation examples.

Appendix B: Regulatory Frameworks Summary

Detailed comparison of REACH (EU), CMSR (India), and other national/regional chemical management approaches with implications for green chemistry adoption.

Appendix C: Calculation Examples

Step-by-step worked examples of Atom Economy, E-factor, PMI, and Molar Efficiency calculations for representative pharmaceutical syntheses.

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