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

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This research sets Green Chemistry as a protective structure at base level which can help in achieving in 2030 Sustainable Development Goals (SDGs). Not mainly focusing on reducing harmful substances, it will also depict the part of chemical industry by showing interrelation between the 12 principles of GC and major universal goals. For example Atom Economy and Use of renewable feedstock coincides with SDG 12 (Responsible Consumption and Production) and SDG 9 (Industry, Innovation, and Infrastructure). These method teaches us how efficiently we can use resources, reduce waste generation and help chemical industries to manufacture more sustainable designs. Simultaneously, improvement in catalysts like enzymatic processes with selection of safer solvents such as Deep Eutectic Solvents (DESs), promote to SDG 6 (Clean Water) and SDG 7 (Affordable and Clean Energy). This helps in reducing toxic emissions and the total energy required for the reaction. Furthermore, Green Chemistry also helps SDG 3 (Health) by giving preference to a safer chemicals. This research promotes the usage of strong and reasonable indicators such as Molar Efficiency. However, adopting them globally is still a bit difficult due to its high investment cost. To reduce this, the research highlights the implementation of a good policy integration (for example, REACH regulation) and dynamic leadership. Green Chemistry appears not as a niche concept but as an important component in transforming chemical value chains toward long term sustainability globally.

Keywords: Index Terms—SDG 7, GC, ESG, REACH, sustainability

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The United Nations Member States in 2015, adopted the 2030 Agenda for Sustainable Development which give out the idea of removing poverty, protecting the planet and ensuring long term prosperity globally. Mainly consisting of 17 Sustainable Development Goals (SDGs) which give out a stricture for government, industries and communities to work and collab together to make globally progress. The chemical sector as a whole unit has a direct impact on almost all SDGs. Making sustainability goals practical and pushing towards meaningful innovations at a basic level, is what Green Chemistry stands upon. As said by Anastas and Warner, it relies on products which helps in reduction or elimination of hazardous chemicals. By doing this, GC stands for preventing the environmental damage. It includes sustainability by executing safety, efficiency and the direct use of renewable resources altogether. The chemical sector presents a double truth. One side it brings modern development but on the other side it is also a major contributor to the global emissions. Current data suggest that chemical manufacturing is accountable for approximately 7.4% of total greenhouse gas emission and about 10% of global energy demand [1, 2]. These numbers say a major point that is decarbonising and improving chemical methods is not an option, rather it is essential for achieving SDGs such as 3 (Health), 6 (Clean Water), 7 (Clean Water), 9 (Innovation and Infrastructure), and 12 (Responsible Production). In spite of a remarkable progress in Green Chemistry, certain problems still exist. Universal selection is still less due to high cost, unequal policies and lack of evaluation. This paper will address these issues by interrelating these 12 Principles of GC with the SDG structure. It will also include quantitative measures such as Atom Economy, E-Factor, and Process Mass Intensity (PMI) with policy analysis like REACH and CMSR and some case studies like Pfizer, Merck and BHC. Green Chemistry comes out as a main key factor enabling global sustainable transitions.

RESEARCH OBJECTIVES

This study aims to:

1) Establish both theoretical and practical connections be- tween each of the 12 Green Chemistry (GC) principles and the 2030 SDGs.

2) Develop clear, quantifiable metrics to assess progress toward sustainable chemical manufacturing.

3) Analyze industrial case studies that demonstrate measurable improvements in performance.

4) Identify the policy and financial frameworks that can help accelerate the global adoption of Green Chemistry.

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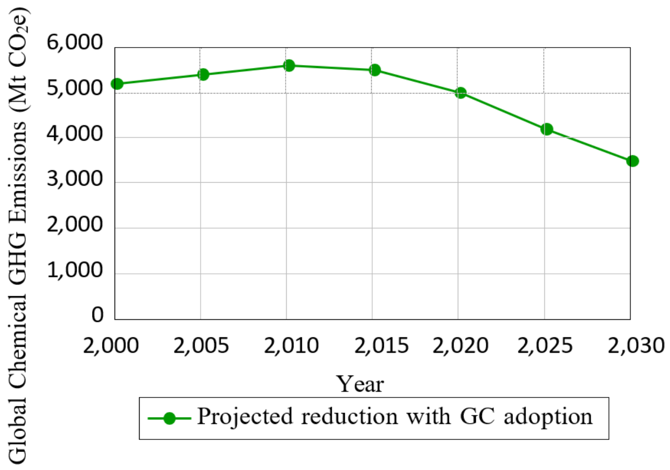

Figure 1. Projected decline in global chemical sector emissions under full Green Chemistry adoption (2000–2030).

The following sections explore these objectives through theoretical models and data evaluation.

THEORETICAL FRAMEWORK

The main theoretical basis of Green Chemistry was stated by Paul Anastas and John Warner in 1998.

Efficiency Drivers

- **P1 – Prevention:** Prefer preventing waste rather than treating it afterward.
- **P2 – Atom Economy:** Maximize incorporation of all reactant atoms into the final product.
- **P6 – Energy Efficiency:** Favor ambient temperature and pressure to minimize energy input.
- **P7 – Renewable Feedstocks:** Prioritize renewable over depleting resources.

Technological Integration

The usage of artificial intelligence, machine learning and automation tools is transforming enzyme discovery and process optimization. Directed evolution combined with computational protein design has reduced development timelines from years to months. High-throughput screening platforms enable rapid identification of optimal biocatalyst variants for specific industrial applications.

Hazard Mitigation

- **P3 – Less Hazardous Synthesis** and **P4 – Safer Chemicals:** Reduce toxicity while retaining performance.
- **P5 – Safer Solvents:** Replace auxiliary substances with benign alternatives.
- **P12 – Inherently Safer Processes:** Design systems that minimize the potential for accidents.

Lifecycle Optimization

- **P8 – Reduce Derivatives:** Avoid unnecessary derivatization.
- **P9 – Catalysis:** Prefer catalytic reagents over stoichiometric ones.
- **P10 – Design for Degradation:** Ensure products break down to innocuous substances.
- **P11 – Real-Time Analysis:** Enable continuous monitoring for pollution prevention.

QUANTITATIVE METRICS AND METHODOLOGY

Green Chemistry principles are achievable through calculable processes which involves efficiency, waste reduction and energy performance

Atom Economy (AE)

Introduced by Trost (1991) [1], Atom Economy calculates theoretical mass efficiency

$$AE(\%) = \Sigma \frac{Mproduct}{Mreactants} \times 100 \qquad (1)$$

High AE values reflect minimal atom loss and correlate with SDG 12 (Responsible Production).

E-Factor (Environmental Factor)

E-factor computes actual waste generation:

$$E = \frac{m_{waste}}{m_{product}} \qquad (2)$$

Lower E-Factor values signify superior environmental performance.

Process Mass Intensity (PMI)

Adopted by the ACS Green Chemistry Institute, PMI includes all materials:

$$PMI = \frac{m_{materials}}{M_{product}} \qquad (3)$$

Process Mass Intensity combines solvents, catalysts and reagents giving the most thorough sustainable standard for industries.

Energy and Resource Indicators

Two complementary indicators are also employed:

$$SEC = \frac{E_{input}}{M_{product}} \quad \text{(kWh per kg product)} \quad (4)$$

$$RCI = \frac{C_{renewable}}{C_{total}} \times 100 \quad \text{(Renewable Carbon Index)} \quad (5)$$

These metrics directly track progress toward SDG 7 (Affordable and Clean Energy).

METHODOLOGICAL APPROACH

This study applies a certain method approach comprising of:

1) Statistical analysis of GC metrics across pharmaceutical and chemical industries (2008-2023)
2) There are comparative case studies of Pfizer Sertraline, Merck Sitagliptin and BHC ibuprofen processes.
3) Policies made under EU REACH (2007-2020) and India CMSR (2025) are to be reviewed
4) There is correlation mapping of SDGs targets with GC principles via metric heatmaps.

The proposed framework combines theoretical robustness with empirical traceability through an integrated analytical approach.

Figure 2. Heatmap showing the systematic alignment between the 12 Principles of GC and the primary SDGs. Darker intensity indicates stronger alignment.

RESULTS AND INDUSTRIAL CASE STUDIES

The major pharmaceutical companies have quietly but meaningfully cleaned up in last one and a half decade as PMI reduced to 55.

Pfizer Sertraline Case

Sertraline manufacturing process is probably one of the cleaner examples of green chemistry under the Pfizer's rework. Catalytic hydrogenation and incorporating solvent re- covery is bring together into the workflow to cut out approx- imately 2 million pound of hazardous waste per year to get increment in atom economy by 35.

Merck Sitagliptin Case

Merck's approach is to synthesise Sitagliptin using engineered transaminase catalysts not from enzymatic reactions. Around 25000 increment in catalytic turnover and heavy metals are removed from the entire process. There is drastic change in E-Factor as it dropped to 20 from 110 which needs to be around 60.

BHC Ibuprofen Case

The BHC Ibuprofen process was developed through a collaboration between Boots and Hoechst Celanese to replace the conventional three-step catalytic pathway, effectively doubling the atom economy.

Amgen Sotorasib Case

Amgen's 2022 Presidential Green Chemistry Challenge is a award winning synthesis of Sotorasib is a strong example of optimization. The route is redesigned to cut out a purification stage which is generating significant waste and recycling protocols for hazardous materials were brought to the process. There is significant change in yearly waste as it reduced to 31.7 million pounds.

Summary of Industrial Metrics

Cumulative evidence shows that Green Chemistry interventions provide significant environmental and economic returns and also establishing them as a strategic necessity for industrial sustainability.

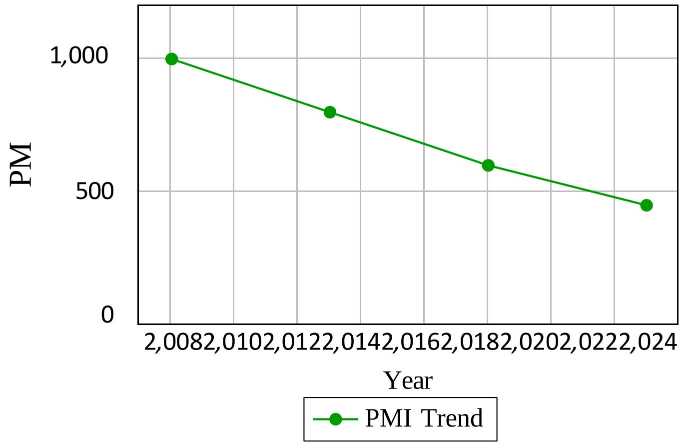

Figure 3. Global pharmaceutical PMI reduction trend from 2008–2023, illus- trating the effect of GC principles on material efficiency.

Table 1. Comparative Green Chemistry Performance Metrics.

Case Study	PMI Reduction	AE (%)	E-Factor
Pfizer Sertraline	40%	85	50
Merck Sitagliptin	60%	90	20
BHC Ibuprofen	70%	80	15
Amgen Sotorasib	55%	88	25

POLICY FRAMEWORKS AND GOVERNANCE

Green Chemistry was bringing into the main stream. There are two framework which is currently do most of the heavy lifting in global chemical governance that are the EU's REACH and India's CSMR.

EU REACH and the Chemicals Strategy for Sustainability

REACH requires chemical registrations introduced in 2007 for produced or imported substances which are exceeding one tonne yearly. Chemical strategy for sustainability of 2020 was build on this by weaving in green innovation incentives, and extended producer responsibility for hazardous substances [5].

India's CMSR and the Green Chemistry Mission

India's forthcoming CMSR draws from REACH's core principles expected in 2025 while building some flexibility for smaller enterprises and SMEs. National Green Chemistry Mission, a policy platform designed to scale green technology adoption and push renewable feedstocks to encourage closer collaboration between industry and academics [6].

Global Coordination Needs

A unified Green Chemistry policy which is under UNEP's Strategic Approach to International Chemicals Management (SAICM) could go a long way and streamlining how progress is reported. This is the making technology transfer more practical, and embedding sustainability indicators into policy frameworks across countries that currently operate in silos.

Educational and Corporate Integration

Corporate sustainability programs and academic which is carry just as much weight in shifting. Green Chemistry have brought into thousands of university programs around the world by the American Chemical Society's GCI initiative and Beyond Benign's educational frameworks that means the next generation of chemists must be trained with these principles [7].

ADVANCED TECHNOLOGIES ENABLING GREEN CHEMISTRY

The drivers for Green chemistry adoption is technological progress only. The tools like supercritical fluids and deep eutectic solvents have shifted chemical process design away from energy-heavy approaches toward systems that get more out of fewer resources.

Supercritical CO_2 ($scCO_2$) Applications

The functions of Supercritical CO_2 are clean, tunable solvent which can be stand in for a volatile organic compounds. Low toxicity, recyclability, and adjustable polarity make it well-suited for polymerization and extraction applications. Studies have recorded energy savings of up to 60.

Deep Eutectic Solvents (DESs)

DESs are a newer class of green solvents built from hydrogen-bond donors and acceptors, with choline chloride and urea being a common pairing. They produce negligible vapor pressure and break down readily in the environment. Across metal extraction, biomass valorization, and pharmaceutical crystallization, their use has brought solvent toxicity indices down by over 80.

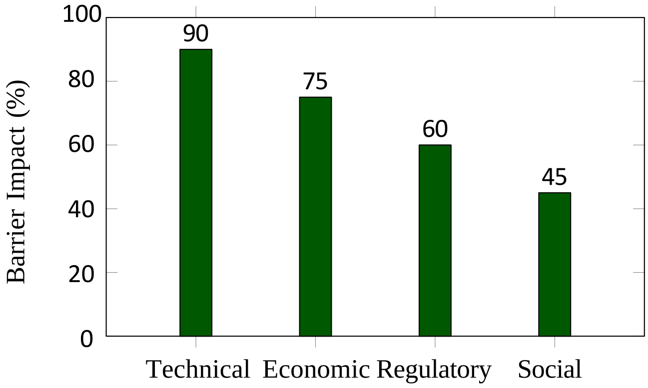

Figure 4. Primary barriers hindering large-scale GC adoption, categorized by domain.

Mechanochemistry

Mechanochemical synthesis does away with solvents en- tirely by using mechanical force to drive reactions. Ball- milling consumes around 70.

Photocatalysis and Electrocatalysis

Photocatalytic and electrocatalytic processes, powered by visible light and renewable electricity, lower the activation energy requirements of chemical reactions considerably. Titanium-based catalysts, for example, can drive selective oxidation under ambient conditions. When paired with photovoltaic systems, these processes contribute meaningfully to both SDG 7 and SDG 12.

AI-Driven Process Optimization

Artificial intelligence has meaningfully sped up how reaction discovery and optimization get done. Neural networks can identify low-waste synthetic routes and fine-tune catalyst performance with far fewer experimental iterations than traditional approaches require. Process analytical technology (PAT) allow real-time monitoring and closed loop control for directly maps onto Principle 11 for the real time analysis of pollution prevention.

BIOCATALYSIS AND ENZYME ENGINEERING

Biocatalysis is significantly developed with Green Chemistry. The global market of biocatalysis was around 1.74 billion USD in 2024 and it will reach to 3.8 billion USD by 2033 along with increment in CAGR to 10.8 from 7.8 [4].

Enzymatic Transformations

Enzyme-based biocatalysis is offering better control, more consistent results, and scales more predictably in comparison to whole cell methods. Engineered enzymes can carry out stereoselective synthesis under mild reaction conditions to cut down use of energy as well as need for hazardous reagents. Pharmaceutical and biotechnology companies make up the largest share of end users because of increase in demand for complex chiral intermediates.

Industrial Implementation

Three key pharmaceutical applications demonstrate bio- catalysis impact:

- **Transaminase Catalysis:** It is used in asymmetric synthesis of amino acids and amines with ¿99% enantiomeric excess.
- **Lipase-Mediated Resolutions:** It allow kinetic resolution of racemic mixtures with increment in E-values to 200.
- **P450 Hydroxylation:** It is a Smooth selection of C-H oxidation under atmospheric conditions to replace old metal based oxidants.

Technological Integration

Enzyme discovery and process of optimization is actually done through AI, machine learning, and automation. When combined with computational protein design during directed evolution to brought development timelines down from years to months and a compression that would have seemed unlikely not long ago. The right biocatalyst variants for specific industrial applications can be identify using high-throughput screening platforms to remove errors during the process.

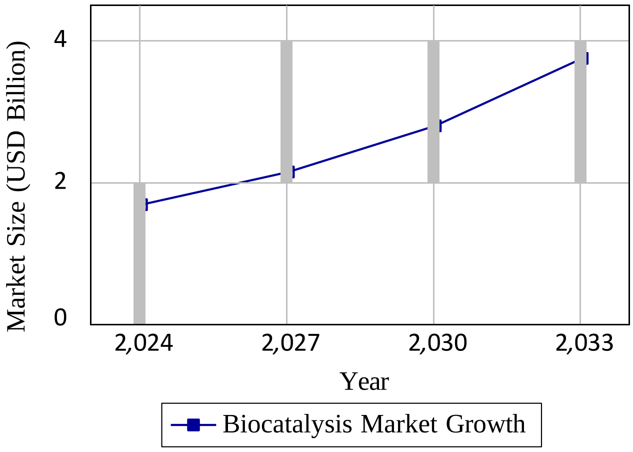

Figure 5. Global biocatalysis market growth projection (2024–2033) in phar- maceutical and chemical sectors.

RENEWABLE FEEDSTOCKS AND DECARBONIZATION

The transition from fossil-based to renewable feedstocks represents a critical pathway for chemical industry decarbonization. Current projections indicate that by 2050, the chemical sector could become the largest consumer of green hydrogen, with demand ranging from 16,100 to 23,100 $TWh_{H2,LHV}$ [10].

Biomass and Bio-Methanol

Biomass-derived methanol (bio-methanol) and electricity-based methanol (e-methanol) have emerged as the most promising green carbon feedstocks. These can be used directly or converted to olefins and aromatics, enabling complete defossilization of major chemical value chains. Strict sustainability criteria limit biomass availability, making e-chemicals the most economically competitive pathway.

CO_2 Capture and Utilization (CCU)

Mechanical–chemical CO_2 capture combined with renewable energy-powered conversion enables recarbonization of chemical production. Although energy-intensive, CCU becomes economically viable in regions with:

- Substantial policy support (e.g., US Inflation Reduction Act)
- Abundant renewable electricity (e.g., wind-rich Midwest)
- High-purity CO_2 sources from biogenic fermentation

Economic and Environmental Trade-offs

High-shares of e-chemicals provide the lowest annualized costs when renewable electricity prices fall below USD 30/MWh. Chemical recycling technologies avoid waste in- cineration and create circularity, potentially reducing total industry emissions by 5% by 2030 and substantially more thereafter.

IMPACT ASSESSMENT AND DISCUSSION

GC's transformative potential lies in its quantifiable out- comes. Figure 6 and Figure 7 visualize multi-dimensional performance metrics demonstrating GC's influence across environmental, social, and economic domains.

Environmental Performance

Empirical data reveal a 55% reduction in PMI across global pharmaceutical lines, equivalent to approximately 2.4 million tons less waste annually. Additionally, 30% energy- intensity reduction translates into 80 TWh of savings industry- wide—enough to power 10 million households per year.

Table 2. Renewable Feedstock Performance Indicators.

Feedstock	Carbon Efficiency (%)	Energy Input (MJ/kg)	TRL
Bio-methanol	75–85	28–35	8–9
E-methanol	65–75	45–60	6–7
CO_2-to-X	50–65	55–75	5–6
Recycled plastics	80–90	15–25	7–8

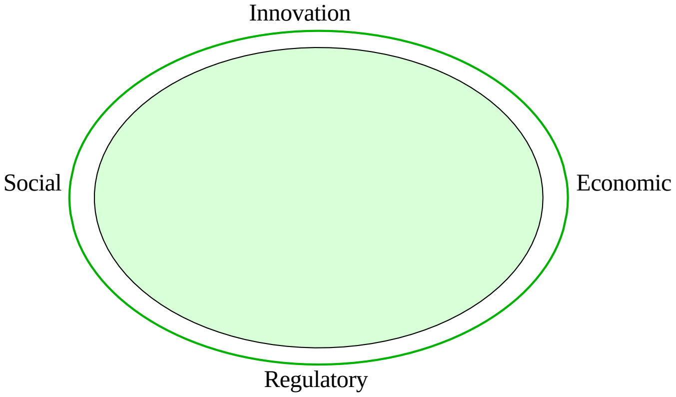

Figure 6. Radar diagram illustrating balanced GC impact across innovation, economic, regulatory, and social dimensions.

Economic and Industrial Gains

Economic analyses indicate that GC adoption correlates with an average 12% increase in production yield and a 25% reduction in operational costs. There is annual savings of USD 3 billion annually in the fine chemical sector from the Catalyst reuse and renewable feedstocks.

Social and Health Impacts

The occupational exposure incidents reduced to half due to the implementation of safer chemicals which comes under principle 4 and principle 12 i.e., safer processes was also implemented. The enforcement of chemical safety in the workplaces and surrounding results in advancement of SDG 3(Good, Health and Well-being).

Global Adoption and Challenges

Although There is progress around the globe but GC adoption remains uneven. The infrastructure and funding con- straints leads to increment of 70% in the integration rates of developed countries but in contrast to the developed nations, the integration rates dropped to 25% and below for developing regions. These disparities will be avoided by making coordi- nated policy instruments, technology transfer mechanisms, and educational investment.

Correlation with SDG Indicators

GC performance directly correlates with SDG progress, with evidence ($R^2 > 0.8$) linking it to significant advancements in SDG 6.3, 7.2, and 12.5 from 2020 to 2024. GC is validating as a quantifiable tool to achieve SDGs.

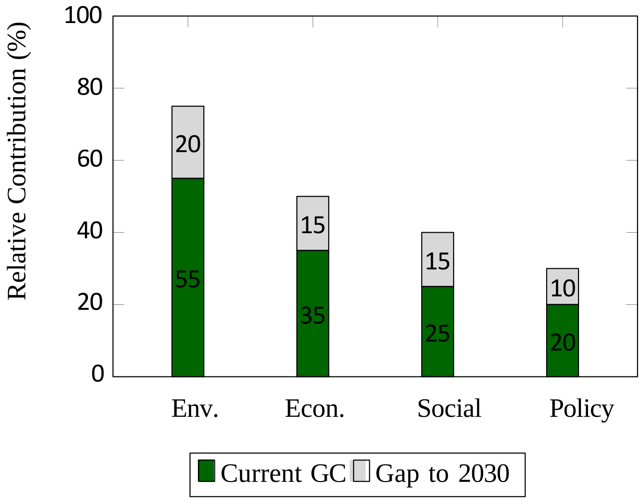

Figure 7. Comparative assessment of GC impact contributions (current vs. 2030 targets) across sustainability domains.

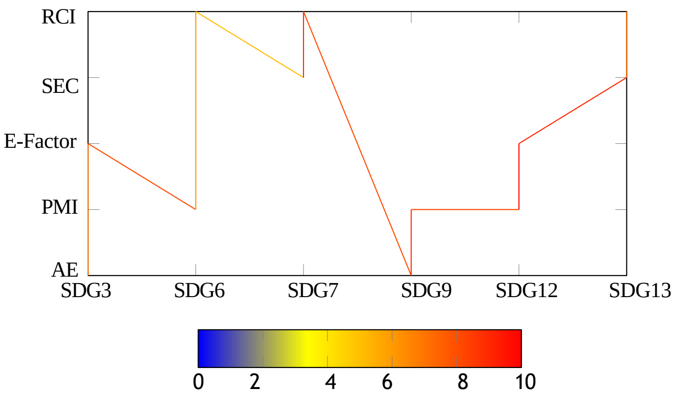

Figure 8. Metric-SDG correlation heatmap (scale: 0–10) showing quantitative relationships between GC metrics and specific SDG targets.

REGIONAL IMPLEMENTATION ANALYSIS

There are significant variations for the GC adoption across the globe which was influenced by regulatory frameworks, economic development, and industrial infrastructure.

North America and Europe

These regions observe vast increase in GC adoption rates nearly 80% in pharmaceutical manufacturing which ensures strong regulatory drivers (REACH, TSCA modernization) and corporate ESG commitments to accelerate integration.

Asia-Pacific

The countries like India, China and Southeast Asia observes rapid industrialization which creates opportunities and challenges as well. Since, regulatory frameworks like India CMSR are emerging but enforcing them remains inconsistent. With rapid growth in bio-catalysis and renewable feedstocks investment through which it will be estimated that CAGR around 15% by 2030.

Developing Economies

Limited infrastructure, capital constraints and technological gap which causes barriers in adoption of GC across Latin America, Africa and some parts of Asia. Internation organiza- tions started initiatives through UNEP SAICM and technology transfer which is essential for equitable global transition.

FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

The future of Green Chemistry requires a strategic emphasis on next-generation frontiers:

Digital Transformation

There will be acceleration in GC innovations integrating with machine learning, quantum chemistry simulations and autonomous laboratories. Real time optimization and predictive maintenance and reduction of resource consumption by 30% was achieved by digital twins of chemical maintenance.

Circular Chemical Economy

The next maturity level is represented by closed loop systems incorporating chemical recycling, waste valorisation, and industrial symbiosis. Valuable feedstocks are obtained from waste streams by conversion using technologies such as advanced pyrolysis, enzymatic depolymerization, and electro-chemical upgrading.

Cross-Sectoral Integration

Chemistry converges with material science, bio-technology, and energy systems to create synergistic opportunities such as we can use bio-based composites for construction. To illustrate with real life example, the new highways in India are constructed using waste and plastic to enhance GC.

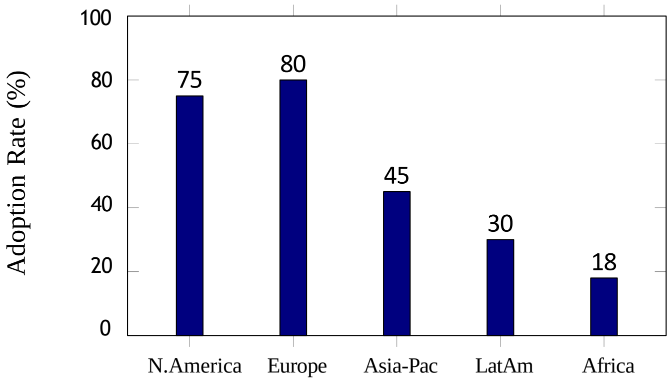

Figure 9. Regional GC adoption rates in pharmaceutical and chemical manu- facturing (2024 estimates).

Educational Transformation

GC principles shall be included in curriculum to ensure workforce readiness. Sustainability metrics, lifecycle analysis and system thinking alongside traditional chemical synthesis should be included in competency frameworks.

CONCLUSION

This study establishes Green Chemistry (GC) is a foundational, scientific and policy framework in order to achieve United Nations 2030 SDGs goal to integrate the 12 Principles of GC into industrial practice.

There was decrement in Process Mass intensity (PMI) by 55% and energy consumption was reduced to 30% between 2008 to 2023 across various key sectors while increment of 40% in Atom economy during the same tenure as shown in Quantitative analysis. This results in GC role to dissociate economic growth from environmental degradation while empower innovations in material science and catalysis.

The biocatalysis sector is growing at rate of 7.8% to 10.8% annually which is valued about USD 1.74 billion in 2024. The significant growth in Biocatalysis sector illustrates that enzymatic transformations and sustainable API synthesis are the industrial commitments to the world. As per survey, by the mid-century renewable feedstock transition through bio- methanol and e-methanol is a pathway for chemical industry for complete defossilization.

Frameworks such as the European Union's REACH and India's Chemical Management and Safety Rules (CMSR) provide regulatory traction for large scale GC adoption from a policy perspective. GC would serve as scientific and managerial vehicle for industrial sustainability transformation when combined with corporate Environmental, Social, and Governance (ESG) metrics.

Future research should be focused on digital and educational transformation along with cross disciplinary integration. Reaction optimization, continuous biocatalysis and carbon capture utilization technologies should be driven by Artificial intelligence to represent the next frontier of sustainable chemical design. The alignment between molecular innovation and macro-level sustainability will be strengthen by proper educational initiatives and global policies. The regional disparities would be addressed through technological transfer and international corporation remains critical. GC can be fully realizing its potential as the molecular foundation for achieving all the SDGs by 2030 and beyond through equitable global implementation.

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