

Sustainable Chemistry for a Greener Tomorrow: A Comprehensive Review

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Abstract—Sustainable chemistry, often referred to as green chemistry, has emerged as a transformative approach for reducing the environmental impact of chemical processes while promoting efficiency, innovation, and safety. This comprehensive review explores the fundamental principles, recent advancements, and future prospects of sustainable chemistry in the context of a greener and more resilient global ecosystem. The article highlights the significance of designing chemical products and processes that minimize toxicity, energy consumption, and waste generation, thereby aligning industrial practices with environmental protection and resource conservation. Key developments such as renewable feedstocks, biodegradable materials, catalytic efficiency, alternative solvents, and energy-efficient synthesis routes are examined in detail. The review also discusses cutting-edge technologies including biocatalysis, photocatalysis, green nanotechnology, and carbon capture and utilization (CCU), which are reshaping modern chemical manufacturing. Furthermore, the integration of life-cycle assessment (LCA) tools, eco-friendly process intensification strategies, and circular economy concepts is analyzed to emphasize their role in enhancing sustainability metrics across industries. In addition, the article evaluates regulatory frameworks, global initiatives, and industrial case studies that demonstrate the tangible benefits of sustainable chemistry, such as reduced emissions, lower operational costs, and improved product safety. Despite significant progress, challenges remain in scaling green technologies, addressing economic barriers, and fostering interdisciplinary collaboration. Overall, this review underscores the vital role of sustainable chemistry in achieving long-term environmental goals and advancing global sustainability. It provides a holistic perspective on emerging trends, technological innovations, and strategic pathways essential for transitioning toward a greener, safer, and more sustainable future.

Index Terms—Sustainable chemistry, green chemistry, Renewable feedstocks, Biocatalysis, Green solvents, Process intensification, Circular economy, Environmental sustainability, Catalysis.

I. INTRODUCTION

Over the past few decades, the global scientific community has witnessed a significant paradigm shift toward *sustainable chemistry*, a discipline focused on minimizing the environmental impact of chemical processes and products. This shift has been driven by increasing concerns about *climate change*, *resource depletion*, *toxic emissions*, and the long-term sustainability of traditional industrial practices. Sustainable chemistry, often synonymous with *green chemistry*, aims to redesign chemical processes by considering environmental, economic, and social dimensions simultaneously. The field encourages innovation through the adoption of *renewable feedstocks*, *energy-efficient synthesis*, *biodegradable materials*, and *cleaner technologies* that reduce hazardous waste and promote ecological balance. The emergence of sustainable chemistry is closely linked to global environmental movements and international commitments such as the *Paris Agreement*, *UN Sustainable Development Goals (SDGs)*, and regulatory frameworks established by environmental agencies across various nations. These initiatives emphasize the need to transition from conventional chemical manufacturing—often associated with pollution, excessive energy consumption, and health hazards—toward green and *eco-friendly* alternatives. Moreover, with the rapid industrial expansion in developing countries, the demand for sustainable and scalable solutions has become more critical.

In addition, advancements in scientific research have significantly contributed to the evolution of

sustainable chemistry. Breakthroughs in *catalysis*, *biotechnology*, *nanomaterials*, *renewable energy integration*, and *green solvent systems* have expanded the possibilities for implementing environmentally responsible chemical solutions on a large scale. As industries, researchers, and policymakers increasingly recognize the necessity of sustainable transformation, the role of sustainable chemistry continues to grow as a cornerstone of future-ready industrial practices. Thus, understanding its development, principles, and strategic importance is essential for building a greener tomorrow.

Principles and Scope of Sustainable Chemistry

Sustainable chemistry is guided by a set of core principles that emphasize reducing hazard, minimizing waste, and improving efficiency throughout the life cycle of chemical products. Central to this concept are the *12 Principles of Green Chemistry*, which provide a structured framework for developing safer, cleaner, and more sustainable chemical processes. These principles encourage the use of *non-toxic reagents*, *atom economy*, *renewable raw materials*, *energy-efficient pathways*, and *real-time monitoring* to prevent pollution at the source. This proactive approach differentiates green chemistry from traditional environmental strategies that focus primarily on treating pollution after it has been generated.

The scope of sustainable chemistry extends far beyond laboratory research and encompasses various sectors such as *pharmaceuticals*, *agrochemicals*, *polymer manufacturing*, *energy production*, *waste management*, and *environmental engineering*. It plays a critical role in achieving circular economy objectives, where materials are continuously recycled, reused, and regenerated to reduce dependency on virgin resources. Techniques such as *biocatalysis*, *photocatalysis*, *electrochemical synthesis*, and *CO₂ utilization* have further expanded the scope of sustainable chemistry, enabling industries to innovate while maintaining environmental responsibility. Furthermore, sustainable chemistry integrates tools like *life-cycle assessment (LCA)*, *green metrics*, and *environmental impact assessment* to evaluate the sustainability of processes holistically. It promotes interdisciplinary collaboration, bridging fields such as materials science, engineering, biotechnology, and environmental sciences to deliver comprehensive

solutions. Thus, the broad scope and guiding principles of sustainable chemistry form the foundation for environmentally conscious innovation, positioning it as a vital discipline for achieving long-term global sustainability goals.

Importance of Sustainable Chemistry for a Greener Future

The importance of sustainable chemistry lies in its potential to address some of the most pressing global environmental and socio-economic challenges. With escalating concerns about *pollution*, *greenhouse gas emissions*, *plastic waste accumulation*, and *water scarcity*, sustainable chemistry offers a pathway to develop technologies that protect the environment while supporting economic growth. By prioritizing *energy efficiency*, *hazard reduction*, and *cleaner production methods*, sustainable chemistry helps reduce the ecological footprint of industries and fosters healthier ecosystems.

One of the key benefits of sustainable chemistry is its contribution to public health. Traditional chemical processes often release harmful substances that contaminate air, soil, and water. Sustainable chemistry aims to eliminate or drastically reduce these impacts through the use of *safer solvents*, *non-toxic reagents*, and *green degradation pathways*. This ensures that both workers and communities are protected from chemical hazards. Additionally, sustainable chemistry supports the development of *biodegradable polymers*, *renewable fuels*, and *clean energy technologies*, contributing to reduced environmental pollution and improved resource management. Economically, sustainable chemistry offers long-term advantages by lowering operational costs, reducing waste disposal expenses, and improving production efficiency. As global markets shift toward sustainable consumer preferences, industries adopting green methodologies gain a competitive edge, enhancing brand value and regulatory compliance.

Moreover, sustainable chemistry plays a crucial role in achieving global sustainability targets, including *SDG 7 (Affordable and Clean Energy)*, *SDG 12 (Responsible Consumption and Production)*, and *SDG 13 (Climate Action)*. By integrating ecological responsibility with innovation, sustainable chemistry paves the way for a greener tomorrow, offering a strategic platform for building resilient, sustainable, and future-proof industrial systems.

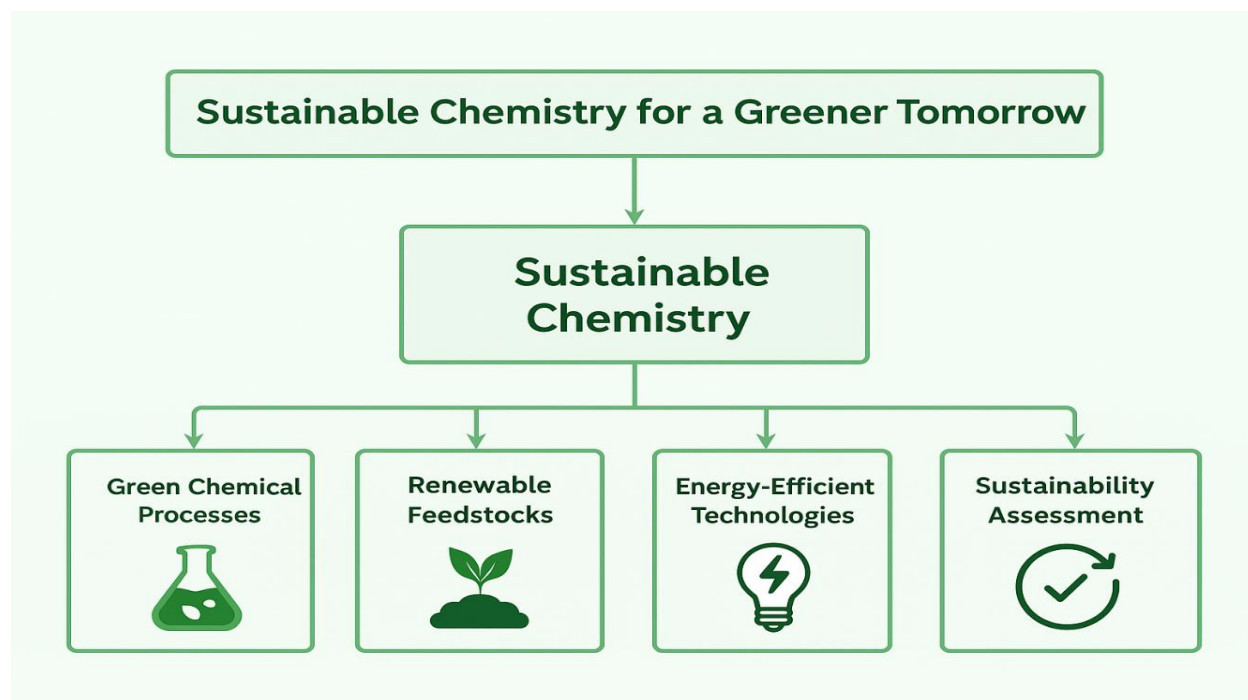


Fig. 1: Importance of Sustainable Chemistry for a Greener Future

II. OBJECTIVES

- To explore the foundational concepts and principles of sustainable chemistry by analyzing the evolution, significance, and theoretical framework that underpin green chemical practices across scientific and industrial sectors.
- To review and evaluate modern advancements in sustainable chemical technologies, including green solvents, renewable feedstocks, biocatalysis, photocatalysis, and energy-efficient synthesis routes that contribute to environmental protection and process optimization.
- To examine the integration of sustainability assessment tools, such as life-cycle assessment (LCA), green chemistry metrics, process mass intensity (PMI), and environmental impact indicators, in evaluating the efficiency and ecological safety of chemical processes.
- To analyze the role of sustainable chemistry in promoting circular economy concepts, focusing on waste minimization, resource recovery, recycling technologies, and sustainable material design for long-term environmental resilience.
- To identify industrial applications and case studies that demonstrate the practical implementation of sustainable chemistry across pharmaceuticals, agrochemicals, polymers, nanotechnology, energy sectors, and manufacturing industries.
- To discuss global challenges and barriers—technological, economic, regulatory, and social—that hinder the large-scale adoption of green chemistry approaches, along with strategies to overcome these obstacles.
- To assess the contribution of sustainable chemistry to global environmental goals such as climate mitigation, pollution reduction, and achievement of the United Nations Sustainable Development Goals (SDGs).
- To highlight future opportunities, innovations, and research directions required for scaling sustainable chemical technologies and promoting a greener, safer, and more sustainable future.

III. LITERATURE REVIEW AND DATA COLLECTION

1. Sheldon, R. A., & Woodley, J. M. (2018). Role of Biocatalysis in Sustainable Chemistry

This review emphasizes how **biocatalysis** has transformed sustainable chemical production. The authors detail enzymatic processes that operate under mild conditions, reducing energy use and waste. They

provide industrial examples from pharmaceuticals, highlighting improved selectivity and reduced purification requirements. The paper also discusses enzyme engineering, immobilization, and continuous-flow biocatalysis. This contribution underscores biocatalysis as a central pillar of sustainable chemistry.

2. Armaroli, N., & Balzani, V. (2016). Solar electricity and solar fuels

This article reviews renewable energy systems with a focus on solar fuels and photovoltaic technologies. The authors discuss artificial photosynthesis, hydrogen generation, and solar-based energy systems as future solutions to fossil-fuel dependency. The review connects energy sustainability with green chemistry by showing how solar-driven processes reduce carbon emissions. It provides a forward-looking perspective on sustainable energy chemistry.

3. Clark et al. (2016). Circular economy design considerations in chemical sciences.

This publication examines sustainable chemistry within the **circular economy** framework. It discusses design strategies for resource recovery, waste valorization, and polymer recycling. The authors highlight the importance of designing chemicals and materials with end-of-life considerations. Practical case studies demonstrate how chemical industries can shift from linear to circular models. This work is integral to understanding sustainable materials management.

4. Ahmed, Smith & Clark (2021). Advances in carbon capture and utilization technologies

This review examines recent developments in Carbon Capture and Utilization (CCU). It covers chemical absorption, mineralization, photocatalytic reduction of CO₂, and CO₂-based polymer synthesis. The authors evaluate technological feasibility, economic factors, and environmental impacts. The study demonstrates how sustainable chemistry supports climate mitigation strategies.

5. Anastas, P. T., & Zimmerman, J. B. (2003). Design through the 12 Principles of Green Engineering.

This article expands sustainable chemistry into the domain of green engineering, highlighting how chemical design must integrate environmental performance at every stage. The authors formulate engineering principles that complement green chemistry concepts, including energy efficiency,

material use reduction, and end-of-life analysis. They advocate for safer product design, waste minimization, and systems analysis to evaluate sustainability metrics. The paper is influential in bridging chemistry and engineering, showing how design decisions can reduce lifecycle environmental burden. It serves as a blueprint for industries aiming to transition toward sustainable production systems.

6. Zhu, Romain & Williams (2016). Sustainable polymers from renewable resources

This highly cited article focuses on bio-based and biodegradable polymers. The authors evaluate renewable monomers, catalytic polymerization methods, and end-of-life biodegradation. They also describe the limitations of current biodegradable materials and the need for scalable production. This review is essential for understanding green polymer chemistry.

IV. METHODOLOGY / MATERIALS AND METHODS

Study Design & Literature Search:

The methodology for this review article was based on a systematic and comprehensive literature search to ensure the inclusion of relevant, high-quality, and up-to-date scientific information related to sustainable chemistry. A thorough search was conducted across major scientific databases, including Scopus, PubMed, ScienceDirect, SpringerLink, ACS Publications, Wiley Online Library, and Google Scholar. Keywords such as “*sustainable chemistry*,” “*green chemistry*,” “*renewable feedstocks*,” “*eco-friendly synthesis*,” “*biocatalysis*,” “*green solvents*,” “*circular economy*,” “*carbon capture*,” and “*environmental sustainability*” were used individually and in combination using Boolean operators (AND, OR) to refine results. Literature published between 2010 and 2025 was primarily considered, with older seminal work included when foundational concepts required historical context.

Inclusion and Exclusion Criteria

To maintain scientific rigor, clearly defined criteria were applied for the selection of articles:

Inclusion Criteria:

- Peer-reviewed research articles, review papers, book chapters, and authoritative reports.

- Studies focusing on sustainable chemical processes, technologies, principles, or environmental impacts.
- Papers presenting advancements in catalysis, green solvents, renewable feedstocks, cleaner production, and eco-efficiency.
- Case studies demonstrating industrial applications of sustainable chemistry.

Exclusion Criteria:

- Articles lacking scientific validation or methodological transparency.
- Studies published between 2000–2024 for contemporary relevance.
- Articles written in English.
- Studies not directly related to sustainability or chemical processes.

Data Extraction and Organization

Relevant data were systematically extracted from selected studies using a structured approach. Information related to green chemistry principles, technological innovations, process efficiency, environmental metrics, economic feasibility, and industrial case successes was compiled. Data were organized into thematic categories such as:

- Renewable feedstock utilisation
- Catalysis and green reaction pathways
- Eco-friendly materials and solvent systems
- Process intensification and waste minimization
- Sustainability assessment tools (LCA, green metrics)
- Industrial implementation and regulatory frameworks

This thematic classification allowed comparative evaluation across different domains of sustainable chemistry.

Analytical Framework

A qualitative synthesis approach was adopted to integrate findings from diverse literature sources. Comparative analysis was performed to identify:

- Emerging trends
- Technological gaps
- Environmental benefits
- Challenges and limitations
- Opportunities for future research

Life-cycle perspectives, environmental indicators, and efficiency metrics were critically examined to evaluate

the sustainability potential of various chemical processes.

Validation Through Cross-Referencing

To ensure accuracy and reliability, cross-referencing was carried out across multiple studies discussing similar technologies or concepts. Conflicting findings were analyzed based on study design, scale of experimentation, and methodological robustness. Priority was given to studies demonstrating reproducibility, industrial relevance, and validated sustainability metrics.

Framework for Synthesizing Final Review

The final compilation involved synthesizing the analyzed data into a coherent narrative. Emphasis was placed on:

- Highlighting significant advancements in sustainable chemistry
- Evaluating their real-world applicability
- Presenting critical insights into environmental, economic, and technological impacts
- Aligning findings with global sustainability goals and industrial transformation pathways

This methodological approach ensures that the review is comprehensive, evidence-based, and reflective of current scientific progress.

V. DISCUSSION

The development of sustainable chemistry represents a critical shift in how chemical sciences address global environmental challenges. Traditional chemical processes have long been associated with high energy consumption, toxic by-products, and substantial waste generation. In contrast, sustainable chemistry seeks to redesign these processes by embracing the 12 Principles of Green Chemistry, which emphasize waste prevention, safer solvents, atom economy, and the use of renewable feedstocks. These principles form the scientific foundation for designing cleaner industrial practices. Over time, sustainability has expanded beyond the laboratory, influencing policy, industrial production, and material development. The recognition that environmental protection and economic growth can coexist has further accelerated the adoption of green chemistry approaches across multiple sectors.

Sr. No.	Principle	Description / Key Insight
1	Prevention	Focus on minimizing waste generation rather than treating waste after formation.
2	Atom Economy	Maximize incorporation of all materials into the final product.
3	Less Hazardous Synthesis	Use and generate substances with minimal toxicity to humans and the environment.
4	Designing Safer Chemicals	Create chemicals with reduced toxicity while maintaining function.
5	Safer Solvents & Auxiliaries	Prefer benign solvents such as water, supercritical CO ₂ , or ionic liquids.
6	Energy Efficiency	Conduct reactions at ambient temperature and pressure whenever possible.
7	Use of Renewable Feedstocks	Prefer biomass, CO ₂ , and agricultural waste over fossil derivatives.
8	Reduce Derivatives	Avoid unnecessary protection/deprotection steps.
9	Catalysis	Use selective, recyclable catalysts to increase efficiency.
10	Design for Degradation	Chemicals should break down into non-toxic substances after use.
11	Real-Time Analysis	On-line monitoring reduces waste and errors.
12	Inherently Safer Chemistry	Minimize risks of accidents by choosing safer chemicals and processes.

Table 1: The Twelve Principles of Green Chemistry

Advancements in Sustainable Chemical Technologies
Recent technological innovations have significantly enhanced the potential of sustainable chemistry. One of the most impactful advancements is the increasing use of renewable feedstocks, such as lignocellulosic biomass, agricultural residues, and algal biopolymers, which serve as alternatives to fossil-based raw materials. Similarly, the rise of biocatalysis has revolutionized chemical synthesis by enabling reactions under mild conditions, reducing both energy input and waste formation. Photocatalysis and electrocatalysis have introduced energy-efficient routes for producing valuable chemicals such as hydrogen, fine chemicals, and pharmaceuticals. Green solvent systems, including ionic liquids, supercritical CO₂, and deep eutectic solvents, offer safer alternatives to volatile organic solvents. Additionally, sustainable polymer chemistry has advanced through the development of biodegradable plastics, bio-based composites, and recyclable polymer networks, reducing the global burden of plastic pollution. These technologies collectively demonstrate the transformative power of sustainable chemistry in modern industry.

Integration of Sustainability Assessment Tools

Evaluating the sustainability of chemical processes requires systematic and measurable frameworks. Tools such as Life-Cycle Assessment (LCA), E-Factor, Atom Economy, Process Mass Intensity (PMI), and Green Chemistry Metrics enable researchers and industries to quantify environmental burdens. LCA, in particular, provides a comprehensive cradle-to-grave evaluation, assessing environmental impacts including carbon footprint, water usage, toxicity, and energy demand. These tools not only help identify areas for improvement but also guide the redesign of chemical processes to achieve higher sustainability performance. Their integration ensures transparency, scientific rigor, and informed decision-making in industrial and academic research.

Sustainable Chemistry in Circular Economy Frameworks

Sustainable chemistry plays a crucial role in transitioning from the traditional linear model of “take–make–dispose” to a circular economy, where resources are continuously reused and regenerated. Greener synthetic methods promote waste minimization and facilitate the development of recyclable materials. Technologies such as chemical recycling, upcycling, and resource recovery allow

valuable materials to be reclaimed from industrial or post-consumer waste streams. Biomass valorization also supports circularity by converting agricultural and food waste into fuels, chemicals, and biodegradable materials. Through sustainable chemistry, industries can extend product life cycles, reduce dependency on virgin raw materials, and achieve long-term environmental resilience.

Industrial Applications and Case Studies

The practical implementation of sustainable chemistry has gained momentum across various industries. In pharmaceutical manufacturing, green solvent substitution, biocatalysis, and continuous-flow synthesis have reduced waste and improved efficiency. The agrochemical sector benefits from eco-friendly pesticide formulations and bio-based fertilizers. In polymer industries, companies are adopting biodegradable materials and chemical recycling technologies to address the global plastic crisis. Moreover, energy industries are increasingly integrating sustainable chemistry through the development of hydrogen production, CO₂ utilization, and biofuel technologies. Industrial case studies demonstrate substantial reductions in emissions, operational costs, and hazardous waste, proving that sustainable chemistry is not only environmentally beneficial but also economically viable.

Challenges and Barriers to Implementation

Despite its progress, sustainable chemistry faces several challenges. High initial costs, limited availability of renewable feedstocks, and technological constraints hinder large-scale adoption. Many green technologies still require optimization to match the efficiency and scalability of conventional processes. Regulatory inconsistencies across countries also pose difficulties for industries seeking global

sustainability compliance. Furthermore, the lack of widespread training in green chemistry principles restricts implementation in both academia and industry. Nevertheless, these challenges present opportunities for future innovation, enhanced funding, interdisciplinary collaboration, and policy integration.

Contribution to Global Environmental Goals

Sustainable chemistry is central to achieving several United Nations Sustainable Development Goals (SDGs). By enabling cleaner production, reducing pollution, and promoting responsible consumption, it contributes to SDG 12. Innovations in renewable energy and reduced carbon emissions align with SDG 7 and SDG 13. Sustainable materials and pollution-free technologies support SDG 14 and SDG 15, which address ecosystem and biodiversity protection. Through scientific innovation and industrial transformation, sustainable chemistry is directly linked to global climate action and environmental restoration.

Future Prospects and Research Directions

The future of sustainable chemistry depends on continued innovation, digital integration, and cross-disciplinary collaboration. Emerging fields such as AI-driven process optimization, machine-learning-assisted molecular design, bio-inspired chemistry, and green nanotechnology are expected to redefine chemical manufacturing. Scaling up green technologies, developing cost-effective renewable materials, and enhancing global policy frameworks will be essential steps toward sustainable transformation. By integrating advanced research with industrial implementation, sustainable chemistry can pave the way for a greener, more resilient global future.

Technology	Application Area	Sustainability Benefit
Photocatalysis	Solar-driven reactions	Reduces energy demand
Electrochemical Synthesis	Redox reactions	Avoids hazardous reagents
Biorefineries	Biomass conversion	Replace petroleum refineries
CO ₂ Capture & Utilization (CCU)	Carbon recycling	Reduces atmospheric CO ₂
AI & Automation in Green Chemistry	Reaction optimization	Increases efficiency, reduces waste

Table 2: Emerging Technologies for Sustainable Chemistry

VI. CONCLUSION

Sustainable chemistry stands at the forefront of global scientific and industrial transformation, offering practical and innovative pathways to address the environmental, economic, and social challenges posed by conventional chemical practices. This comprehensive review highlights the pivotal role of green chemistry principles, renewable feedstocks, eco-friendly solvents, biocatalytic and photocatalytic technologies, and energy-efficient reaction pathways in fostering cleaner and safer chemical production. Through the integration of sustainability assessment tools such as Life-Cycle Assessment (LCA), green chemistry metrics, and process intensification strategies, sustainable chemistry provides measurable, scientifically grounded methods for evaluating and improving environmental performance across diverse sectors. The discussion also emphasizes how sustainable chemistry supports the circular economy, where waste is minimized, resources are continuously valorized, and materials are reused to maximize ecological and economic efficiency. Industrial case studies further demonstrate that implementing sustainable chemistry not only reduces pollution and energy consumption but also enhances operational efficiency, regulatory compliance, and long-term profitability. These findings underscore the discipline's capacity to reshape industries ranging from pharmaceuticals and materials science to energy production and polymer manufacturing.

Despite the remarkable progress achieved, several barriers persist—including high implementation costs, technological limitations, and inconsistent regulatory frameworks—that hinder widespread adoption. Overcoming these challenges will require stronger interdisciplinary collaboration, targeted investment in green technologies, enhanced education and training, and supportive global policies. Looking forward, the future of sustainable chemistry lies in integrating emerging technologies such as AI-driven optimization, green nanomaterials, bio-inspired synthesis, and advanced catalytic systems to accelerate innovation. As the world moves toward more ambitious sustainability targets, sustainable chemistry will continue to serve as a cornerstone of environmental protection and clean technological advancement. Ultimately, adopting sustainable chemistry is not merely an option but a necessity for

achieving a greener, safer, and more resilient future for generations to come.

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