



Sustainable Chemistry Approaches for Tackling Plastic Pollution, Capturing Co₂, and Advancing Energy Storage and Renewable Energy

Dr. Vinod Kumar Singh

Associate Professor, Department of Chemistry,
S.P.P.G. College, Shohratgarh, Siddharthnagar, U.P. India

DOI : <https://doi.org/10.5281/zenodo.17107233>

ARTICLE DETAILS

Research Paper

Accepted: 16-08-2025

Published: 10-09-2025

Keywords:

Sustainable Chemistry Approaches, Plastic Pollution, Co₂, Energy Storage and Renewable Energy

ABSTRACT

Sustainable chemistry offers innovative pathways to address pressing global challenges such as plastic pollution, rising CO₂ levels, and the need for efficient energy solutions. This study explores cutting-edge chemical approaches for converting plastic waste into valuable products, developing advanced materials and catalysts for CO₂ capture and utilization, and enhancing the performance of energy storage systems. Furthermore, it examines the integration of renewable energy sources with sustainable chemical processes to reduce environmental impact and promote a circular economy. By highlighting recent advancements and future prospects, this work underscores the critical role of sustainable chemistry in building a cleaner, greener, and more resilient future. The transition toward a low-carbon, circular economy requires innovative chemical strategies that simultaneously address plastic waste accumulation, atmospheric CO₂ mitigation, and the global demand for efficient energy systems. This study presents a comprehensive analysis of recent advances in sustainable chemistry targeting three interconnected domains: (i) catalytic de-polymerization and chemical up-cycling of post-consumer plastics into monomers and high-value chemicals; (ii) design and synthesis of advanced sorbent materials, metal-organic frameworks (MOFs), and electrochemical



systems for CO₂ capture, conversion, and storage; and (iii) development of next-generation materials for high-capacity batteries, super-capacitors, and integrated renewable energy storage platforms. The findings highlight the pivotal role of sustainable chemistry in reducing environmental burdens, advancing resource recovery, and enabling a resilient, carbon-neutral energy future.

INTRODUCTION

The dual crises of environmental degradation and climate change have amplified the urgency for sustainable technological interventions. Among the most pressing challenges are the rapid accumulation of plastic waste, the steady rise in atmospheric CO₂ concentrations, and the need for efficient, low-carbon energy systems. Conventional waste management strategies, such as landfilling and incineration, not only fail to address the root causes of plastic pollution but also contribute to greenhouse gas emissions and the depletion of finite resources. Likewise, current CO₂ mitigation efforts, while advancing, remain insufficient to meet the targets outlined in the Paris Agreement, necessitating accelerated innovation in carbon capture and utilization (CCU) technologies.

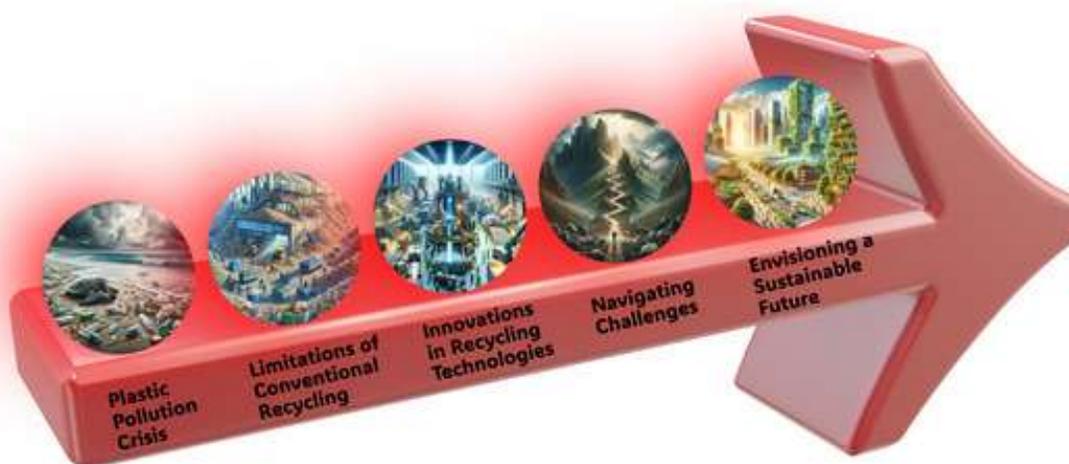
Sustainable chemistry, with its principles grounded in waste minimization, resource efficiency, and environmental compatibility, presents transformative solutions to these global challenges. Catalytic depolymerization and chemical upcycling of plastics have emerged as promising strategies for converting post-consumer waste into monomers, fuels, and functional materials, thereby closing material loops and promoting a circular economy. In parallel, the development of advanced CO₂ sorbents—such as functionalized porous carbons, metal–organic frameworks (MOFs), and hybrid nanomaterials—has enabled higher capture capacities and selective conversion into value-added chemicals, including fuels and polymer precursors.

In the energy sector, the increasing penetration of intermittent renewable sources such as solar and wind underscores the demand for high-performance energy storage systems. Sustainable chemistry contributes to this goal through the design of novel electrode materials, electrolyte formulations, and redox-active compounds for batteries, supercapacitors, and hybrid energy storage devices. The integration of renewable energy technologies with sustainable chemical processes can further reduce lifecycle emissions, enhance system efficiency, and improve economic viability.



This paper critically reviews recent advances in sustainable chemistry approaches for (i) tackling plastic pollution via chemical recycling and upcycling pathways, (ii) capturing and utilizing CO₂ through advanced material and catalytic innovations, and (iii) enhancing the performance of energy storage systems to complement renewable energy adoption. The discussion emphasizes mechanistic insights, scalability potential, and techno-economic considerations, aiming to bridge laboratory-scale developments with industrial and policy-level implementation. By identifying key challenges and research gaps, this work provides a roadmap for leveraging sustainable chemistry to accelerate the transition toward a resilient, low-carbon, and resource-efficient future.

The central objective of this review paper is to examine, in detail, the present status and future potential of innovative plastic waste recycling technologies within the framework of the circular economy. By exploring recent advancements, existing challenges, and emerging opportunities in chemical recycling, biological degradation, and other novel approaches, this work emphasizes how such innovations can enable a waste exchange system in which discarded materials are treated as valuable resources. Such a system supports a closed-loop model where materials are continually recovered and repurposed, thereby reducing environmental harm and promoting sustainable patterns of production and consumption. This comprehensive review highlights the pivotal role of technological progress in tackling one of the most urgent environmental issues of our era. Embedding advanced recycling methods into a circular economy framework can transform plastic waste from an environmental burden into an economic and industrial asset, fostering sustainable development. This transition not only mitigates ecological impacts but also creates economic value by converting waste into resources, supporting industrial growth, and advancing green economic initiatives.





REVIEW OF RELATED LITERATURE

Sustainable Chemistry and Circular Economy: The concept of sustainable chemistry, as defined by Anastas and Warner (1998), is grounded in the principles of designing chemical products and processes that reduce or eliminate the use and generation of hazardous substances. Recent studies highlight its central role in advancing a circular economy (Geissdoerfer et al., 2017), wherein waste materials are continuously reintegrated into the production cycle. In this framework, plastics, CO₂, and energy storage materials are not treated as terminal waste streams but as resources for revalorization.

Chemical Recycling and Up-cycling of Plastics: Conventional mechanical recycling often suffers from polymer degradation and loss of material properties (Hopewell et al., 2009). In contrast, chemical recycling—including pyrolysis, gasification, hydrolysis, and catalytic depolymerization—breaks down polymers into their monomeric or chemical constituents, enabling the production of virgin-quality materials (Ragaert et al., 2017). Recent advancements in catalyst design, such as single-site catalysts (Zhao et al., 2021) and bifunctional nanocatalysts (Liu et al., 2022), have significantly improved conversion efficiency and selectivity. Additionally, **upcycling** strategies aim to produce higher-value chemicals, such as specialty lubricants, surfactants, and functional monomers, from waste plastics.

CO₂ Capture, Utilization, and Storage (CCUS): The rising urgency of climate change mitigation has propelled research into CCUS technologies. Materials such as metal–organic frameworks (Sumida et al., 2012), amine-functionalized porous solids (Wang et al., 2011), and ionic liquids (Zhang et al., 2019) have demonstrated high CO₂ adsorption capacities and tunable selectivity. Beyond capture, CO₂ utilization offers the potential to produce fuels, chemicals, and polymers through catalytic hydrogenation, electrochemical reduction, and photochemical transformation (Aresta et al., 2017). Integrated approaches combining capture and conversion are emerging as promising pathways for reducing the overall energy intensity of CCUS systems.

Sustainable Energy Storage Materials and Systems: The increasing reliance on intermittent renewable energy sources necessitates advanced energy storage technologies. Lithium-ion batteries (LIBs) dominate the market, but concerns over resource scarcity and environmental impacts have spurred research into sodium-ion, potassium-ion, and multivalent-ion batteries (Slater et al., 2013). Sustainable chemistry contributes by developing bio-derived electrolytes, recyclable electrode materials, and green synthesis routes for battery components (Nazar et al., 2014). Similarly, supercapacitors and redox flow batteries



benefit from eco-friendly electrode materials such as biomass-derived carbons and conductive polymers (Wang et al., 2016).

Integration of Sustainable Chemistry with Renewable Energy Systems: Recent work emphasizes the **synergistic integration** of renewable energy sources with sustainable chemical processes. Solar-driven CO₂ reduction (Hao et al., 2020), wind-powered electrolytic hydrogen production, and biomass valorization coupled with renewable electricity are being explored to minimize lifecycle carbon footprints. Techno-economic assessments (TEAs) and life cycle assessments (LCAs) are increasingly applied to guide decision-making, ensuring that novel processes remain environmentally and economically viable at scale (Garcia-Garcia et al., 2021).

SUSTAINABLE CHEMISTRY APPROACHES

Sustainable chemistry offers an integrated framework for addressing critical environmental challenges such as **plastic pollution**, **CO₂ emissions**, and the need for **efficient energy storage and renewable energy systems**. By applying **green chemistry principles**—including waste minimization, renewable feedstock utilization, and energy efficiency—innovations in materials science and process engineering can create closed-loop, eco-friendly solutions.

PLASTIC POLLUTION MITIGATION

Plastic waste is one of the most pressing environmental threats. Sustainable chemistry approaches focus on:

Chemical recycling & up cycling – breaking down plastics into monomers or higher-value products.

Biodegradation using enzymes or microbes – enabling natural decomposition of plastics.

Circular economy resource recovery – converting waste plastics into new materials and products to reduce landfill dependency.

CO₂ CAPTURE & UTILIZATION (CCU)

- CO₂ emissions from industrial processes and energy generation contribute to climate change. Sustainable chemistry aims to:



- Develop **advanced adsorbents** such as **metal-organic frameworks (MOFs)** and porous carbons for high-efficiency capture.
- Use **catalytic and electrochemical methods** to convert CO₂ into useful chemicals, fuels, and polymers. Integrate CCU with renewable energy systems to enhance sustainability.

ENERGY STORAGE & RENEWABLES

- Transitioning to renewable energy requires reliable storage systems. Sustainable chemistry contributes by:
 - Designing **green battery materials** with low environmental impact.
 - Employing **bio-based electrolytes** for safer, biodegradable energy storage.
 - Advancing **super capacitors and flow batteries** for large-scale renewable energy integration.

INTEGRATION ACROSS DOMAINS

The synergy between these three pillars enables a **circular and low-carbon economy**:

- **Plastic waste conversion** can generate feedstock for energy and CO₂ capture technologies.
- **CO₂-derived materials** can be used in renewable energy devices.
- **Renewable energy systems** can power recycling and CCU processes, further reducing emissions.

The **interconnection** among these domains creates a synergistic effect. For example, captured CO₂ can be used to produce polymers or fuels using renewable-powered chemical processes; recycled plastics can serve as raw materials for energy storage components; and renewable energy drives the operation of CO₂ capture systems and recycling plants. This closed-loop system not only minimizes environmental impact but also stimulates green economic growth through resource efficiency, circularity, and technological innovation.

NEED AND IMPORTANCE OF THE STUDY

The escalating environmental crisis, characterized by persistent plastic pollution, rising atmospheric CO₂ concentrations, and the global demand for clean, efficient energy systems, underscores the urgent need



for transformative technological solutions. Conventional waste management, carbon mitigation, and energy storage strategies are often fragmented, resource-intensive, and environmentally taxing. In contrast, **sustainable chemistry** offers integrated, science-driven approaches that simultaneously address these challenges through innovation, efficiency, and circular resource management.

Plastic Pollution Crisis:

- An estimated 300 million tons of plastic waste are generated annually, with a significant fraction persisting in landfills and marine environments for centuries.
- Conventional recycling is insufficient, leading to environmental accumulation, ecosystem disruption, and microplastic contamination in food and water systems.
- Chemical recycling and upcycling can transform this waste into high-value products, reducing environmental burdens while recovering valuable resources.

Rising CO₂ Levels and Climate Change:

- Global CO₂ emissions are the primary driver of climate change, with current concentrations exceeding 420 ppm.
- Carbon capture, utilization, and storage (CCUS) technologies are essential to meeting net-zero targets.
- Sustainable chemistry enables efficient capture, conversion, and integration of CO₂ into industrial value chains, reducing reliance on fossil carbon.

Energy Transition and Storage Gaps:

- The growing share of intermittent renewable energy (solar, wind) requires advanced storage solutions to ensure grid stability.
- Conventional batteries face challenges in cost, sustainability, and recyclability.
- Green synthesis of electrodes, bio-based electrolytes, and recyclable battery systems can improve energy storage while minimizing environmental impact.

IMPORTANCE

- **Environmental Protection:** Mitigates pollution, reduces greenhouse gas emissions, and supports biodiversity conservation.



- **Resource Efficiency:** Promotes circular economy models where waste streams are transformed into valuable resources.
- **Climate Mitigation:** Contributes directly to reducing the carbon footprint and achieving international climate goals.
- **Technological Innovation:** Encourages development of novel materials, catalysts, and processes that can be scaled for industrial adoption.
- **Economic Viability:** Generates value-added products and green jobs, fostering sustainable industrial growth.
- **Policy Alignment:** Supports compliance with environmental regulations, green energy targets, and sustainable development goals (SDGs).

Sustainable chemistry approaches are not only scientifically necessary but also economically and socially imperative to tackle plastic pollution, mitigate climate change through CO₂ management, and enable a global transition toward clean, renewable, and resilient energy systems.

RENEWABLE ENERGY AND CLIMATE CHANGE

The global demand for energy and related services—essential for social and economic development as well as human welfare and health—is steadily rising. Energy is required to meet basic human needs such as lighting, cooking, heating or cooling, mobility, and communication, as well as to power industrial and productive activities.

Since around 1850, the widespread adoption of fossil fuels (coal, oil, and natural gas) has driven a rapid expansion of energy supply, but also led to significant increases in carbon dioxide (CO₂) emissions. The provision of energy services has been a major contributor to the historical rise in atmospheric greenhouse gas (GHG) concentrations. According to the IPCC Fourth Assessment Report (AR4), most of the observed global warming since the mid-20th century is very likely due to the increase in human-induced GHG emissions.

Fossil fuel consumption remains the dominant source of global anthropogenic GHG emissions, with CO₂ concentrations surpassing 390 ppm—39% above pre-industrial levels—by the end of 2010. Emissions continue to rise despite growing awareness of their environmental impact.

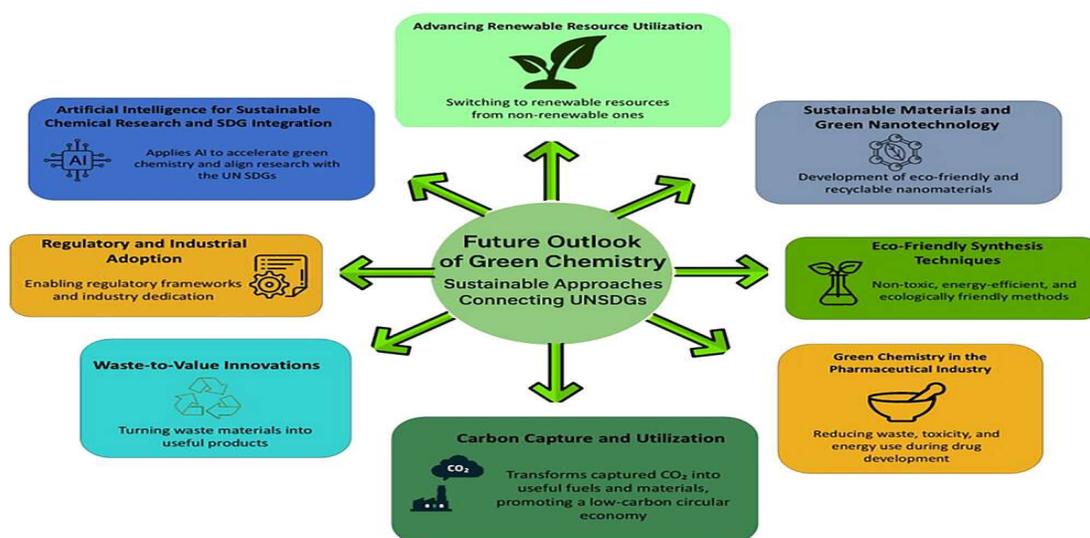
There are several strategies to reduce GHG emissions from the energy sector while continuing to meet global energy needs. These include energy conservation, improved efficiency, switching to lower-



carbon fossil fuels, renewable energy (RE), nuclear power, and carbon capture and storage (CCS). A balanced mitigation portfolio requires evaluating each option's emission reduction potential, contribution to sustainable development, and associated risks and costs.

This report focuses on the critical role that renewable energy technologies can play as part of such a mitigation strategy, highlighting their potential to lower GHG emissions while supporting long-term sustainability.

FUTURE PERSPECTIVE OF CHEMISTRY APPROACHES FOR TACKLING PLASTIC POLLUTION, CAPTURING CO₂, AND ADVANCING ENERGY STORAGE AND RENEWABLE ENERGY



The future of sustainable chemistry lies in creating a deeply integrated and adaptive system that simultaneously addresses environmental degradation, climate change, and energy security. Several key trends are expected to shape this trajectory:

Advanced Plastic Waste Valorization: Future innovations will move beyond conventional recycling toward molecular-level depolymerization, up cycling, and the development of smart, self-degradable polymers. Artificial intelligence and machine learning are expected to optimize sorting, processing, and conversion pathways, enabling a zero-plastic-waste economy.

Next-Generation CO₂ Capture and Conversion: Research will focus on low-energy, high-efficiency capture technologies such as electrochemical separation and biomimetic materials. CO₂ will increasingly



be seen as a feedstock for manufacturing synthetic fuels, carbon-based nanomaterials, and green chemicals, powered by renewable energy sources.

Breakthroughs in Energy Storage and Renewables: The coming decades will witness the large-scale deployment of solid-state batteries, hydrogen storage systems, and bio-inspired supercapacitors. Coupled with decentralized renewable energy generation, these systems will enable continuous, carbon-free power supply to industries, cities, and transportation networks.

System Integration and Circular Economy Models: Future systems will merge plastic waste recycling, CO₂ utilization, and renewable energy in fully circular industrial ecosystems. For example, renewable-powered CO₂ conversion could produce monomers for sustainable plastics, while recycling facilities generate materials for energy storage devices.

Policy, Collaboration, and Global Scaling: Success will depend on strong policy incentives, international cooperation, and cross-disciplinary research. By combining scientific innovation with regulatory frameworks and public engagement, sustainable chemistry will transition from niche applications to mainstream global adoption.

Overall, the future perspective envisions a resource-positive economy where waste streams are eliminated, CO₂ becomes a raw material, and renewable-powered energy systems replace fossil fuels—ensuring environmental resilience, economic competitiveness, and improved quality of life worldwide.

SIGNIFICANCE OF THE STUDY

This study holds significant relevance at the intersection of environmental protection, climate change mitigation, and sustainable technological innovation. By addressing plastic pollution, CO₂ capture and utilization, and energy storage for renewable integration within a unified sustainable chemistry framework, the research contributes to advancing global sustainability goals while offering tangible benefits for science, industry, and society.

Scientific Contribution: Expands the knowledge base on advanced chemical recycling and up cycling technologies for plastics, including catalyst development and reaction optimization.

It Provides insights into the synthesis and application of novel materials—such as MOFs, functionalized carbons, and green electrolytes—targeted at CO₂ capture, conversion, and sustainable energy storage.



Integrates three traditionally separate domains into a single conceptual framework, demonstrating cross-sectoral synergies that enhance resource efficiency.

Environmental Impact: It offers pathways to significantly reduce persistent plastic waste in terrestrial and marine ecosystems, mitigating micro-plastic contamination and biodiversity loss.

Contributes to lowering atmospheric CO₂ concentrations, thereby supporting climate change mitigation and global temperature stabilization targets. Promotes a circular economy model in which waste streams are reintegrated into production systems, minimizing raw material extraction and associated ecological damage.

Industrial and Economic Relevance: Provides scalable solutions for industries seeking sustainable alternatives to fossil-based feedstock's and non-recyclable materials. Enhances competitiveness by generating high-value products from waste streams, thereby creating new revenue opportunities. Supports the development of green jobs and the growth of clean technology sectors.

Policy and Societal Benefits: Aligns with international frameworks such as the Paris Agreement, Sustainable Development Goals (SDGs), and national renewable energy and waste management policies. Equips policymakers with scientifically validated strategies for integrated waste, carbon, and energy management. Raises public awareness on the interconnected nature of environmental challenges and the role of sustainable chemistry in addressing them.

CONCLUSION:

Sustainable chemistry offers a transformative pathway to address some of the most critical environmental and energy challenges of our time—plastic pollution, excessive CO₂ emissions, and the urgent need for efficient renewable energy storage. By integrating green chemistry principles with advanced materials science, biotechnology, and circular economy models, it is possible to design systems where waste becomes a valuable resource, CO₂ is repurposed into fuels and chemicals, and renewable energy supports a carbon-neutral economy.

Innovations in plastic waste valorization are enabling the shift from traditional disposal methods to high-value recycling and biodegradable polymer development. Next-generation CO₂ capture technologies are transitioning from high-energy industrial systems to low-energy, scalable, and economically viable solutions, while also providing feedstocks for sustainable products. Simultaneously,



breakthroughs in renewable energy storage are ensuring that intermittent energy sources like solar and wind can reliably power both industrial processes and communities.

The interconnected application of these sustainable chemistry approaches creates powerful synergies—recycling processes powered by renewables, CO₂-derived materials for advanced batteries, and industrial ecosystems designed for zero waste. This integrated strategy not only mitigates environmental harm but also opens economic opportunities, supports green innovation, and enhances global resilience against climate change.

In the coming decades, widespread adoption of these approaches—supported by policy frameworks, cross-sector collaboration, and public engagement—will be essential to achieving a sustainable, carbon-neutral, and resource-positive future. Sustainable chemistry is not merely a scientific discipline; it is a foundation for building a cleaner, healthier, and more equitable world.

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