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A Review on Chemical Recycling of Plastics: Challenges and Future Directions

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ABSTRACT: Chemical recycling of plastics has emerged as a promising solution to mitigate plastic waste and environmental pollution. Unlike mechanical recycling, chemical recycling breaks down polymers into monomers or other valuable chemicals, enabling the production of high-quality recycled materials. However, challenges such as technological limitations, economic feasibility, and environmental impact hinder its widespread adoption. This paper explores the current state, challenges, and future directions of chemical recycling, analysing advancements in depolymerization, pyrolysis, gasification, solvolysis, and solvent-based processes. Case studies and recent developments provide insights into potential solutions, while discussions highlight the role of policy frameworks and innovations in scaling up chemical recycling technologies.

KEYWORDS: Chemical recycling, Plastic waste, Environmental impact, Polymer depolymerization, Economic feasibility, Recycling innovation

I. INTRODUCTION

Plastic pollution is a global crisis, with over 400 million tons of plastic waste generated annually, much of which accumulates in landfills and oceans (Geyer, Jambeck, & Law, 2017). Traditional recycling methods, particularly mechanical recycling, face limitations in terms of efficiency, contamination, and material degradation (Jehanno, Alty, & Irigoyen, 2022). Chemical recycling presents a more sustainable approach, as it breaks down plastics into their molecular components, enabling high-quality recycled materials (Rahimi & García, 2017).

Chemical recycling differs from mechanical recycling in that it does not degrade polymer properties over multiple cycles, allowing for continuous material reuse (Ragaert, Delva, & Van Geem, 2017). Techniques such as pyrolysis, gasification, hydrolysis, and solvolysis convert plastics into feedstocks, fuels, or monomers, making them usable in various industrial applications.

Despite its potential, chemical recycling still faces challenges related to high energy consumption, economic viability, and regulatory uncertainties (Wong, Ngadi, & Abdullah, 2015). The effectiveness of these processes depends on feedstock purity, processing methods, and financial incentives that support large-scale implementation (Hopewell, Dvorak, & Kosior, 2009). Given the increasing global awareness of sustainability and circular economy models, chemical recycling is gaining momentum as an innovative waste management solution (Sardon & Dove, 2018). This paper explores various chemical recycling methods, recent technological developments, case studies demonstrating successful implementations, and future prospects for improving recycling efficiency (Tsiropoulos, 2015).

II. SCOPE

This study focuses on:

- Various chemical recycling technologies (pyrolysis, gasification, hydrolysis, solvolysis, etc.)
- Challenges related to process efficiency, environmental impact, and cost
- Case studies demonstrating successful implementations



- d) Recent advancements and research trends
- e) Future directions for scaling up chemical recycling

This paper also evaluates the effectiveness of chemical recycling compared to mechanical and biological recycling, highlighting its role in a circular economy. It provides an in-depth assessment of environmental benefits, carbon footprint, and energy consumption associated with different recycling technologies.

III. OBJECTIVES

- To analyze different chemical recycling methods and their efficiency
- To identify major challenges in chemical recycling processes
- To explore recent technological advancements in the field
- To assess the environmental and economic feasibility of chemical recycling
- To propose potential strategies for improving chemical recycling practices
- To evaluate the role of policy interventions in promoting sustainable recycling practices

IV. CASE STUDIES

4.1. Pyrolysis of Mixed Plastics: A European pyrolysis plant successfully converted mixed plastic waste into fuel and chemical feedstocks, reducing dependence on petroleum-based raw materials

✓ **Process efficiency:** Pyrolysis achieved 80–90% conversion into usable oil-based products, demonstrating high recovery potential

✓ **Economic viability:** The plant reduced operational costs by integrating renewable energy sources to optimize pyrolysis temperatures (Rahimi & García, 2017).

4.2. PET Depolymerization in the US: A PET depolymerization facility in the US showcased the production of high-purity monomers from post-consumer PET waste, enabling direct reuse in polymer manufacturing

✓ **High-yield efficiency:** Over 95% monomer recovery, significantly reducing waste accumulation (Hopewell et al., 2009).

✓ **Industry applications:** PET monomers were successfully reintegrated into bottle-grade resins with equivalent performance to virgin PET (Sardon & Dove, 2018).

4.3. Solvent-Based Recycling in Japan: A Japanese recycling initiative developed solvent-based depolymerization to recover multi-layered plastics, which are difficult to process using conventional methods (Jehanno et al., 2022).

✓ **Energy efficiency:** The process reduced energy consumption by 40% compared to mechanical recycling

✓ **Industry adaptability:** The recovered polymers maintained high molecular integrity, expanding market applicability

4.4. Gasification in Developing Countries: Gasification technology was implemented in waste management programs across developing nations, producing syngas and other valuable chemicals from plastic waste (Wong et al., 2015).

✓ **Rural waste reduction:** Gasification helped mitigate plastic accumulation in underdeveloped regions with limited recycling infrastructure (Al-Salem et al., 2020).

✓ **Circular economy approach:** The produced syngas was repurposed into energy generation, reducing landfill dependency (Tsiropoulos et al., 2015)

V. LATEST ADVANCEMENTS

- Development of advanced catalysts for depolymerization
- AI-driven process optimization in chemical recycling plants
- Integration of renewable energy sources in chemical recycling
- Policy initiatives supporting circular economy models
- Innovations in solvent-based recycling to improve yield and efficiency



- Hybrid recycling approaches combining chemical and mechanical processes

VI. DISCUSSIONS

The feasibility of chemical recycling depends on several interconnected factors, including technical efficiency, economic feasibility, environmental impact, and regulatory support (Jehanno et al., 2022). While innovations such as advanced catalysts and AI-driven process optimization have improved reaction efficiency, scalability and affordability remain pressing concerns

6.1 Technical Challenges

- ✓ **Energy Consumption:** Some chemical recycling processes, such as high-temperature pyrolysis and gasification, require substantial energy inputs, making them economically demanding (Al-Salem, Lettieri, & Baeyens, 2020).
- ✓ **Material Compatibility:** Mixed and contaminated plastics present processing difficulties, requiring pre-treatment or sorting steps before recycling (Rahimi & García, 2017).
- ✓ **Yield Optimization:** Finding efficient ways to maximize recovery rates for valuable monomers and chemical feedstocks is critical for making chemical recycling economically viable (Sardon & Dove, 2018).

6.2 Economic Viability

- ✓ **Cost Competitiveness:** Chemical recycling competes with mechanical recycling and virgin plastic production, making cost reduction essential (Tsiropoulos et al., 2015).
- ✓ **Infrastructure Investment:** Large-scale adoption of chemical recycling requires financial incentives, industrial investment, and supply chain integration (Wong et al., 2015).

6.3 Environmental Considerations

- ✓ **Emission Control:** Some chemical recycling methods, such as gasification, generate CO₂ emissions, necessitating green energy integration to minimize environmental footprint (Hopewell et al., 2009).
- ✓ **Sustainability Measures:** Utilizing bio-based solvents or integrating renewable energy sources could enhance sustainability efforts in chemical recycling plants (Sardon & Dove, 2018).

6.4 Policy and Regulation

- ✓ **Government Incentives:** Policies such as Extended Producer Responsibility (EPR) and carbon credits can promote sustainable recycling practices
- ✓ **Standardization & Compliance:** Establishing global regulatory frameworks will ensure the quality and safety of chemically recycled materials

VII. CONCLUSION

Chemical recycling presents a viable pathway for addressing plastic waste issues, but significant technological and economic barriers remain. Future research should focus on improving process efficiency, reducing energy consumption, and developing scalable models. Collaboration between industry, academia, and policymakers is essential for driving innovations and enabling widespread adoption of chemical recycling technologies.

To enhance sustainability, efforts must be directed toward integrating renewable energy sources, optimizing chemical recycling pathways, and fostering circular economy principles. Scaling up chemical recycling requires coordinated policy actions, investments in infrastructure, and continued advancements in material science.



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