Catalytic Routes for Plastic Waste Recycling: Current Advances and Remaining Challenge

Abdus Samreen
Department of Chemical Engineering, Vignan's Foundation for Science, Technology and Research (Deemed to be University), Vadlamudi, Guntur-522213, Andhra Pradesh, INDIA

***Abstract*— The rapid accumulation of plastic waste has driven the development of sustainable recycling strategies, with catalytic degradation emerging as an effective approach for plastic conversion. Catalytic processes enable the breakdown of complex polymeric materials into smaller, value-added hydrocarbons and fuels under controlled thermal or chemical conditions. Common plastics such as polyethylene and polypropylene can be efficiently converted using metal-based and solid acid catalysts, including zeolites, metal oxides, and supported transition metals. Recent advances in catalyst design, such as improved surface acidity, pore structure, and metal dispersion—have enhanced degradation efficiency and product selectivity. Reaction parameters including temperature, catalyst loading, and residence time play a critical role in governing conversion rates and product distribution. When integrated with existing chemical recycling technologies, catalytic degradation offers a scalable and economically viable pathway for plastic waste management. This review summarizes the degradation mechanisms, catalyst systems, operational parameters, and current challenges associated with catalytic plastic recycling, highlighting its potential role in advancing circular plastic economies.**

***Index Terms*— Catalytic Degradation; Plastic Waste Recycling; Heterogeneous Catalysts; Polymer Conversion; Circular Economy.**

I. INTRODUCTION

The widespread use of synthetic plastics has led to an unprecedented increase in plastic waste generation, creating severe environmental and ecological challenges. Conventional disposal methods such as landfilling and incineration are associated with long degradation times, secondary pollution, and greenhouse gas emissions, while mechanical recycling often suffers from material down-cycling and limited applicability to mixed or contaminated plastic streams. These limitations have accelerated interest in chemical recycling technologies, particularly catalytic degradation, as sustainable alternatives for plastic waste management [1-3].

Catalytic degradation involves the controlled cleavage of polymer chains into smaller molecules using solid or homogeneous catalysts under thermal or chemical conditions. Unlike non-catalytic thermal processes, catalytic systems enable lower operating temperatures, improved conversion efficiency, and enhanced selectivity toward valuable products such as liquid fuels, waxes, lubricants, and chemical feedstocks. Commonly used catalysts include zeolites, metal oxides, supported transition metals, and bifunctional catalysts, each offering distinct advantages in terms of acidity, pore structure, and active sites for polymer cracking [4].

Among various plastic types, polyolefins such as polyethylene and polypropylene dominate global plastic production and are particularly suitable for catalytic conversion due to their hydrocarbon-rich backbone. The catalytic degradation of these polymers proceeds through chain scission, β-scission, and hydrogen transfer reactions, producing a wide distribution of hydrocarbons ranging from light gases to liquid fuels. Catalyst properties, including surface acidity, metal dispersion, and textural characteristics, strongly influence reaction pathways and product distribution.

Recent research efforts have focused on catalyst optimization, reactor design, and process integration to enhance conversion efficiency and economic feasibility. Advances in hierarchical zeolites, metal-supported catalysts, and co-processing strategies have demonstrated improved performance and stability.

Despite these developments, challenges related to catalyst deactivation, product selectivity control, and scalability remain significant barriers to industrial implementation.

This review critically examines the mechanisms, catalyst systems, operational parameters, and current challenges associated with the catalytic degradation of plastic waste. By highlighting recent advances and identifying key research gaps, the review aims to provide insights into the role of catalytic degradation in advancing circular economy strategies and reducing reliance on virgin plastic production

II. MECHANISM OF CATALYTIC DEGRADATION OF PLASTIC WASTE

Catalytic degradation of plastic waste involves the transformation of long-chain polymer molecules into smaller hydrocarbons through a series of thermally activated, catalyst-assisted reactions. Unlike non-catalytic thermal cracking, catalytic processes lower activation energy and promote selective bond cleavage through interactions between polymer chains and active catalytic sites. The overall mechanism depends on polymer structure, catalyst acidity or metal functionality, and reaction conditions, but generally proceeds through adsorption, chain scission, and secondary transformation steps.

For polyolefin plastics such as polyethylene and polypropylene, degradation is primarily initiated by C–C bond cleavage along the polymer backbone. Upon heating, polymer chains soften or melt and diffuse toward the catalyst surface, where they adsorb onto acidic or metal active sites. On acidic catalysts such as zeolites and solid acids, protonation of the polymer chain leads to the formation of carbenium ions, which undergo β-scission reactions to generate shorter hydrocarbon fragments. These fragments may further undergo isomerization, oligomerization, and hydrogen transfer reactions, contributing to a broad product distribution [5].

In metal-supported catalysts, additional pathways such as hydrogenation–dehydrogenation cycles become significant. Metal sites facilitate the stabilization of reactive intermediates and suppress excessive coke formation by promoting hydrogen transfer reactions. This bifunctional mechanism—combining acidic cracking and metallic hydrogenation—enhances product selectivity toward saturated hydrocarbons and reduces solid residue formation.

Secondary reactions play a crucial role in determining final product composition. Light hydrocarbons formed during initial scission may undergo further cracking to gases, while heavier fragments can cyclize and aromatize, particularly on strong acid catalysts with constrained pore structures. Excessive aromatization and polycondensation can lead to coke deposition, which progressively blocks active sites and causes catalyst deactivation.

For plastics containing heteroatoms or functional groups, such as polyethylene terephthalate or polyvinyl chloride, degradation mechanisms additionally involve deoxygenation, dechlorination, and depolymerization reactions. These processes are influenced by catalyst composition and may generate corrosive or inhibitory byproducts, further emphasizing the need for tailored catalyst design [4,5].

Overall, the catalytic degradation mechanism is governed by complex interactions between polymer structure, catalyst properties, and operating conditions. A detailed understanding of these mechanistic pathways is essential for rational catalyst design, improved process control, and the development of efficient and selective plastic recycling technologies.

III. CURRENT RESEARCH

Recent research on catalytic degradation of plastic waste has focused on enhancing catalyst performance, improving process efficiency, and expanding product selectivity toward valuable hydrocarbons and chemical feedstocks. A significant area of progress involves the design and development of advanced heterogeneous catalysts. Zeolites, particularly hierarchical and mesoporous structures, have attracted considerable attention due to their tunable acidity, defined pore architecture, and strong cracking ability, which facilitate polymer chain scission and improved product distribution. Modifications such as nanoscale structuring, hierarchical porosity, and metal incorporation have further enhanced catalytic activity and resistance to coke deposition.

Metal oxides and mixed metal catalysts, including alumina-, silica-, and ceria-based systems, have been explored for their thermal stability and acid–base properties that influence polymer breakdown pathways. Supported transition metals (e.g., Ni, Pt, Ru) have shown promise in promoting hydrogen transfer reactions, reducing char formation, and steering product spectra toward light alkanes and alkenes. Bifunctional catalysts that combine acid sites with hydrogenation/dehydrogenation functionalities have been identified as effective systems for controlling reaction routes and minimizing undesirable byproducts [6].

Process intensification strategies, such as co-feeding hydrogen, use of reactive atmospheres, and coupling catalytic degradation with pyrolysis or gasification, have been investigated to enhance conversion rates and product selectivity. Integration of catalytic cracking units with continuous reactor designs—such as fluidized beds and circulating catalytic reactors—has been examined to improve heat transfer and catalyst–polymer contact, addressing scale-up challenges.

Advanced characterization techniques, including in situ spectroscopy and temperature-programmed analyses, have deepened understanding of reaction mechanisms and catalyst deactivation pathways. Kinetic modeling and computational studies have begun to elucidate polymer–catalyst interactions and guide rational catalyst design [7-8].

Despite progress, research continues to prioritize strategies that minimize energy input, extend catalyst lifetime, and enable processing of mixed and contaminated plastic feeds. Emerging work also emphasizes coupling catalytic degradation with post-reforming and upgrading stages to yield tailor-made fuels and chemical precursors, aligning plastic recycling with broader chemical manufacturing value chains.

IV. FUTURE PERSPECTIVES AND RESEARCH GAPS

Although significant advancements have been achieved in the catalytic degradation of plastic waste, several research gaps must be addressed to enable practical and large-scale implementation. Future studies should prioritize the development of robust and multifunctional catalysts capable of processing mixed and contaminated plastic streams while maintaining high activity and resistance to deactivation. Designing catalysts with controlled acidity, hierarchical porosity, and enhanced regeneration capability remains essential for improving selectivity toward targeted fuels and chemical feedstocks [9].

Greater emphasis is required on process integration and scalability, particularly through continuous reactor systems that ensure efficient heat transfer and catalyst–polymer interaction. Research on coupling catalytic degradation with downstream upgrading processes, such as hydroprocessing or reforming, could further enhance product quality and commercial value. Additionally, systematic investigations into catalyst lifetime, regeneration cycles, and long-term stability under industrially relevant conditions are still limited [10-12].

From a sustainability perspective, comprehensive techno-economic analyses and life-cycle assessments are necessary to evaluate the true environmental and economic benefits of catalytic degradation relative to conventional recycling and disposal routes. Future research should also explore the utilization of low-cost, waste-derived, or naturally occurring catalysts to reduce material and operational costs. Addressing these research gaps through interdisciplinary approaches and policy support will be crucial for establishing catalytic degradation as a key component of circular plastic economy frameworks [13].

V. CHALLENGES AND LIMITATIONS

Despite substantial progress, the catalytic degradation of plastic waste continues to face multifaceted challenges spanning technical, economic, environmental, and regulatory domains. Catalyst deactivation due to coke formation, sintering, and poisoning by additives and halogenated compounds remains a critical limitation, particularly when processing real-world mixed plastic waste. Feedstock heterogeneity, including multilayer plastics and composite materials, complicates reaction pathways and hinders consistent product quality. Controlling product selectivity toward high-value fuels or chemical feedstocks remains difficult, as degradation reactions are sensitive to catalyst properties and operating conditions. From an economic perspective, high energy demands, catalyst preparation costs, and regeneration requirements affect process viability at scale. Additionally, reactor design and scale-up challenges, such as efficient heat transfer, catalyst–polymer contact, and continuous operation, limit industrial deployment. Environmental concerns related to secondary emissions, catalyst disposal, and uncertain life-cycle impacts, combined with the lack of standardized regulations and market acceptance for chemically recycled products, further impede commercialization. Addressing these interconnected challenges through integrated catalyst design, process optimization, life-cycle assessment, and supportive policy frameworks is crucial for advancing catalytic degradation as a sustainable and circular solution for plastic waste management [14-15].

VI. CONCLUSION

Catalytic degradation has emerged as a promising chemical recycling strategy for addressing the growing challenge of plastic waste accumulation. By facilitating controlled polymer chain scission through tailored catalytic pathways, this approach enables the conversion of diverse plastic feedstocks into value-added fuels and chemical intermediates while operating under milder conditions than non-catalytic thermal processes. Advances in catalyst design, including the development of hierarchical zeolites, metal-supported systems, and bifunctional catalysts, have significantly improved conversion efficiency, product selectivity, and resistance to deactivation. A deeper understanding of degradation mechanisms has further supported rational catalyst optimization and process control.

Despite these advancements, several challenges related to feedstock heterogeneity, catalyst stability, energy demand, and scalability continue to hinder industrial deployment. Current research increasingly emphasizes process integration, continuous reactor operation, and comprehensive techno-economic and life-cycle assessments to bridge the gap between laboratory-scale studies and commercial implementation. Overall, catalytic degradation represents a viable pathway toward sustainable plastic waste management, and continued interdisciplinary efforts in catalyst engineering, process design, and policy support will be crucial for establishing its role within circular plastic economy frameworks.

REFERENCES

[1] Yansaneh, O. Y., & Zein, S. H. (2022). Latest advances in waste plastic pyrolytic catalysis. *Processes*, *10*(4), 683.

[2] Shi, Y., Diao, X., Ji, N., Ding, H., Ya, Z., Xu, D., ... & Zhang, S. (2024). Advances and challenges for catalytic recycling and upgrading of real-world mixed plastic waste. *ACS Catalysis*, *15*(2), 841-868.

[3] Kwon, T., Jeong, H., Kim, M., Jung, S., & Ro, I. (2024). Catalytic approaches to tackle mixed plastic waste challenges: a review. *Langmuir*, *40*(33), 17212-17238..

[4] Martín, A. J., Mondelli, C., Jaydev, S. D., & Pérez-Ramírez, J. (2021). Catalytic processing of plastic waste on the rise. *Chem*, *7*(6), 1487-1533.

[5] Mishra, R., Kumar, A., Singh, E., & Kumar, S. (2023). Recent research advancements in catalytic pyrolysis of plastic waste. *ACS Sustainable Chemistry & Engineering*, *11*(6), 2033-2049.

[6] Alrazen, H. A., Aminossadati, S. M., Mahmood, H. A., Hussein, A. K., Ahmad, K. A., Dol, S. S., ... & Fattah, I. M. R. (2025). A review of the pathways, limitations, and perspectives of plastic waste recycling. *Materials for Renewable and Sustainable Energy*, *14*(3), 50.

[7] Garcia, J. M. (2016). Catalyst: design challenges for the future of plastics recycling. *Chem*, *1*(6), 813-815.

[8] Wang, H., & Tsang, S. C. E. (2024). Recent advances in polyolefin plastic waste upcycling via mild heterogeneous catalysis route from catalyst development to process design. *Cell Reports Physical Science*, *5*(7).

[9] Lee, J. E., Lee, D., Lee, J., & Park, Y. K. (2025). Current methods for plastic waste recycling: Challenges and opportunities. *Chemosphere*, *370*, 143978..

[10] Kumagai, S., Nakatani, J., Saito, Y., Fukushima, Y., & Yoshioka, T. (2020). Latest trends and challenges in feedstock recycling of

polyolefinic plastics. *Journal of the Japan Petroleum Institute*, *63*(6), 345-364.

[11] Zhang, S., Li, M., Zuo, Z., & Niu, Z. (2023). Recent advances in plastic recycling and upgrading under mild conditions. *Green Chemistry*, *25*(18), 6949-6970.

[12] Milescu, R. A. (2025). The Role of Catalysts in Waste Polymer Upcycling: Recent Developments and Future Trends.

[13] Zhou, H., Wang, Y., Ren, Y., Li, Z., Kong, X., Shao, M., & Duan, H. (2022). Plastic waste valorization by leveraging multidisciplinary catalytic technologies. *ACS Catalysis*, *12*(15), 9307-9324.

[14] Zhang, L., Song, S., Zhang, H., & Wang, X. (2026). Advances of rare earth-based catalysts for recycling CO 2 and plastic waste. *Chemical Society Reviews*.

[15] Anwar, M., Konnova, M. E., & Dastgir, S. (2025). Circular plastic economy for sustainable development: current advances and future perspectives. *RSC Sustainability*.