
SUSTAINABLE SOLUTIONS: ASSESSING THE ENVIRONMENTAL IMPACT OF ADVANCED PLASTIC WASTE RECYCLING

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ABSTRACT

The global escalation of plastic waste has led to growing environmental and health concerns, prompting the need for more sustainable recycling strategies. This systematic literature review explores the development and effectiveness of plastic recycling technologies and their environmental impacts. Using the PRISMA method, 40 peer-reviewed studies from 2013 to 2023 were analyzed. Bibliometric analysis using VOSviewer revealed three major research clusters: technological innovations, sustainability and health impacts, and policy frameworks. The findings highlight that conventional mechanical recycling is limited by polymer degradation and contamination, while chemical and catalytic recycling offer promising alternatives for recovering high-quality outputs from mixed plastic waste. Advanced sorting technologies and supportive regulatory measures, such as Extended Producer Responsibility (EPR), further enhance recycling efficiency. The review concludes that integrating innovative recycling methods with environmental policy is critical for building a sustainable and circular plastic economy. Recommendations for future research include improving life cycle assessments, addressing economic feasibility, and enhancing public participation in plastic waste management.

Keywords: catalytic recycling; circular economy; chemical recycling; environmental impact; plastic waste

1. INTRODUCTION

The rapid proliferation of plastic products, driven by their low cost, versatility, and durability, has led to a global crisis of plastic waste accumulation that threatens environmental sustainability, public health, and natural ecosystems. Since the 1950s, global plastic production has escalated from approximately 2 million tonnes annually to over 400 million tonnes in recent years, with an estimated 8.3 billion tonnes produced cumulatively by 2015. Alarmingly, only around 9% of this waste has been effectively recycled, while the vast majority ends up in landfills, incinerators, or the natural environment (Shi et al., 2024; Kalauni et al., 2025). These conditions have created a pressing need for effective and sustainable waste management solutions, particularly in the realm of plastic recycling technologies.

The global scale and persistence of plastic pollution are driven by several interconnected factors: inadequate waste management infrastructure, insufficient technical capabilities for processing complex or hazardous plastic types, weak regulatory enforcement, and widespread reliance on single-use plastics. In many developing countries, the absence of efficient collection systems and treatment facilities exacerbates the leakage of plastic into terrestrial and marine ecosystems. Inadequately managed plastics fragment into microplastics that infiltrate food chains,

water sources, and even the atmosphere, posing risks to biodiversity and human health. The COVID-19 pandemic further intensified this crisis, increasing the consumption of disposable plastic products and overwhelming already strained waste management systems (Yelemessova et al., 2025).

Conventional disposal methods, such as landfilling and incineration, while historically prevalent, are increasingly viewed as unsustainable. Landfills not only occupy valuable land resources but also release harmful leachates that contaminate soil and groundwater. Meanwhile, incineration processes contribute to significant greenhouse gas emissions and the release of toxic byproducts, particularly when plastics containing brominated flame retardants or heavy metals are involved (Anuar et al., 2025). These environmental and public health consequences highlight the urgent necessity of transitioning toward more sustainable, circular approaches to plastic waste management.

Among the available solutions, recycling stands out as a cornerstone of sustainable waste management. However, the recycling landscape is marked by technological, economic, and environmental complexities. Mechanical recycling, the most established and widely used method, typically involves shredding, melting, and reprocessing plastics into new products. While effective for relatively pure plastic streams, mechanical recycling suffers from notable drawbacks, including the degradation of polymer quality over successive cycles, contamination issues, and limited applicability to mixed or multi-layered plastics (Kalauni et al., 2025; Jiang & Bateer, 2025). As a result, mechanical recycling often results in downcycling—where materials are converted into products of lower quality and limited use—undermining the potential for a truly circular plastic economy.

To address these limitations, research attention has shifted toward chemical recycling technologies, which aim to break down plastic polymers into their constituent monomers or valuable intermediates. Techniques such as pyrolysis, solvolysis, and catalytic depolymerization offer the potential to recover high-purity outputs from heterogeneous plastic waste streams. Catalytic approaches, in particular, have demonstrated promise in processing mixed and contaminated plastics under relatively mild conditions, producing valuable hydrocarbons or monomers suitable for reuse in manufacturing (Saxena, 2025; Kopperi et al., 2025). Pyrolysis, a thermochemical decomposition process conducted in the absence of oxygen, transforms plastic waste into fuels, gases, and waxes, effectively combining waste valorization with energy recovery (Sudalaimuthu et al., 2025). However, these technologies also face challenges—including high energy requirements, catalyst degradation, secondary pollution, and high capital investment—which hinder their large-scale deployment and long-term feasibility.

Assessing the environmental sustainability of recycling technologies requires robust analytical tools, such as life cycle assessment (LCA). LCAs provide a systematic framework for evaluating the environmental impacts of recycling processes from cradle to grave, including energy use, emissions, resource consumption, and waste generation. Recent studies suggest that optimized chemical recycling systems can reduce overall greenhouse gas emissions and energy consumption compared to incineration or landfilling, particularly when integrated with renewable energy sources and efficient feedstock pretreatment systems (Jiang & Bateer, 2025). Nonetheless, the effectiveness of recycling technologies depends not only on technical performance but also on policy alignment, market incentives, and public participation.

This complex intersection of technology, regulation, and behavior necessitates a multidisciplinary approach to plastic waste recycling. Integrated strategies that combine technical

innovations with policy instruments—such as extended producer responsibility (EPR), landfill taxes, or recycling subsidies—can create favorable conditions for scaling up advanced recycling methods (Pruess & Garrett, 2025). Moreover, public education campaigns, product eco-design, and industry commitments to recyclability and recycled content are essential for promoting closed-loop systems. Global efforts, such as the United Nations' Global Plastics Treaty and regional circular economy frameworks, further emphasize the growing momentum toward sustainable plastic management.

Despite growing interest and significant progress in plastic recycling, the current body of literature remains fragmented across disciplines, methodologies, and regional contexts. There is a need for a comprehensive, systematic synthesis of research to evaluate the state-of-the-art in plastic recycling technologies and to identify the most environmentally and economically viable solutions. To date, no single review has adequately integrated the comparative environmental impacts of different recycling technologies, particularly in relation to their technological maturity, scalability, and compatibility with existing waste streams.

2. RESEARCH METHOD

This study employed a systematic literature review (SLR) method to identify, analyze, and synthesize peer-reviewed articles concerning plastic waste recycling technologies and their environmental impacts. To ensure rigor, transparency, and reproducibility, the review process was conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines and included both qualitative synthesis and quantitative bibliometric analysis using VOSviewer.

2.1. Search Strategy

A structured and comprehensive search strategy was implemented across four major databases—Scopus, Web of Science, ScienceDirect, and Google Scholar—due to their extensive indexing of high-quality journals in environmental science, engineering, and waste management. The search targeted studies published between 2013 and 2023 to capture the most recent developments in plastic recycling technologies. The search terms employed Boolean operators and relevant keywords such as:

("plastic waste" OR "plastic recycling") AND ("recycling technology" OR "mechanical recycling" OR "chemical recycling" OR "pyrolysis" OR "catalytic depolymerization") AND ("environmental impact" OR "life cycle assessment" OR "LCA").

Only English-language articles were included. Reference management and duplicate screening were conducted using Mendeley.

2.2. Inclusion and Exclusion Criteria

To ensure relevance and quality, the following inclusion and exclusion criteria were applied:

Table 1 Example of table description

Criteria	Inclusion	Exclusion
Publication Year	2013–2023	Before 2013
Language	English	Non-English
Article Type	Peer-reviewed journal articles, conference proceedings	Reviews, editorials, theses, grey literature
Focus Area	Plastic recycling technologies and environmental impact	Non-plastic materials, general waste management
Methodological Content	Empirical data, LCA, environmental impact assessment	Theoretical frameworks without technological analysis

After screening, a total of **45 articles** met the inclusion criteria and were selected for in-depth review and analysis.

2.3. The PRISMA

From an initial pool of 60 identified records, a structured and transparent screening process led to the final inclusion of 40 high-quality studies. This indicates a rigorous review strategy, with clear filtering at multiple stages—particularly to ensure that only studies addressing **plastic waste, recycling technologies**, and their **environmental impacts** were included. The process aligns with PRISMA best practices and ensures that the resulting synthesis is based on relevant, reliable, and focused evidence.

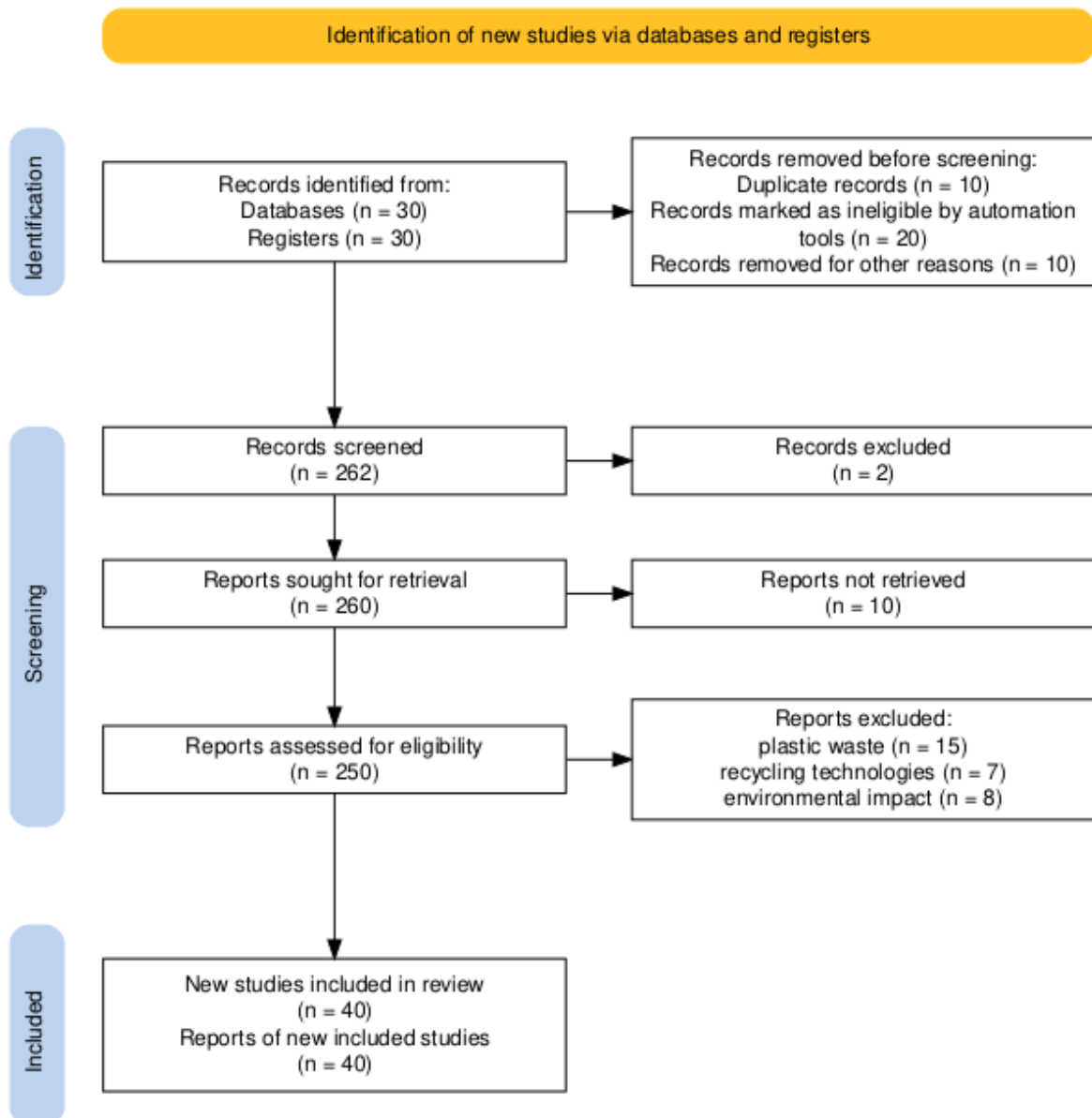


Figure 1. PRISMA Flow Diagram of Study Selection Process

Source: Authors' own work

2.4. Data Extraction and Synthesis

Data were extracted using a standardized extraction sheet developed in Microsoft Excel. The following variables were collected for each article:

- Author(s) and publication year
- Title and journal
- Geographic scope
- Type of plastic waste analyzed

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Figure 2 (Network Visualization) displays the relationships between terms, where each node represents a keyword and connecting lines show co-occurrence strength. This visualization suggests an integrated research network, where clusters of interest span from "chemical recycling" and "PET hydrolysis" to "human health" and "microplastic."

The network visualization illustrates the keyword co-occurrence map generated through VOSviewer, where each node represents a keyword and the connecting lines indicate the frequency and strength of co-occurrence between terms. Larger nodes such as “study,” “recycling technology,” “sustainability,” and “human health” reflect higher frequency and centrality, signifying their prominence within the literature. The dense interconnections between keywords demonstrate a tightly interlinked body of research, where environmental concerns (e.g., “plastic pollution,” “microplastic,” “single-use plastic”), technological developments (e.g., “chemical recycling technology,” “hydrolysis,” “gasification”), and policy aspects (e.g., “extended producer responsibility,” “EPR”) form interconnected thematic clusters. This structure indicates that scholarly work in this field increasingly adopts a multidisciplinary approach, combining scientific innovation, environmental sustainability, and regulatory frameworks to address the complex issue of plastic waste management. The presence of bridging terms such as “issue,” “role,” and “methodology” suggests active integration between technical analysis and broader sustainability considerations in recent studies.

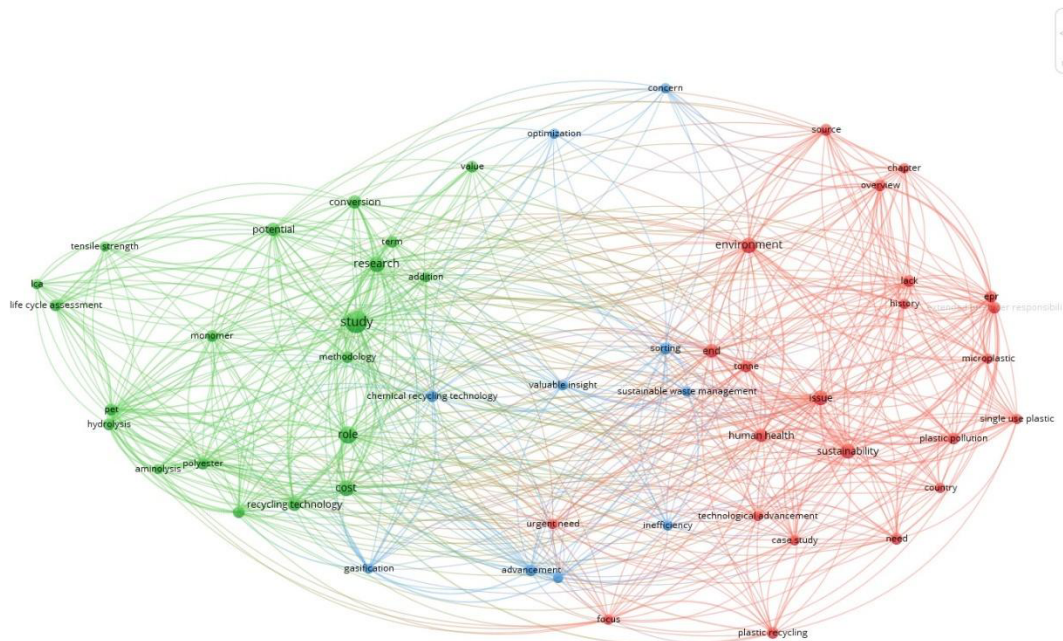


Figure 4. Cluster Visualization

Figure 4 (Cluster Visualization) groups keywords into colored clusters representing distinct thematic concentrations. The **green cluster** focuses on technological and scientific elements like

"PET," "hydrolysis," and "circular economy." The **red cluster** covers environmental and societal aspects such as "plastic pollution," "EPR," and "human health," while the **blue cluster** bridges gaps with concepts like "advancement," "concern," and "optimization." This reinforces that studies in this domain are multidisciplinary, intersecting environmental science, technology, and policy.

The cluster visualization map generated using VOSviewer categorizes keywords into distinct thematic groups, represented by different colors, to reveal major research domains within the literature. The **green cluster** on the left centers on technological and material aspects of plastic recycling, including terms such as "recycling technology," "hydrolysis," "PET," "polyester," and "life cycle assessment." This cluster highlights the engineering and scientific focus on polymer breakdown and mechanical or chemical treatment processes. The **red cluster**, predominantly on the right, emphasizes environmental and social concerns, with keywords like "plastic pollution," "microplastic," "sustainability," "EPR (Extended Producer Responsibility)," and "human health." These reflect the growing discourse on the broader ecological and policy-related implications of plastic waste. The **blue cluster**, situated at the top and lower center, bridges the technical and societal domains with keywords like "optimization," "advancement," "technological advancement," and "concern," suggesting a conceptual intersection where innovation meets policy and sustainability needs. This visualization demonstrates that the field of plastic recycling is inherently interdisciplinary, combining technical innovation with environmental protection and policy initiatives aimed at achieving a sustainable circular economy.

2.2. Environmental and Technological Context

Plastic production has surged dramatically—from 2 million tonnes in 1950 to 8.3 billion tonnes by 2015—resulting in approximately 6.3 billion tonnes of waste. Most of this waste is mismanaged, leading to environmental degradation and human health concerns (Shi et al., 2024; Kalauni et al., 2025). The predominant disposal methods—landfilling and incineration—have proven environmentally detrimental, causing soil, water, and air pollution, especially in underdeveloped waste infrastructure regions (Nafiu et al., 2025).

Landfills leach hazardous chemicals into groundwater, while incineration emits greenhouse gases and toxic byproducts. These unsustainable practices underline the need for advanced recycling technologies that offer both environmental and economic benefits.

2.3. Challenges in Mechanical Recycling

Traditional mechanical recycling, though widely implemented, is plagued with limitations. Studies show a progressive degradation of polymer quality with each recycling cycle due to thermal breakdown and impurity buildup (Perli et al., 2025; Jiang & Bateer, 2025). This not only limits the utility of recycled products but also undermines the concept of a circular economy by resulting in lower-value end products—a process known as downcycling.

Such technological constraints drive the demand for more efficient and versatile recycling strategies that can process heterogeneous waste streams without compromising material integrity.

2.4. Emergence of Chemical and Catalytic Recycling

In response, chemical recycling—particularly catalytic depolymerization—has emerged as a breakthrough solution. By breaking plastics into monomers or usable energy sources, it offers a pathway to produce high-quality materials from mixed plastic waste (Perli et al., 2025). Techniques like **hydrolysis**, **aminolysis**, and **gasification** demonstrate promise in tackling waste that is not recyclable through mechanical means.

Moreover, machine learning-enabled sorting systems and advanced spectroscopy aid in the accurate separation of polymers, optimizing the input for chemical recycling (Jasiński et al., 2025).

2.5. Integrative Approaches and Policy Support

The integration of chemical recycling with advanced sorting systems significantly enhances the recyclability and quality of output. This strategy addresses two major industry concerns: material degradation and processing mixed waste streams. It also opens avenues for high-value resource recovery, helping bridge economic gaps in recycling viability (Shi et al., 2024).

Furthermore, policy instruments like **Extended Producer Responsibility (EPR)** and public engagement campaigns are critical to ensure widespread adoption and investment in these technologies (Kalauni et al., 2025; Nafiu et al., 2025).

2.6. Implications for Sustainability and Human Health

Microplastics and persistent toxins from mismanaged plastics infiltrate food and water systems, threatening aquatic life and public health (Sahu & Varma, 2025). Single-use plastics, often non-recyclable, exacerbate this issue, especially post-COVID-19 when usage surged globally.

Hence, the combination of **advanced chemical recycling**, **sustainable design**, and **regulatory alignment** is essential. Such a system not only enhances recycling performance but also safeguards human and ecological health, supporting the transition to a circular economy.

2.7. Summary of Key Findings

- Mechanical recycling is inadequate for mixed or degraded plastics.
- Chemical recycling, particularly catalytic depolymerization, shows promise for sustainable material recovery.
- Bibliometric analysis reveals strong thematic connections between environmental impact, technological innovation, and public policy.
- Integrated recycling strategies and regulatory frameworks are essential to address the multifaceted risks posed by plastic waste.

4. CONCLUSION

The global plastic waste crisis, driven by rapid industrialization and increasing reliance on single-use plastics, has led to urgent calls for sustainable waste management solutions. This systematic literature review examined the state-of-the-art plastic recycling technologies and assessed their environmental implications through bibliometric analysis and thematic synthesis. The results

highlight that while mechanical recycling remains prevalent, it suffers from significant limitations in processing mixed or degraded plastic waste, leading to downcycling and reduced material utility.

In contrast, chemical recycling—particularly catalytic depolymerization and hydrolysis—emerges as a promising alternative capable of recovering high-value outputs from heterogeneous plastic streams. These methods, when coupled with advanced sorting technologies, offer improved material recovery efficiency and reduced environmental impact. The bibliometric analysis using VOSviewer revealed three dominant research clusters: technological innovation, environmental and human health concerns, and regulatory frameworks—demonstrating the multidisciplinary nature of this field.

To achieve long-term sustainability, the integration of advanced recycling technologies must be supported by effective policy instruments such as Extended Producer Responsibility (EPR), as well as public awareness and participation. Furthermore, addressing the challenges of high energy demands, scalability, and economic feasibility remains critical for the broader implementation of chemical recycling processes.

Future research should focus on optimizing these emerging technologies through life cycle assessments, developing circular design principles, and creating cross-sector collaborations. By combining scientific innovation with regulatory and societal engagement, a comprehensive and circular approach to plastic waste management can be realized—one that reduces pollution, preserves resources, and promotes environmental justice on a global scale.

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