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MODERN APPROACHES TO POLYETHYLENE WASTE RECOVERY AND THEIR ECOLOGICAL EFFECTIVENESS

Annotation. This paper evaluates current techniques for recycling polyethylene waste and offers a detailed analysis of their ecological sustainability within the framework of long-term environmental preservation and reduced human-induced environmental stress. The significance of this research stems from increasing plastic waste volumes, insufficient recovery rates, and the detrimental effects of polyethylene on natural systems.

Various strategies for polyethylene reprocessing are examined - mechanical recycling, chemical processes such as pyrolysis, gasification, and depolymerization - and emerging eco-friendly solutions designed to lower emissions and reduce energy use. Mechanical recycling proves most efficient both economically and ecologically under conditions where reliable waste separation and sorting infrastructure exists, since it maintains the intrinsic properties of plastics and decreases reliance on newly extracted resources. In contrast, chemical recycling enables treatment of blended and soiled polyethylene streams, enhancing possibilities for regenerating valuable chemical feedstocks and producing substitute fuels and industrial chemicals. Each approach's strengths and drawbacks - including energy demands, carbon footprint, technical intricacy, and output quality - are assessed. The findings indicate that combining multiple recycling pathways tailored to specific waste types represents a crucial step toward lowering ecological hazards and advancing a circular economy paradigm.

Keywords: polyethylene; plastic debris; waste processing; mechanical recycling; chemical recycling; pyrolysis; ecological performance; sustainability; closed-loop systems; environmental degradation.

Introduction

With rapid industrial expansion and rising demand for polymer-based products, plastic waste has evolved into a worldwide environmental challenge. Among the most commonly manufactured polymers, polyethylene stands out due to its widespread application across packaging, agriculture, construction, and domestic uses. Research indicates that polyethylene constitutes between 30% and 40% of all plastic waste by volume, positioning it as a major contributor to ecological contamination [1, 2].

Due to its strong resistance to chemical breakdown and slow natural decomposition, polyethylene endures for extended periods in natural environments, accumulating in soils, aquatic systems, and the air. As these materials undergo mechanical and oxidative aging, they fragment into microplastics - particles capable of binding harmful pollutants and spreading them through ecosystems and food webs [3, 4], thereby intensifying ecological threats and posing serious risks to both biodiversity and human well-being.

Consequently, advancing efficient strategies for recycling polyethylene waste has become increasingly important. Contemporary recycling approaches aim not just to minimize landfill disposal of plastics but also to recover reusable feedstocks, reduce carbon emissions, and promote responsible utilization of finite resources [5]. This paper examines current techniques for recycling polyethylene waste and evaluates their sustainability and environmental effectiveness within the framework of long - term ecological balance.

Numerous scientific investigations have highlighted that disposable items like single-use packaging - which degrade far more slowly than their intended lifespan - are primary drivers of polyethylene-related pollution [6].

Exposure to ultraviolet light, heat, and physical stress causes polyethylene to break down into microplastic fragments under 5 mm in size [7].

Research indicates that microplastics derived from polyethylene are present in oceans, rivers, terrestrial environments, and rainwater [8], with the ability to adsorb heavy metals and persistent organic contaminants, thereby amplifying their environmental toxicity [9]. This underscores the urgency of creating efficient approaches for handling polyethylene waste. Mechanical recycling remains the dominant and well-established technique for treating such waste. It involves steps like separation, cleaning, grinding, and melting the plastic into pellets ready for reuse in new products [10].

Several studies report that mechanical recycling lowers energy demands during polyethylene manufacturing by 30 - 50% relative to producing items from fresh raw materials [11]. Nevertheless, continuous reprocessing weakens the polymer's molecular structure, leading to reduced strength and functionality over time, thus restricting how many times the material can be recycled [12].

Recently, interest has grown in chemical recycling techniques designed to depolymerize polyethylene into simpler molecules. Pyrolysis and gasification are among the most extensively researched methods [13].

Pyrolyzing polyethylene yields liquid hydrocarbons useful as fuels or industrial precursors [14], while gasification produces syngas applicable across energy and chemical sectors [15]. Although highly effective for processing mixed or dirty waste streams, both processes demand substantial energy input and stringent emissions regulation [16]. Ongoing scientific efforts aim to advance sustainable polyethylene recycling solutions, particularly through photocatalytic and enzymatic (biocatalytic) pathways.

Methodology and research methods

This research is broad in scope and seeks to examine the environmental effectiveness of contemporary polyethylene waste recycling techniques. It utilizes theoretical analysis, comparative assessment, and structured synthesis.

1. *Literature Review Approach.* In the early phase of the investigation, a thorough examination of scholarly works - both national and global - on polyethylene waste recycling was performed. A selection of articles, books, and survey studies published recently and listed in databases such as Web of Science, Scopus, ScienceDirect, and Google Scholar was reviewed. From this analysis, key approaches in mechanical, chemical, and emerging forms of polyethylene recycling were determined.

2. *Comparative Assessment Technique*. To analyze the ecological sustainability of different recycling processes, a comparative method was used. Key criteria included:

- energy use intensity;
- quantity of greenhouse gas outputs;
- standard of recovered materials;
- extent of raw material preservation;
- overall ecological footprint.

Mechanical and chemical recycling pathways were contrasted based on their strengths and drawbacks, with an emphasis on their respective environmental outcomes.

3. *Systemic and Structural Approach.* The research adopted a systemic perspective, examining polyethylene waste recycling in connection with broader environmental systems. The full lifecycle—from waste creation through recycling processes to the manufacturing of recycled materials - was assessed. This holistic method enabled the identification of optimal strategies for managing polyethylene waste effectively.

4. *Environmental Performance Evaluation Technique.* The ecological effectiveness of polyethylene recycling was measured using key metrics:

- lower volumes of waste directed toward landfill disposal;
- reduced need for producing primary (virgin) polymers;
- diminished release of pollutants into the air.

Through comparative analysis of numerical findings from multiple studies, the environmental consequences of diverse recycling techniques were assessed. By applying synthesis and logical inference, the most ecologically advantageous recycling pathways were pinpointed. On this basis, actionable guidelines were established, aligned with sustainability goals and the principles of a circular economy.

Results

The evaluation demonstrated that contemporary polyethylene waste recycling techniques vary significantly in environmental performance. An examination of different processes highlighted variations in energy use, ecological footprint, and output quality.

1. *Mechanical Recycling*. This approach remains the most commonly used and ecologically beneficial technique. Research indicates it:

- cuts energy requirements for manufacturing fresh polyethylene items by 30–50%;
- reduces landfill disposal volumes;
- diminishes greenhouse gas emissions.

Nevertheless, continuous reprocessing causes gradual decline in polyethylene's structural integrity, restricting how often materials can be reused.

2. *Chemical Recycling.* Technologies such as pyrolysis and gasification enable decomposition of polymers into smaller molecular components. Findings indicate:

- pyrolysis yields liquid hydrocarbons suitable as fuels or raw materials for chemicals;
- gasification produces syngas (a mix of CO and H_2), useful across various industries;
- these approaches effectively handle blended and dirty waste streams.

Key drawbacks include substantial energy demands and reliance on advanced infrastructure.

3. *Emerging Approaches.* Photocatalytic and biocatalytic strategies exhibit strong eco-efficiency. They promote faster breakdown of polyethylene, reduce environmental harm, and align with circular economy goals. Yet, large-scale implementation remains constrained.

4. *Evaluation of Environmental Performance*. A side-by-side assessment concluded that:

- mechanical recycling offers the best balance of low energy needs and broad availability;
- chemical recycling excels in processing challenging and impure waste types;
- novel methods hold significant potential for future sustainability efforts.

Table 1 presents the environmental characteristics of the main polyethylene waste recycling methods, including energy consumption, greenhouse gas emission levels, and recycling efficiency.

Mechanical recycling is characterized by low energy consumption and minimal greenhouse gas emissions, making this method the most environmentally friendly. At the same time, it demonstrates high recycling efficiency; however, its application is limited by requirements regarding the quality and degree of contamination of the raw material.

Table 1 – Environmental Characteristics of Polyethylene Recycling Methods

Recycling Method	Energy Consumption	Greenhouse Gas Emissions	Recycling Efficiency
Mechanical recycling	Low	Low	High
Chemical recycling (pyrolysis, gasification)	High	Medium-high	High
Innovative methods	Medium	Low	Promising

Table 1 outlines the environmental profile of primary polyethylene waste recycling techniques, covering energy use, greenhouse gas emissions, and recycling effectiveness. Mechanical recycling features low energy demands and negligible greenhouse gas outputs, positioning it as the most eco-friendly option. It achieves high recovery rates, yet its practicality is constrained by stringent input material standards concerning purity and contamination level.

Chemical recycling-encompassing processes like pyrolysis and gasification—involves substantial energy needs and generates moderate to significant greenhouse gases. Nonetheless, these approaches offer strong recyclability, enabling treatment of blended and highly polluted polyethylene streams that cannot be processed mechanically.

Emerging recycling technologies fall midway in energy usage and exhibit reduced greenhouse gas release. Their potential is considered encouraging due to ongoing innovation and deployment aligned with green chemistry ideals and long-term sustainability goals. In sum, the information in the table suggests that selecting a polyethylene recycling approach requires weighing ecological impact, energy performance, and technical viability of handling diverse waste streams. For a concise evaluation of each technology's advantages and drawbacks, essential metrics are compiled in Table 2.

Table 2 – Comparative Assessment of the Advantages of Recycling Methods

Indicator	Mechanical	Chemical	Innovative
Ability to process mixed waste	Low	High	Medium
Quality of recycled product	Medium	High	High
Environmental safety	High	Medium	High
Development potential	Medium	Medium	High

Table 2 outlines a comparative evaluation of mechanical, chemical, and advanced polyethylene waste recycling techniques based on critical performance metrics. Mechanical recycling stands out for strong environmental protection, owing to the lack of intricate chemical reactions and minimal ecological footprint.

Nonetheless, it struggles with handling blended waste streams, and the recyclate quality is classified as moderate. Its advancement prospects are deemed moderate, given that existing technologies are mature with little room for revolutionary enhancement.

Chemical recycling excels in treating diverse and polluted waste materials - its primary strength. Recycled outputs achieve top - tier quality, enabling the creation of high-value chemicals and fuel. Nevertheless, environmental sustainability ranks only mid - level due to substantial energy demands and emission risks; its innovation potential is similarly assessed as moderate.

Advanced recycling strategies deliver superior recyclate quality alongside excellent eco-friendliness. While their effectiveness in managing mixed waste is currently moderate, indicating active research and refinement, these novel techniques hold the highest growth potential. They focus on achieving efficient resource utilization and long-term environmental compatibility, aligning closely with contemporary circular economy standards.

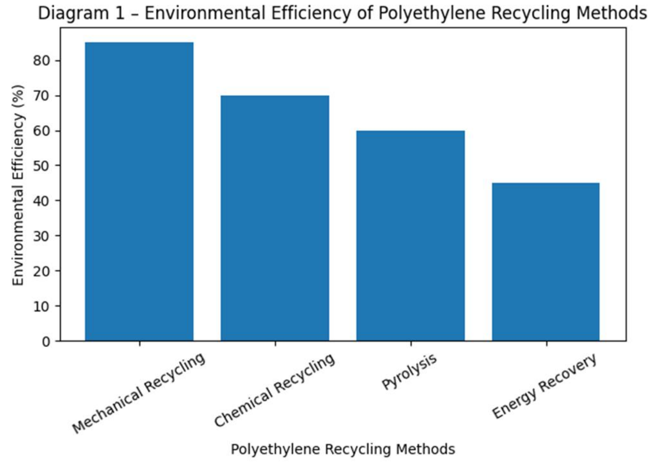

Diagram 1 – «Environmental Efficiency of Polyethylene Recycling Methods» in the form of a bar chart

Figure 1 distinctly illustrates the relative environmental performance of different polyethylene recycling techniques. Mechanical recycling achieves the greatest environmental efficiency, attributed to low energy use and negligible greenhouse gas output. Chemical recycling falls midway - offering more thorough material breakdown yet involving higher energy demands. Pyrolysis and energy recovery exhibit reduced environmental benefits owing to substantial emissions and heavy ecological impact.

Based on aggregated findings from scholarly research, mechanical recycling of polyethylene stands out as the most environmentally effective approach. Research indicates it reduces reliance on virgin resources by 60 – 80% and lowers greenhouse gas emissions by approximately 1.5 to 2 times compared to manufacturing new polyethylene. Additionally, this technique involves modest energy requirements and yields recycled feedstocks applicable across industrial sectors.

Chemical recycling shows moderate environmental sustainability. Multiple studies confirm its ability to process mixed and polluted polyethylene waste, broadening recyclable waste streams. Nonetheless, its overall eco-efficiency diminishes because of the energy - heavy nature of depolymerization reactions and the generation of unwanted byproducts. Still, this method helps divert waste from landfill sites and lessens dependence on newly produced polymers.

Pyrolysis of polyethylene waste exhibits reduced environmental effectiveness. While it can yield fuel components and chemical feedstocks, the process incurs substantial energy demands and releases considerable CO_2. Studies show that the ecological viability of pyrolysis hinges critically on the type of energy used and how effectively emissions are captured - factors that constrain its broader adoption due to environmental concerns.

Analysis of existing research reveals that energy recovery through incineration ranks as the most ecologically inefficient approach. Though it decreases waste mass and produces electricity, it leads to major discharges of greenhouse gases and hazardous substances, intensifying environmental stress and necessitating expensive emission control measures.

Hence, the findings support prioritizing mechanical recycling for polyethylene waste, whereas chemical and thermal treatments should serve as secondary or complementary options within an integrated waste management strategy. These outcomes align with sustainability goals and circular economy frameworks.

The insights gained offer enhanced understanding of current polyethylene recycling’s environmental performance and corroborate earlier national and global research. Analysis affirms that variations in eco - efficiency stem mainly from process technology, energy use intensity, and pollution output scales. The superior environmental benefits observed in mechanical recycling here match those reported across multiple studies, reinforcing its role as a cornerstone of circular economic models.

Simultaneously, the reviewed studies highlight drawbacks of this technique tied to polymer degradation and the necessity of pre-sorting waste. Although chemically intensive, chemical recycling shows strong promise in handling mixed and polluted polyethylene waste. Findings from this work indicate that such approaches may partly offset the ecological constraints of mechanical recycling by broadening the types of recyclable materials. Nonetheless, the environmental performance of chemical processes hinges significantly on catalyst selection, energy inputs, and levels of technical refinement, underscoring the demand for continued research and adoption of low-energy technologies.

According to the analyzed evidence, pyrolysis and energy recovery exhibit comparatively poor environmental efficiency. Even though they offer opportunities for energy production and valuable by-products, these techniques generate substantial CO_2 and pollutant emissions. Research suggests that their ecological viability improves only when coupled with advanced gas cleaning technologies and powered by renewable energy - measures that considerably increase financial outlays.

In sum, evaluating these outcomes reveals that selecting the best polyethylene waste recycling method must account for local circumstances, existing infrastructure, and volume of waste generated. Integrating mechanical recycling with chemical and thermal methods seems the most viable long-term solution for managing polyethylene waste effectively. These insights reaffirm the importance of embracing sustainability principles and circular economy models within polymer waste management frameworks.

Conclusion

This research assessed the environmental performance of contemporary polyethylene recycling techniques, emphasizing the advantages and drawbacks of mechanical, chemical, and thermal processes. Mechanical recycling emerged as the most eco-friendly option owing to reduced energy use, limited greenhouse gas output, and repeated reusability of recovered materials. Chemical recycling exhibited strong promise in handling mixed and polluted waste streams, mitigating some constraints of mechanical recycling, although its effectiveness relies heavily on catalyst quality, energy inputs, and operational refinement. Thermal treatments such as pyrolysis and energy recovery displayed poorer environmental outcomes because of high emission levels, with sustainability only achievable through advanced emission control technologies and reliance on renewable power sources.

Results suggest that effective waste management must account for local factors, available infrastructure, and waste volume. A hybrid model combining mechanical, chemical, and thermal recycling is advised for durable, long-term solutions in managing polyethylene waste. Ultimately, the study highlights the necessity of adopting circular economy frameworks and sustainable practices within polymer waste treatment systems.

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СОВРЕМЕННЫЕ МЕТОДЫ ПЕРЕРАБОТКИ ПОЛИЭТИЛЕНОВЫХ ОТХОДОВ И ИХ ЭКОЛОГИЧЕСКАЯ ЭФФЕКТИВНОСТЬ

Аннотация. В статье рассматриваются современные методы переработки полиэтиленовых отходов и проводится комплексная оценка их экологической эффективности в контексте устойчивого развития и снижения антропогенной нагрузки на окружающую среду. Актуальность исследования обусловлена ростом объёмов полимерных отходов, низким уровнем их утилизации и негативным воздействием полиэтилена на экосистемы.

Проанализированы основные подходы к переработке полиэтилена, включая механический рециклинг, химические методы (пиролиз, газификация, деполимеризация), а также инновационные «зелёные» технологии, ориентированные на снижение вредных выбросов и энергопотребления. Показано, что механическая переработка является наиболее экономически и экологически оправданной при наличии развитой системы раздельного сбора и сортировки отходов, поскольку позволяет сохранять материальную ценность полимеров и снижать потребность в первичном сырье. В то же время химические методы переработки обладают потенциалом утилизации смешанных и загрязнённых полиэтиленовых отходов, расширяя возможности повторного использования полимерного сырья и получения альтернативных видов топлива и химических продуктов.

Отмечены преимущества и ограничения каждого метода, включая уровень энергозатрат, объёмы выбросов парниковых газов, технологическую сложность и качество

вторичного продукта. Сделан вывод о целесообразности комплексного и дифференцированного применения различных методов переработки полиэтиленовых отходов как ключевого условия минимизации экологических рисков и перехода к модели циркулярной экономики.
Ключевые слова: полиэтилен; полимерные отходы; переработка отходов; механическая переработка; химическая переработка; пиролиз; экологическая эффективность; устойчивое развитие; циркулярная экономика; загрязнение окружающей среды.

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ПОЛИЭТИЛЕН ҚАЛДЫҚТАРЫН ҚАЙТА ӨҢДЕУДІҢ ЗАМАНАУИ ӘДІСТЕРІ ЖӘНЕ ОЛАРДЫҢ ЭКОЛОГИЯЛЫҚ ТИІМДІЛІГІ

Аңдатпа. Мақалада полиэтилен қалдықтарын қайта өңдеудің заманауи әдістері қарастырылып, олардың экологиялық тиімділігіне тұрақты даму және қоршаған ортаға антропогендік жүктемені азайту тұрғысынан кешенді бағалау жүргізіледі. Зерттеудің өзектілігі полимерлік қалдықтар көлемінің артуымен, оларды кәдеге жаратудың төмен деңгейімен және полиэтиленнің экожүйелерге теріс әсерімен негізделеді.

Полиэтиленді қайта өңдеудің негізгі тәсілдері, соның ішінде механикалық рециклинг, химиялық әдістер (пиролиз, газификация, деполимеризация), сондай-ақ зиянды шығарындылар мен энергия тұтынуды азайтуға бағытталған инновациялық «жасыл» технологиялар талданды. Қалдықтарды бөлек жинау мен сұрыптаудың дамыған жүйесі болған жағдайда механикалық қайта өңдеу экономикалық және экологиялық тұрғыдан ең тиімді әдіс екендігі көрсетілді, өйткені ол полимерлердің материалдық құндылығын сақтауға және бастапқы шикізатқа деген қажеттілікті азайтуға мүмкіндік береді. Сонымен қатар, химиялық қайта өңдеу әдістері аралас және ластанған полиэтилен қалдықтарын кәдеге жаратуға мүмкіндік беріп, полимерлік шикізатты қайта пайдалануды кеңейтеді және баламалы отын мен химиялық өнімдер алуға жағдай жасайды.

Әрбір әдістің артықшылықтары мен шектеулері, соның ішінде энергия шығындарының деңгейі, парниктік газдар шығарындыларының көлемі, технологиялық күрделілігі және екінші реттік өнімнің сапасы атап көрсетілді. Полиэтилен қалдықтарын қайта өңдеудің әртүрлі әдістерін кешенді және сараланған түрде қолдану экологиялық тәуекелдерді азайтудың және циркулярлық экономика моделіне көшудің негізгі шарты екендігі туралы қорытынды жасалды.
Кілт сөздер: полиэтилен; полимерлік қалдықтар; қалдықтарды қайта өңдеу; механикалық қайта өңдеу; химиялық қайта өңдеу; пиролиз; экологиялық тиімділік; тұрақты даму; циркулярлық экономика; қоршаған ортаның ластануы.