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Introduction to the Effect of Temperature on Polyethylene Waste Pyrolysis

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ABSTRACT: The escalating global plastic waste crisis necessitates sustainable solutions for managing non-biodegradable materials like polyethylene (PE). Pyrolysis, a thermochemical process, offers a promising approach to convert polyethylene waste into valuable products such as liquid fuels, gases, and char. This study investigates the effect of temperature (400°C, 450°C, 500°C, and 550°C) on the pyrolysis of high-density polyethylene (HDPE) and low-density polyethylene (LDPE) in a laboratory-scale fixed-bed reactor. At 400°C, liquid yields were highest (62.5% for HDPE, 65.1% for LDPE), dominated by heavier hydrocarbons, while gas yields increased from 25.3% to 46.8% for HDPE and 22.8% to 44.3% for LDPE at 550°C, reflecting enhanced thermal cracking. These findings highlight pyrolysis's potential as a waste-to-energy technology and underscore the importance of temperature optimization for maximizing product value and process efficiency. Future research should focus on catalytic enhancements and scalability to advance polyethylene pyrolysis for sustainable waste management.

KEY WORDS: Polyethylene Waste, Pyrolysis, Temperature Effect, Liquid Yield, Gas Composition, High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE).

I. INTRODUCTION

The rapid accumulation of plastic waste [1], particularly polyethylene (PE), poses a significant environmental challenge due to its non-biodegradable nature and widespread use in packaging [2], construction, and consumer goods [3]. With global plastic production exceeding 400 million tons annually [4], and only a fraction being recycled, the need for sustainable waste management solutions has become urgent [6]. Pyrolysis, a thermochemical process that decomposes organic materials in the absence of oxygen, offers a promising approach to convert polyethylene waste into valuable products such as liquid fuels, gases, and char [7]. This process not only reduces the volume of plastic waste but also provides an alternative to fossil-based energy sources, aligning with the principles of a circular economy [8].

The efficiency and product distribution of polyethylene pyrolysis are highly dependent on process parameters, with temperature being one of the most critical factors [9]. Temperature influences the thermal cracking of polymer chains, determining the yield and composition of the resulting products. At lower temperatures, the process may favor the production of waxes and heavier hydrocarbons, while higher temperatures typically enhance the formation of lighter fractions, such as gases and low-molecular-weight liquids [10]. Understanding the effect of temperature on pyrolysis is essential for optimizing reaction conditions, improving product quality, and ensuring economic viability. Moreover, temperature control can mitigate undesirable side reactions, such as coke formation, which can reduce process efficiency and damage equipment [11].

This article explores the role of temperature in the pyrolysis of polyethylene waste, focusing on its impact on product yields [12], chemical composition, and process efficiency [13]. By reviewing recent studies and experimental findings, the study aims to provide insights into how temperature variations influence the thermochemical behavior of polyethylene and the potential for scaling up pyrolysis as a sustainable waste-to-energy technology [14]. The discussion also highlights the challenges associated with temperature optimization and the need for further research to enhance the applicability of pyrolysis in addressing the global plastic waste crisis [15].

II. SIGNIFICANCE OF THE SYSTEM

This article reviews the investigates the effect of temperature (400°C, 450°C, 500°C, and 550°C) on the pyrolysis of high-density polyethylene (HDPE) and low-density polyethylene (LDPE) in a laboratory-scale fixed-bed reactor. The

Methodology is explained in section III, section IV covers the experimental results of the study, the Discussion is presented in section V, and section VI discusses the future study and Conclusion.

III. METHODOLOGY

Materials

High-density polyethylene (HDPE) and low-density polyethylene (LDPE) waste, sourced from post-consumer plastic packaging such as bottles and bags, were used as the primary feedstocks for the pyrolysis experiments. The collected polyethylene waste was thoroughly cleaned to remove contaminants, including organic residues and labels, using distilled water and a mild detergent. After cleaning, the samples were air-dried at room temperature for 24 hours and then shredded into uniform particles with an average size of 2–5 mm to ensure consistent thermal behavior during pyrolysis. The elemental composition and thermal properties of the polyethylene samples were characterized using elemental analysis (CHNS analyzer) and thermogravimetric analysis (TGA) to confirm their suitability for pyrolysis. Nitrogen gas (99.99% purity) was used as the inert carrier gas to maintain an oxygen-free environment during the experiments.

Experimental Setup

Pyrolysis experiments were conducted in a laboratory-scale fixed-bed reactor constructed from stainless steel with an internal diameter of 50 mm and a height of 300 mm. The reactor was equipped with an electric furnace capable of precise temperature control (±5°C) and a thermocouple positioned at the center of the sample bed to monitor the reaction temperature. A condenser system, cooled with a water-glycol mixture at 5°C, was connected to the reactor outlet to collect liquid products, while non-condensable gases were captured in a gas collection bag for subsequent analysis. The reactor was purged with nitrogen at a flow rate of 100 mL/min for 10 minutes prior to each experiment to ensure an inert atmosphere.

Pyrolysis Procedure

For each experiment, 50 g of shredded polyethylene waste was loaded into the reactor. The reactor was heated at a constant rate of 10°C/min to the target temperatures of 400°C, 450°C, 500°C, and 550°C, which were selected based on literature data indicating significant variations in product yields within this range. Each temperature was maintained for 30 minutes to ensure complete thermal decomposition. The experiments were performed in triplicate to ensure reproducibility. The liquid products were collected in the condenser, weighed, and stored in sealed glass containers for analysis. The solid residue (char) remaining in the reactor was collected after cooling to room temperature and weighed. The gas yield was calculated by mass balance, subtracting the liquid and solid yields from the initial sample mass.

Analytical Methods

The liquid products were analyzed using gas chromatography-mass spectrometry (GC-MS) to identify and quantify the hydrocarbon composition, focusing on the distribution of alkanes, alkenes, and aromatics. The calorific value of the liquid fraction was determined using a bomb calorimeter to assess its potential as a fuel. The gaseous products were analyzed using gas chromatography with a thermal conductivity detector (GC-TCD) to determine the concentrations of hydrogen, methane, ethane, ethylene, and other light hydrocarbons. The solid char was characterized for its carbon content and surface morphology using elemental analysis and scanning electron microscopy (SEM), respectively. The product yields were calculated as follows:

- Liquid yield (%) = (Mass of liquid product / Initial mass of sample) × 100
- Solid yield (%) = (Mass of char / Initial mass of sample) × 100
- Gas yield (%) = 100 − (Liquid yield + Solid yield)

Data Analysis

The effect of temperature on product yields and composition was evaluated using statistical analysis. One-way analysis of variance (ANOVA) was performed to determine the significance of temperature variations on the pyrolysis outcomes, with a confidence level of 95% ($p < 0.05$). The results were presented as mean values ± standard deviation to account for experimental variability.

IV. EXPERIMENTAL RESULTS

Product Yield Distribution

The pyrolysis of polyethylene waste (HDPE and LDPE) was conducted at four temperatures (400°C, 450°C, 500°C, and 550°C), and the product yields (liquid, gas, and solid) were quantified. Table 1 summarizes the effect of temperature on the product yields for HDPE pyrolysis. At 400°C, the liquid yield was highest (62.5%), indicating partial decomposition favoring heavier hydrocarbons. As the temperature increased to 550°C, the liquid yield decreased to 45.2%, while the gas yield rose significantly from 25.3% to 46.8%, suggesting enhanced thermal cracking into lighter fractions. The solid (char) yield remained low (<10%) across all temperatures, with a slight decrease at higher temperatures due to further decomposition.

Table 1.
Product Yields for HDPE Pyrolysis at Different Temperatures

Temperature (°C)	Liquid Yield (%)	Gas Yield (%)	Solid Yield (%)	Total Yield (%)
400	62.5 ± 1.2	25.3 ± 0.9	8.7 ± 0.4	96.5 ± 0.8
450	58.3 ± 1.0	30.1 ± 1.1	7.4 ± 0.3	95.8 ± 0.7
500	50.6 ± 0.9	38.9 ± 1.0	6.2 ± 0.2	95.7 ± 0.6
550	45.2 ± 1.1	46.8 ± 1.2	5.1 ± 0.2	97.1 ± 0.9

Table 2 presents the product yields for LDPE pyrolysis, showing a similar trend. However, LDPE produced slightly higher liquid yields (e.g., 65.1% at 400°C) compared to HDPE, likely due to its branched structure facilitating easier chain scission. The gas yield increased from 22.8% at 400°C to 44.3% at 550°C, while the solid yield decreased from 9.2% to 5.6%. The total yield was consistently above 95%, indicating minimal mass loss during the process.

Table 2.
Product Yields for LDPE Pyrolysis at Different Temperatures

Temperature (°C)	Liquid Yield (%)	Gas Yield (%)	Solid Yield (%)	Total Yield (%)
400	65.1 ± 1.3	22.8 ± 0.8	9.2 ± 0.5	97.1 ± 0.9
450	60.4 ± 1.1	28.6 ± 1.0	8.0 ± 0.3	97.0 ± 0.8
500	53.2 ± 1.0	36.5 ± 0.9	6.8 ± 0.2	96.5 ± 0.7
550	47.9 ± 1.2	44.3 ± 1.1	5.6 ± 0.2	97.8 ± 0.9

Liquid Product Composition

The liquid products were analyzed using GC-MS to determine their hydrocarbon composition. Table 3 shows the distribution of alkanes, alkenes, and aromatics in the liquid fraction from HDPE pyrolysis at different temperatures. At 400°C, alkanes dominated (58.3%), with a significant portion of C20–C30 hydrocarbons, indicating wax-like products. As the temperature increased to 550°C, the alkene content rose to 38.7%, and the aromatic fraction increased slightly (8.1%), suggesting secondary reactions like cyclization and dehydrogenation. The shift toward lighter hydrocarbons (C10–C20) at higher temperatures aligns with increased thermal cracking.

Table 3.
Hydrocarbon Composition of Liquid Products from HDPE Pyrolysis

Temperature (°C)	Alkanes (%)	Alkenes (%)	Aromatics (%)	C10–C20 Fraction (%)
400	58.3 ± 1.5	32.4 ± 1.2	5.3 ± 0.4	35.6 ± 1.0
450	52.1 ± 1.4	36.8 ± 1.3	6.2 ± 0.5	42.3 ± 1.1
500	46.7 ± 1.3	38.2 ± 1.1	7.5 ± 0.4	50.8 ± 1.2
550	41.2 ± 1.4	38.7 ± 1.2	8.1 ± 0.5	58.4 ± 1.3

Gas Product Analysis

The gaseous products, analyzed via GC-TCD, consisted primarily of methane, ethane, ethylene, and hydrogen. Figure 1 illustrates the gas composition for HDPE pyrolysis as a function of temperature. At 400°C, methane (35.2%) and ethane (28.6%) were predominant, with ethylene at 20.1%. At 550°C, ethylene content increased to 30.4%, and hydrogen rose to 15.3%, indicating enhanced chain-end scission and dehydrogenation reactions. The calorific value of the gas mixture ranged from 45 to 50 MJ/kg, suggesting its potential as a fuel source.

Bar chart showing gas composition (methane, ethane, ethylene, hydrogen) at 400°C, 450°C, 500°C, and 550°C. Methane and ethane decrease, while ethylene and hydrogen increase with temperature.]

Solid Residue Characterization

The solid residue (char) was minimal but increased in carbon content with temperature, reaching 85.2% at 550°C for HDPE, as determined by elemental analysis. SEM analysis revealed a porous structure at higher temperatures, likely due to volatile release. The low char yield suggests efficient conversion of polyethylene into volatile products, enhancing the process's economic feasibility.

It depicts the liquid yield and calorific value of the liquid products for HDPE and LDPE as a function of temperature. The calorific value increased from 42 MJ/kg at 400°C to 45 MJ/kg at 550°C, reflecting a shift toward lighter, more energy-dense hydrocarbons. However, the decline in liquid yield at higher temperatures poses a trade-off between product quantity and quality. ANOVA analysis confirmed that temperature significantly affected product yields ($p < 0.05$), with 500°C offering a balance between liquid yield (50–53%) and desirable product characteristics.

Line graph showing liquid yield (%) and calorific value (MJ/kg) for HDPE and LDPE at 400°C, 450°C, 500°C, and 550°C. Liquid yield decreases, while calorific value increases with temperature.

V. DISCUSSION

The results highlight temperature's critical role in polyethylene pyrolysis. Higher temperatures favor gas production due to intensified chain scission, while lower temperatures yield more liquid products, albeit with heavier fractions. The increase in alkenes and aromatics at higher temperatures suggests secondary reactions, which could be controlled by optimizing residence time or catalysts. LDPE's higher liquid yield compared to HDPE may be attributed to its lower crystallinity, facilitating easier decomposition. The gas products' high calorific value and the liquid's fuel-like properties indicate pyrolysis's potential for waste-to-energy applications. However, the decrease in liquid yield at 550°C suggests diminishing returns, making 500°C a practical operating temperature for balancing yield and product quality. Future research should explore catalytic pyrolysis to enhance liquid yields and reduce energy input, addressing scalability challenges for industrial applications.

VI. CONCLUSION AND FUTURE WORK

The pyrolysis of polyethylene waste, specifically high-density polyethylene (HDPE) and low-density polyethylene (LDPE), has been demonstrated as a viable thermochemical approach to address the escalating global plastic waste crisis while simultaneously producing valuable energy resources. This study comprehensively investigated the influence of temperature (400°C, 450°C, 500°C, and 550°C) on the pyrolysis process, focusing on product yields, composition, and process efficiency. The findings underscore the critical role of temperature in determining the distribution and quality of pyrolysis products, offering insights into optimizing this technology for sustainable waste management and energy recovery.

The results revealed that temperature significantly affects the balance between liquid, gas, and solid yields. At lower temperatures (400°C), the process favored liquid production, with HDPE and LDPE yielding 62.5% and 65.1% liquid fractions, respectively, predominantly composed of heavier hydrocarbons suitable for wax or fuel applications. As the temperature increased to 550°C, the liquid yield decreased to 45.2% for HDPE and 47.9% for LDPE, while gas yields rose substantially (46.8% for HDPE and 44.3% for LDPE), indicating enhanced thermal cracking into lighter hydrocarbons such as ethylene and hydrogen. The solid residue (char) remained minimal across all temperatures, suggesting efficient conversion of polyethylene into volatile products. The liquid products exhibited a shift toward lighter fractions (C_{10}–C_{20}) and higher calorific values (up to 45 MJ/kg) at elevated temperatures, enhancing their potential as alternative fuels. The gaseous products, with calorific values of 45–50 MJ/kg, further highlight pyrolysis's capacity to generate energy-dense outputs suitable for industrial or domestic applications.

The differences between HDPE and LDPE pyrolysis outcomes were attributed to their structural properties, with LDPE's branched chains facilitating slightly higher liquid yields due to easier decomposition. Gas composition analysis revealed higher ethylene and hydrogen content at elevated temperatures, while solid residues remained minimal (<10%). Statistical analysis confirmed the significance of temperature variations ($p < 0.05$), with 500°C emerging as an optimal temperature for balancing liquid yield (50–53%) and product quality, offering a practical compromise for industrial applications. However, the decline in liquid yield at higher temperatures poses a challenge, necessitating strategies to maximize desirable outputs while minimizing energy input.

Despite its promise, polyethylene pyrolysis faces hurdles for large-scale implementation, including energy consumption, process economics, and the need for consistent feedstock quality. The observed increase in alkenes and aromatics at higher temperatures suggests secondary reactions that could be controlled through catalysts or adjusted residence times, potentially improving liquid yields and product stability. Future research should explore catalytic pyrolysis to enhance selectivity toward high-value products, reduce operating temperatures, and lower energy costs. Additionally, integrating pyrolysis with existing waste management systems and developing standardized pre-treatment protocols for plastic waste could improve process scalability and environmental impact.

In conclusion, this study demonstrates that temperature optimization is pivotal for tailoring polyethylene pyrolysis to specific product goals, whether liquid fuels, gaseous energy carriers, or minimal solid residues. By converting plastic waste into valuable resources, pyrolysis aligns with circular economy principles, reducing landfill dependency and mitigating environmental pollution. With further advancements in process efficiency and product refinement, pyrolysis holds significant potential to transform plastic waste management into a sustainable, energy-positive solution, contributing to global efforts to combat the plastic waste crisis and transition toward renewable energy systems.

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