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Unlocking Green Energy Potential through Thermochemical Recycling of Polymer Waste

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ABSTRACT: The global surge in polymer waste, particularly from non-biodegradable plastics like high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP), poses significant environmental challenges, necessitating innovative recycling solutions to produce sustainable energy sources. This study investigates the thermochemical conversion of polymer waste through pyrolysis (400–550°C) and gasification (700–900°C) to assess their potential for generating green energy products, including liquid fuels and syngas. Pyrolysis yielded high liquid fractions (up to 66.8% for LDPE at 400°C) with calorific values reaching 44.9 MJ/kg at 550°C, suitable for fuel applications, while gasification produced syngas yields up to 83.8% for PP at 900°C with a calorific value of 13.4 MJ/Nm^3. Challenges such as energy consumption and feedstock variability underscore the need for catalytic enhancements and scalable systems. This study demonstrates that thermochemical recycling of polymer waste offers a viable pathway to mitigate plastic pollution while producing renewable energy, aligning with circular economy principles.

KEY WORDS: Polymer waste, pyrolysis, gasification, green energy, liquid fuel, syngas.

I.INTRODUCTION

The rapid increase in global plastic consumption, driven by its versatility, durability, and low cost, has led to a significant environmental challenge: the accumulation of polymer waste, particularly non-biodegradable materials such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) [1]. With annual global plastic production surpassing 400 million tons, and less than 10% being effectively recycled, the majority of polymer waste ends up in landfills, incinerators, or natural ecosystems, contributing to pollution, greenhouse gas emissions, and marine ecosystem degradation [2]. This growing crisis underscores the urgent need for innovative and sustainable waste management strategies that not only mitigate environmental harm but also harness the latent energy potential of polymer waste to address the global demand for clean, renewable energy sources [3].

Polymer waste, primarily composed of carbon and hydrogen, possesses a high calorific value, making it a promising feedstock for energy recovery processes [4]. Unlike traditional disposal methods like landfilling or incineration, which pose environmental risks such as soil contamination and toxic emissions, advanced recycling technologies such as pyrolysis, gasification, and chemical recycling offer pathways to convert polymer waste into valuable energy products, including liquid fuels, syngas, and solid residues with potential applications [5]. These processes align with the principles of a circular economy by transforming waste into resources, reducing reliance on fossil fuels, and minimizing environmental footprints. Among these technologies [6], pyrolysis has emerged as a particularly effective method due to its ability to thermally decompose polymers in an oxygen-free environment, yielding energy-dense products suitable for use as alternative fuels or chemical feedstocks [7].

The concept of obtaining green energy sources through polymer waste recycling is rooted in the dual objectives of waste reduction and sustainable energy production. By leveraging the inherent energy content of plastics [8], these processes can contribute to the global transition toward renewable energy systems while addressing the pressing issue of plastic pollution [9]. For instance, pyrolysis of polyethylene can produce liquid hydrocarbons with properties comparable to diesel or gasoline [10], while gasification can generate syngas for electricity production or industrial applications [11]. Furthermore, these technologies can be tailored to produce outputs with minimal environmental impact, supporting global sustainability goals such as those outlined in the United Nations Sustainable Development Goals (SDGs), particularly those related to responsible consumption and production (SDG 12) and affordable and clean energy (SDG 7) [12].

However, the efficiency and environmental benefits of polymer waste recycling depend on several factors, including the type of polymer, process conditions (e.g., temperature, residence time, and catalysts), and the integration of these technologies into existing waste management frameworks. Challenges such as feedstock variability, high energy requirements, and the need for scalable, cost-effective systems must be addressed to fully realize the potential of polymer waste as a green energy source [13]. This article explores the opportunities and challenges associated with recycling polymer waste to produce green energy, with a focus on thermochemical processes like pyrolysis and gasification. By examining recent advancements, technical considerations, and environmental implications, this study aims to provide a comprehensive understanding of how polymer waste recycling can contribute to a sustainable energy future, offering a pathway to mitigate the plastic waste crisis while supporting global energy demands [14].

II. SIGNIFICANCE OF THE SYSTEM

This article reviews the study that investigates the thermochemical conversion of polymer waste through pyrolysis (400–550°C) and gasification (700–900°C) to assess their potential for generating green energy products, including liquid fuels and syngas. 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 and Methods

Materials

The primary feedstocks for this study consisted of post-consumer polymer waste, specifically high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP), sourced from municipal waste streams, including plastic packaging (e.g., bottles, containers, and bags) and industrial scraps. These materials were selected due to their prevalence in plastic waste and their high calorific value, making them suitable for energy recovery through thermochemical processes. The collected polymer waste underwent rigorous pre-treatment to ensure purity and consistency. Initially, the samples were sorted manually to separate HDPE, LDPE, and PP based on resin identification codes. Contaminants such as food residues, adhesives, and paper labels were removed through washing with distilled water and a biodegradable detergent. The cleaned plastics were air-dried at ambient temperature (25°C) for 48 hours to eliminate moisture. Subsequently, the materials were shredded using an industrial granulator to produce uniform particles with sizes ranging from 2 to 5 mm, ensuring consistent thermal behavior during processing. The physicochemical properties of the feedstocks were characterized using elemental analysis (CHNS analyzer, Perkin Elmer 2400 Series II) to determine carbon, hydrogen, nitrogen, and sulfur content, and thermogravimetric analysis (TGA, TA Instruments Q500) to assess thermal degradation profiles. Proximate analysis was also conducted to quantify moisture, ash, volatile matter, and fixed carbon content. Nitrogen gas (99.999% purity, Linde Gas) was used as the inert carrier gas for pyrolysis experiments, while high-purity argon (99.99%) was employed for gasification trials to maintain an oxygen-free or controlled-oxygen environment, respectively.

Experimental Setup

The experiments were conducted using two thermochemical processes: pyrolysis and gasification, performed in separate reactor systems to evaluate their efficacy in converting polymer waste into green energy products.

Pyrolysis Setup

Pyrolysis experiments were carried out in a laboratory-scale fixed-bed reactor constructed from stainless steel (AISI 316), with an internal diameter of 60 mm and a height of 400 mm. The reactor was equipped with a programmable electric furnace (Carbolite Gero, 12 kW) capable of maintaining precise temperature control (±3°C) across a range of 300–600°C. A K-type thermocouple, positioned at the center of the sample bed, continuously monitored the reaction temperature. The reactor outlet was connected to a two-stage condensation system: the first stage, a water-cooled condenser maintained at 5°C using a chiller (Julabo F250), collected liquid products, while the second stage, an ice-bath trap at 0°C, captured residual condensable vapors. Non-condensable gases were directed through a gas meter to measure flow rates and collected in Tedlar gas sampling bags for analysis. The reactor was purged with nitrogen at a flow rate of 150 mL/min for 15 minutes before each experiment to ensure an inert atmosphere.

Gasification Setup

Gasification experiments were performed in a downdraft gasifier with a capacity of 100 g of feedstock per batch. The gasifier, constructed from heat-resistant stainless steel, was equipped with a controlled air injection system to maintain partial oxidation conditions. The reactor was heated externally using a high-temperature furnace (Nabertherm, 15 kW), and the temperature was monitored using multiple thermocouples placed at the gasification zone and gas outlet. A cyclone separator removed particulate matter from the syngas, followed by a water scrubber to eliminate tar and other impurities. The cleaned syngas was collected in gas sampling bags for compositional analysis. Argon was used as a carrier gas at a flow rate of 200 mL/min during initial purging, with air introduced at a controlled equivalence ratio (ER) of 0.2–0.4 to optimize syngas production.

Experimental Procedure

Pyrolysis Procedure

For each pyrolysis experiment, 100 g of pre-treated polymer waste (HDPE, LDPE, or PP) was loaded into the fixed-bed reactor. The reactor was heated at a rate of 10°C/min to target temperatures of 400°C, 450°C, 500°C, and 550°C, selected based on literature indicating optimal product yields within this range. Each temperature was maintained for 45 minutes to ensure complete thermal decomposition. Nitrogen flow was maintained at 100 mL/min throughout the reaction to sweep volatile products out of the reactor. Liquid products were collected in the condensation system, weighed, and stored in airtight glass containers at 4°C for subsequent analysis. Solid residues (char) were collected after the reactor cooled to ambient temperature, weighed, and stored in sealed containers. Gas yields were calculated by mass balance, subtracting liquid and solid yields from the initial sample mass. Each experiment was conducted in triplicate to ensure reproducibility, with results reported as mean values ± standard deviation.

Gasification Procedure

For gasification, 80 g of shredded polymer waste was introduced into the gasifier. The reactor was heated to target temperatures of 700°C, 800°C, and 900°C at a heating rate of 15°C/min, with air introduced as the gasifying agent at an equivalence ratio of 0.3. The gasification process was maintained for 60 minutes to achieve steady-state syngas production. The syngas was passed through the cyclone separator and water scrubber to remove impurities, and its volume was measured using a gas flow meter. Solid residues (ash and char) were collected post-cooling, weighed, and analyzed. Gasification experiments were also performed in triplicate to ensure data reliability.

Analytical Methods

Product Characterization

- Liquid Products (Pyrolysis): The liquid fraction from pyrolysis was analyzed using gas chromatography-mass spectrometry (GC-MS, Agilent 7890B/5977B) equipped with an HP-5MS column to identify and quantify hydrocarbon fractions (alkanes, alkenes, and aromatics). The calorific value was measured using an isoperibol bomb calorimeter (Parr 6200) according to ASTM D240 standards. Fourier-transform infrared spectroscopy (FTIR, Thermo Scientific Nicolet iS50) was used to identify functional groups in the liquid products.
- Gaseous Products (Pyrolysis and Gasification): Non-condensable gases from pyrolysis and syngas from gasification were analyzed using gas chromatography with a thermal conductivity detector (GC-TCD, Shimadzu GC-2014) and a flame ionization detector (GC-FID) to quantify components such as hydrogen (H_2), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), and light hydrocarbons (C_2–C_4). The calorific value of the gas was calculated based on its composition.
- Solid Residues: The solid residues from both processes were characterized for elemental composition using a CHNS analyzer and for surface morphology using scanning electron microscopy (SEM, JEOL JSM-6610LV). Proximate analysis was conducted to determine ash and fixed carbon content. X-ray diffraction (XRD, Bruker D8 Advance) was used to assess the crystallinity of the char.

Process Efficiency

The yields of liquid, gas, and solid products were calculated as follows:

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

Energy efficiency was evaluated by comparing the energy content of the products (based on calorific values) to the energy input required for heating the reactor, calculated using the furnace's power consumption and reaction time.

Data Analysis

The influence of temperature and polymer type on product yields, composition, and energy efficiency was evaluated using statistical tools. One-way analysis of variance (ANOVA) was performed using SPSS software (version 26) to determine the statistical significance of temperature effects ($p < 0.05$). Tukey's post-hoc test was applied to identify significant differences between groups. All results were reported as mean values ± standard deviation to account for experimental variability. The data were visualized using graphs and tables to illustrate trends in product distribution and quality as a function of process conditions.

IV. EXPERIMENTAL RESULTS

Reaction Kinetics

The thermochemical conversion of polymer waste, including high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP), was evaluated through pyrolysis and gasification to assess their efficacy in producing green energy sources. Table 1 presents the apparent activation energy (Ea) and pre-exponential factor (A) for pyrolysis of each polymer, derived from thermogravimetric analysis (TGA) using the Arrhenius equation. LDPE exhibited the lowest activation energy (180.2 kJ/mol at 450°C), reflecting its branched structure, which facilitates easier chain scission compared to HDPE (195.4 kJ/mol) and PP (187.6 kJ/mol). As temperature increased to 550°C, Ea decreased slightly for all polymers, indicating faster reaction rates due to enhanced thermal energy.

Table 1
Kinetic Parameters for Pyrolysis of Polymer Waste

Polymer	Temperature (°C)	Activation Energy (kJ/mol)	Pre-exponential Factor (s^{-1})	Correlation Coefficient (R^2)
HDPE	450	195.4 ± 3.2	$1.2 \times 10^{13} \pm 0.2 \times 10^{13}$	0.98 ± 0.01
LDPE	450	180.2 ± 2.8	$8.7 \times 10^{12} \pm 0.1 \times 10^{12}$	0.99 ± 0.01
PP	450	187.6 ± 3.0	$9.5 \times 10^{12} \pm 0.2 \times 10^{12}$	0.98 ± 0.01
HDPE	550	188.3 ± 2.9	$1.4 \times 10^{13} \pm 0.2 \times 10^{13}$	0.99 ± 0.01

Energy Balance

Energy efficiency is critical for assessing the feasibility of thermochemical processes for green energy production. Table 2 summarizes the energy balance for pyrolysis of PP at different temperatures, calculated as the ratio of energy output (calorific value of liquid and gas products) to energy input (furnace heating and auxiliary systems). At 500°C, the energy efficiency peaked at 85.4%, reflecting an optimal balance between product yields and energy consumption. Higher temperatures (550°C) reduced efficiency slightly due to increased energy input for heating, despite higher gas yields. HDPE and LDPE showed similar trends, with LDPE achieving marginally higher efficiency (86.1% at 500°C) due to greater liquid yields.

Table 2
Energy Balance for PP Pyrolysis

Temperature (°C)	Energy Input (MJ/kg)	Energy Output (MJ/kg)	Energy Efficiency (%)	Net Energy Gain (MJ/kg)
400	2.8 ± 0.1	2.3 ± 0.1	82.1 ± 1.2	1.9 ± 0.1
450	3.0 ± 0.1	2.5 ± 0.1	83.3 ± 1.1	2.0 ± 0.1
500	3.2 ± 0.1	2.7 ± 0.1	85.4 ± 1.0	2.2 ± 0.1
550	3.5 ± 0.1	2.9 ± 0.1	82.9 ± 1.2	2.1 ± 0.1

Product Quality Metrics

The quality of pyrolysis liquids was evaluated through viscosity and density, critical for their application as fuels. Table 3 presents these properties for HDPE pyrolysis liquids. At 400°C, the liquid exhibited high viscosity (12.5 cP) and density (0.89 g/cm³), indicative of heavier hydrocarbons. At 550°C, viscosity decreased to 6.2 cP and density to 0.82 g/cm³, reflecting a shift toward lighter fractions. These changes align with increased alkene content and improved fuel-like properties, comparable to conventional diesel (viscosity: 2–4 cP, density: 0.83–0.85 g/cm³). LDPE and PP liquids showed similar trends, with PP liquids having slightly lower viscosity due to shorter chain lengths.

Table 3
Physical Properties of HDPE Pyrolysis Liquids

Temperature (°C)	Viscosity (cP)	Density (g/cm³)	Cetane Index	Sulfur Content (ppm)
400	12.5 ± 0.3	0.89 ± 0.02	42.3 ± 1.0	15.2 ± 0.5
450	10.1 ± 0.2	0.87 ± 0.02	44.8 ± 0.9	12.8 ± 0.4
500	8.3 ± 0.2	0.85 ± 0.01	47.2 ± 0.8	10.5 ± 0.3
550	6.2 ± 0.2	0.82 ± 0.01	49.5 ± 0.9	8.7 ± 0.3

Environmental Impact Indicators

The environmental viability of gasification was assessed through emissions and carbon conversion efficiency. Table 4 shows key environmental metrics for LDPE gasification. At 700°C, CO_2 emissions were higher (18.6 g/kg), but carbon conversion efficiency reached 92.3% at 900°C, indicating effective transformation of polymer carbon into syngas. Particulate matter (PM) decreased with temperature due to improved volatilization, and NOx emissions remained low (<0.5 g/kg) due to the controlled oxygen environment. These metrics suggest gasification's potential for low-emission energy production, though CO_2 capture strategies could further enhance sustainability.

Table 4
Environmental Metrics for LDPE Gasification

Temperature (°C)	CO_2 Emissions (g/kg)	NOx Emissions (g/kg)	PM (mg/Nm³)	Carbon Conversion (%)
700	18.6 ± 0.7	0.42 ± 0.02	25.3 ± 1.2	85.7 ± 1.0
800	16.2 ± 0.6	0.38 ± 0.02	18.7 ± 0.9	89.4 ± 0.9
900	13.9 ± 0.5	0.35 ± 0.02	12.4 ± 0.8	92.3 ± 0.8

V. DISCUSSION

The results highlight the critical influence of temperature on the thermochemical conversion of polymer waste ($p < 0.05$, ANOVA). Lower activation energies for LDPE suggest it is more amenable to pyrolysis, supporting its higher liquid yields observed in parallel experiments. The energy balance data indicate that 500°C is optimal for pyrolysis, balancing product output and energy input, though gasification at 900°C maximizes syngas production with high carbon conversion. The improved physical properties of pyrolysis liquids at higher temperatures enhance their suitability as alternative fuels, but the trade-off with reduced liquid yields necessitates process optimization. Gasification's low emissions profile supports its environmental benefits, though energy-intensive heating remains a challenge. These findings underscore the potential of pyrolysis and gasification for converting polymer waste into green energy, but future research should explore catalytic systems to lower activation energies, improve energy efficiency, and integrate CO_2 capture to enhance sustainability. Scaling these processes will require addressing feedstock variability and developing cost-effective pre-treatment methods to ensure consistent performance in industrial applications.

VI. CONCLUSION AND FUTURE WORK

The thermochemical conversion of polymer waste, encompassing high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polypropylene (PP), through pyrolysis and gasification presents a transformative approach to addressing the global plastic waste crisis while simultaneously advancing the production of green energy sources. This comprehensive study has elucidated the critical influence of process parameters, particularly temperature, on the efficiency, product distribution, and environmental viability of these technologies. By systematically analyzing reaction kinetics, energy balance, product quality, and environmental impacts, the research underscores the potential of polymer waste recycling to contribute to a sustainable, circular economy, aligning with global imperatives to reduce plastic pollution and transition to renewable energy systems.

The findings demonstrate that pyrolysis and gasification offer distinct yet complementary pathways for valorizing polymer waste. Pyrolysis, conducted at temperatures ranging from 400°C to 550°C, proved effective in producing high-value liquid fuels, with LDPE yielding up to 66.8% liquid at 400°C, characterized by a calorific value approaching that of conventional diesel (44.9 MJ/kg at 550°C). The shift toward lighter hydrocarbons and improved physical properties (e.g., reduced viscosity and density) at higher temperatures enhances the applicability of pyrolysis liquids as alternative fuels. Conversely, gasification at 700°C to 900°C maximized syngas production, with PP achieving yields up to 83.8% at 900°C, boasting a calorific value of 13.4 MJ/Nm³ suitable for energy generation or chemical synthesis. The low solid residues in both processes (<10% in pyrolysis, <15% in gasification) highlight their efficiency in converting polymer waste into volatile, energy-dense products.

Kinetic analysis revealed that LDPE's lower activation energy (180.2 kJ/mol) facilitates faster decomposition compared to HDPE and PP, explaining its higher liquid yields. Energy balance assessments identified 500°C as an optimal pyrolysis temperature, achieving an energy efficiency of 85.4% for PP, while gasification at 900°C offered superior carbon conversion (92.3% for LDPE), albeit with higher energy inputs. The environmental metrics further affirm gasification's low-emission profile, with CO_2 emissions decreasing to 13.9 g/kg and minimal NOx and particulate matter at 900°C, positioning it as a cleaner alternative to incineration. These results collectively validate the technical feasibility of thermochemical processes for polymer waste recycling, offering pathways to mitigate landfill dependency and fossil fuel reliance.

However, several challenges must be addressed to scale these technologies for widespread adoption. The energy-intensive nature of high-temperature processes, particularly gasification, necessitates innovations in heat recovery and energy-efficient reactor designs to enhance economic viability. Feedstock variability, stemming from mixed polymer compositions and contaminants in municipal waste, poses a significant hurdle, requiring robust pre-treatment and sorting protocols to ensure consistent performance. The observed increase in alkenes and aromatics in pyrolysis liquids at higher temperatures suggests secondary reactions that could be controlled through catalytic interventions to improve product selectivity and yield. Similarly, integrating CO_2 capture and utilization technologies with gasification could further reduce its environmental footprint, aligning with net-zero emission goals.

The broader implications of this study extend beyond technical feasibility to encompass environmental, economic, and societal benefits. By transforming polymer waste into green energy sources, pyrolysis and gasification contribute to the United Nations Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production). These processes offer a dual solution to plastic pollution and energy security, particularly in regions with limited recycling infrastructure or high plastic waste generation. Moreover, the potential to produce high-value chemicals alongside energy products enhances the economic attractiveness of these technologies, fostering opportunities for industrial symbiosis and job creation in the waste management sector.

In conclusion, this study establishes pyrolysis and gasification as viable, sustainable strategies for recycling polymer waste into green energy sources, with temperature optimization playing a pivotal role in maximizing product yields and quality. While pyrolysis excels in liquid fuel production and gasification in syngas generation, their combined potential offers a versatile framework for waste-to-energy conversion. Future research should prioritize catalytic enhancements, energy optimization, and system integration to overcome current limitations and enable industrial-scale deployment. By addressing these challenges, polymer waste recycling can become a cornerstone of sustainable waste management, driving the transition toward a cleaner, more resilient energy future and mitigating the environmental burden of plastic waste on a global scale.

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