Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/BA08.20250194
Published: December 20, 2025

Challenges and Opportunities in Plastic Pyrolysis: A Review on Feedstock Effects, Catalysis, and Engine Fuel Viability

Khalid Mahmud Saifullah, Aniruddha Roy Protya and Md Ashfak Hossain
Department of Mechanical Engineering
Bangladesh University of Engineering and Technology
Dhaka-1000, Bangladesh
SaifullahKhalid3238@gmail.com, protya99@gmail.com, ashfakhossain152001@gmail.com

MD. Alifur Rahman
Department of Electrical and Electronic Engineering
Khulna University of Engineering & Technology
Khulna-9203, Bangladesh
Alifkueteee@gmail.com

Abstract

Pyrolysis is a promising feedstock recycling method for converting diverse plastic wastes—including polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET)—into valuable fuels and chemicals. Product yields are highly dependent on feedstock composition. Polystyrene consistently yields the most liquid oil (up to 70%), rich in valuable aromatics. Polypropylene also provides high oil yields (up to 90%), with its oil having physicochemical properties closest to diesel. Catalysis, particularly with zeolites (ZSM-5, NZ), is shown to be essential for lowering reaction temperatures and steering selectivity toward high-value aromatics (BTX). Furthermore, co-pyrolysis of plastics with biomass (e.g., wood) reveals non-additive synergistic effects that reduce char residue and enhance carbon conversion. This synergy is proposed to be physical for PP and PET (melt-phase interaction) but chemical for plastics like polycarbonate, which show an overlapping activation energy distribution with biomass. Also, the produced liquid oil possesses a high heating value (HHV) (41.7–44.2 MJ/kg), but its direct application in diesel engines is problematic. Engine trials show poor combustion, including long ignition delays, higher heat release rates, and significantly increased NOx, HC, and CO emissions, attributed to the high content of unsaturated alkenes and aromatics. Future work should focus on developing more robust catalysts, such as mesoporous zeolites, to ensure long-term stability. Finally, a deeper understanding of the complex synergistic mechanisms in co-pyrolysis and expanded system-wide LCAs are needed to fully optimize pyrolysis-based bio refineries.

Keywords
Plastic Pyrolysis, Feedstock Composition, Catalysis, Co-pyrolysis Synergy, Engine Fuel Viability.

1. Introduction

The accumulation of plastic waste has become one of the most pressing environmental challenges of the 21st century. With global plastic production surpassing 380 million tons annually and the generation of over 300 million tons of plastic waste each year, the inadequate recycling of plastic materials has caused significant harm to ecosystems and human health. Despite the increasing consumption of plastic, it is estimated that only 9% of all plastic waste is effectively recycled, while approximately 79% accumulates in landfills or the natural environment. Traditional waste management methods, such as landfilling and incineration, have proven unsustainable, prompting the exploration of more effective waste treatment technologies. Among these, plastic pyrolysis has emerged as a promising alternative for converting plastic waste into valuable products, including oil, gas, and char. Pyrolysis, a thermochemical process that decomposes plastic in the absence of oxygen at temperatures ranging from 350°C to 800°C, offers a potential solution for reducing the environmental footprint of plastic waste while generating fuels that can substitute conventional petroleum-based products.

Despite the growing interest in plastic pyrolysis, several challenges remain, particularly regarding feedstock selection, catalyst efficiency, and the viability of pyrolysis products as engine fuels. The variability in plastic waste composition, including diverse polymer types and contaminants, complicates the process, leading to inconsistent product yields and quality. Additionally, the effectiveness of catalysts in improving pyrolysis efficiency and product distribution remains an ongoing area of research. While pyrolysis oils have demonstrated potential for use in engines, studies have shown that these oils can be used to generate fuels with up to 75% energy yield, but further optimization is necessary for fuel compatibility and environmental impact.

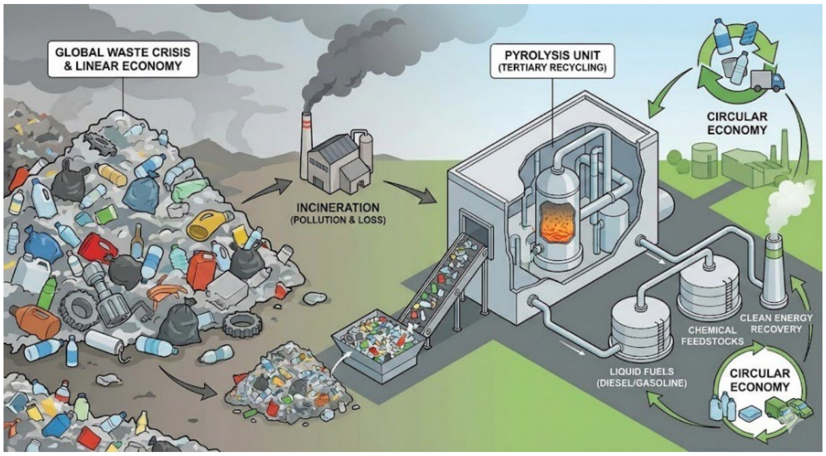


Figure 1. Schematic overview of the plastic pyrolysis pathway

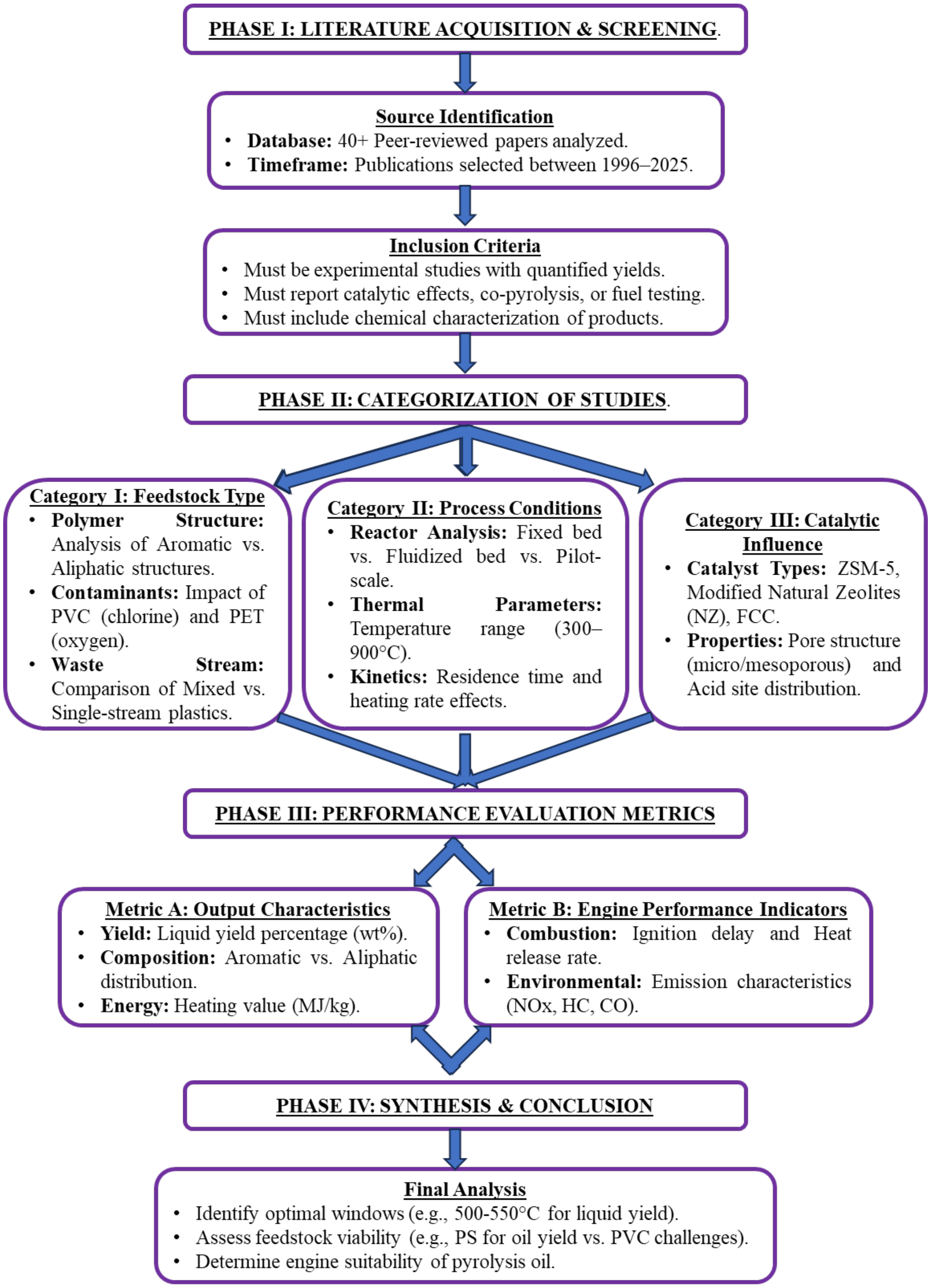
This review aims to provide a comprehensive analysis of the current state of plastic pyrolysis, focusing on feedstock effects, catalytic innovations, and the viability of pyrolysis-derived fuels for engine applications. By examining the key challenges and emerging opportunities in these areas, this paper seeks to highlight the potential of pyrolysis as a sustainable waste-to-energy solution and explore pathways for its industrial-scale implementation.

1.1 Objectives

- To analyze the impact of various plastic feedstocks (PE, PP, PS, PET, PVC) on pyrolysis product yield and composition.
- To compare the efficiency of thermal versus catalytic pyrolysis in optimizing liquid fuel quality and selectivity.
- To evaluate the physicochemical properties and performance of plastic pyrolysis oil as a direct fuel for internal combustion engines.
- To assess the techno-economic feasibility and environmental sustainability of scaling up plastic pyrolysis for commercial application.

2. Research Methodology

This study employs a systematic review methodology in Figure 2, analyzing over 40 peer-reviewed experimental papers published between 1996 and 2025 to evaluate the efficacy of plastic pyrolysis. The research framework categorizes findings into three core investigation parameters: feedstock type, which assesses the impact of polymer structures (aromatic vs. aliphatic) and contaminants like PVC ; process conditions, comparing reactor technologies and thermal kinetics across a 300–900°C range ; and catalytic influence, examining the role of catalysts such as ZSM-5 and their pore structures. The study synthesizes these factors to evaluate commercial viability, measuring success through output characteristics—specifically liquid yield and heating value —and engine performance metrics, including ignition delay and emission profiles.



PHASE I: LITERATURE ACQUISITION & SCREENING.

Source Identification
- **Database:** 40+ Peer-reviewed papers analyzed.
- **Timeframe:** Publications selected between 1996–2025.

Inclusion Criteria
- Must be experimental studies with quantified yields.
- Must report catalytic effects, co-pyrolysis, or fuel testing.
- Must include chemical characterization of products.

PHASE II: CATEGORIZATION OF STUDIES.

Category I: Feedstock Type
- **Polymer Structure:** Analysis of Aromatic vs. Aliphatic structures.
- **Contaminants:** Impact of PVC (chlorine) and PET (oxygen).
- **Waste Stream:** Comparison of Mixed vs. Single-stream plastics.

Category II: Process Conditions
- **Reactor Analysis:** Fixed bed vs. Fluidized bed vs. Pilot-scale.
- **Thermal Parameters:** Temperature range (300–900°C).
- **Kinetics:** Residence time and heating rate effects.

Category III: Catalytic Influence
- **Catalyst Types:** ZSM-5, Modified Natural Zeolites (NZ), FCC.
- **Properties:** Pore structure (micro/mesoporous) and Acid site distribution.

PHASE III: PERFORMANCE EVALUATION METRICS

Metric A: Output Characteristics
- **Yield:** Liquid yield percentage (wt%).
- **Composition:** Aromatic vs. Aliphatic distribution.
- **Energy:** Heating value (MJ/kg).

Metric B: Engine Performance Indicators
- **Combustion:** Ignition delay and Heat release rate.
- **Environmental:** Emission characteristics (NOx, HC, CO).

PHASE IV: SYNTHESIS & CONCLUSION

Final Analysis
- Identify optimal windows (e.g., 500-550°C for liquid yield).
- Assess feedstock viability (e.g., PS for oil yield vs. PVC challenges).
- Determine engine suitability of pyrolysis oil.

Figure 2. Flow chart of review process.

3. Pyrolysis Process

Pyrolysis is a thermochemical decomposition process that involves heating organic materials, such as plastic waste, at elevated temperatures typically ranging from 300°C to 900°C in an oxygen-free or oxygen-limited environment

(Jahirul et al., 2022). Unlike incineration, which combusts waste to generate heat and ash, pyrolysis degrades long-chain polymer molecules into smaller, less complex molecules, resulting in three primary value-added products: a liquid fraction (pyrolysis oil), a non-condensable gas fraction (syngas), and a solid residue known as char (Armenise, 2021). This technology is particularly advantageous for waste management because it can effectively process heterogeneous and contaminated plastic wastes that are otherwise difficult to recycle through traditional mechanical means, converting them back into valuable hydrocarbon feedstocks or fuels (Seah et al., 2023).

The fundamental chemical mechanism driving plastic pyrolysis is the breaking of carbon-carbon bonds within the polymer chain, a process generally referred to as scission. For polyolefins like polyethylene (PE) and polypropylene (PP), this degradation primarily occurs via random chain scission, which produces a complex mixture of alkanes, alkenes, and alkadienes (Supriyanto et al., 2021). The process is broadly categorized into thermal pyrolysis and catalytic pyrolysis. While thermal pyrolysis requires high temperatures and often yields products with a wide distribution of carbon chain lengths, catalytic pyrolysis utilizes acid catalysts such as zeolites to significantly lower the required activation energy and reaction temperature (Miandad et al., 2016). The addition of catalysts not only improves energy efficiency but also enhances product selectivity, directing the reaction towards the production of valuable gasoline and diesel-range hydrocarbons while minimizing the formation of heavy waxes (Peng et al., 2022).

The yield and quality of the resulting pyrolysis products are heavily dependent on the specific type of plastic feedstock and the operating parameters employed. Polystyrene (PS) is considered an excellent feedstock as it can yield over 90% liquid oil, consisting mainly of styrene monomers, whereas high-density polyethylene (HDPE) tends to produce significant amounts of solid wax that may require further upgrading (Miandad et al., 2017). Conversely, feedstocks like polyvinyl chloride (PVC) and polyethylene terephthalate (PET) pose technical challenges; PVC releases hazardous hydrogen chloride gas that corrodes equipment, while PET produces benzoic acid which can sublime and clog reactor systems (Kiran et al., 2000). Consequently, optimizing reaction conditions—such as maintaining temperatures between 500°C and 550°C—is crucial for maximizing liquid oil production and ensuring the process is technically feasible for industrial application (Jahirul et al., 2022).

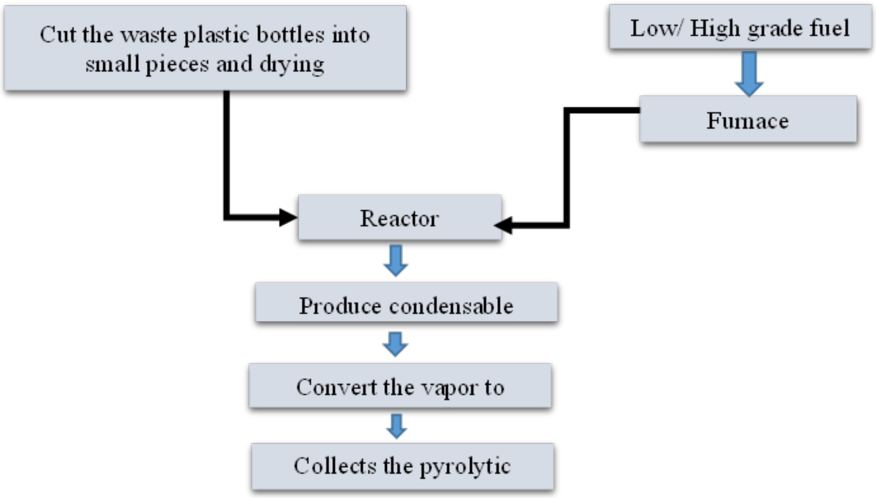


Figure 3. Schematic Methodology of Plastic Pyrolysis

3.1 Feedstock Type in Plastic Pyrolysis: Insights and Differences

The feedstock type in plastic pyrolysis plays a crucial role in determining the efficiency and quality of the pyrolysis process. Key factors that influence the process include the polymer structure, the presence of contaminants and the nature of the feedstock.

- **Polymer Structure**
  The structure of the polymer significantly affects the thermal degradation during pyrolysis. Aromatic polymers like polystyrene (PS) and polyvinyl chloride (PVC) exhibit different pyrolytic behaviors compared to aliphatic polymers such as polyethylene (PE) and polypropylene (PP) (Kiran et al., 2000), (Armenise et al., 2021), (Saxena, 2024).

- **Contaminant Presence**
  The presence of contaminants in plastic waste significantly influences the pyrolysis process. Common contaminants like PVC and PET complicate the pyrolysis process due to their chemical properties and degradation behaviors (Saxena, 2024),(Armenise et al., 2021).
- **Mixed vs. Single-Stream Plastic Waste**
  The composition of the plastic waste plays a significant role in the pyrolysis process. Mixed plastic waste (a combination of various polymers and contaminants) presents more challenges than single-stream plastic waste (composed of a single polymer type) (Saxena, 2024), (Jha & Kannan, 2020).

Table 1. Feedstock Comparison in Plastic Pyrolysis

Feedstock	Polymer Structure	Contaminants	Yield Composition	Challenges	Reference
PE (Polyethylene)	Aliphatic (Simple Hydrocarbons)	Low contaminants	High gas yield, moderate oil	Low liquid yield, high energy input	Kiran et al., 2000; Saxena, 2024
PS (Polystyrene)	Aromatic (Benzene Rings)	Low contaminants	High liquid yield, low gas	Toxic gas formation, slow decomposition	Jha & Kannan, 2020; Saxena, 2024
PVC (Polyvinyl Chloride)	Aromatic (Chlorinated)	High chlorine content	High gas, low liquid	Toxic gas formation (HCl, dioxins)	Kiran et al., 2000; Jha & Kannan, 2020
PET (Polyethylene Terephthalate)	Aromatic (Crystalline)	Low contaminants	Moderate liquid, high char	High temperature required, solid residue	Saxena, 2024; Armenise et al., 2021
Mixed Plastics	Heterogeneous (Various Polymers)	Mixed contaminants	Unpredictable yields	Inconsistent yields, higher energy cost	Saxena, 2024; Armenise et al., 2021

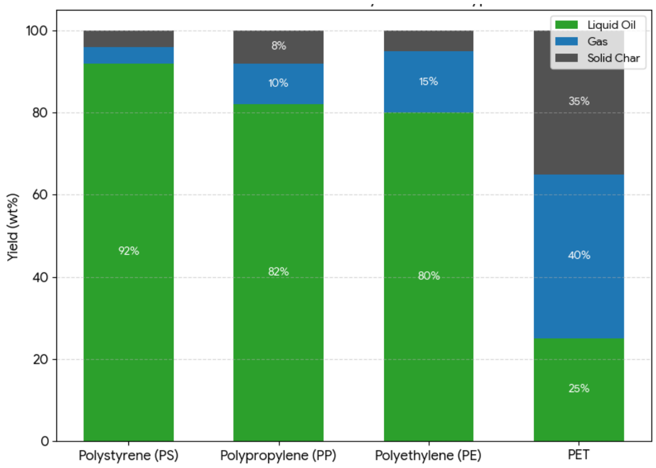


Figure 4. Product Distribution by Feedstock

The feedstock type in plastic pyrolysis significantly influences the process efficiency, product yields (Figure 4), and overall economic feasibility. The polymer structure, the presence of contaminants like PVC and PET, and the nature of the waste (mixed vs. single-stream) all play crucial roles in determining the success of the pyrolysis process. As highlighted, the challenges in processing mixed and contaminated plastics make the use of single-stream plastics more desirable for commercial pyrolysis operations. Catalytic pyrolysis and advanced sorting technologies are emerging as solutions to enhance product quality and process efficiency, but challenges remain in scaling these technologies for large-scale industrial applications (Kiran et al., 2000; Saxena, 2024).

3.2 Influence of Process Conditions on Pyrolysis Efficiency

The efficiency of plastic pyrolysis and the distribution of its products (oil, gas, char) are fundamentally governed by the operational parameters. The choice of reactor technology, operating temperature, and the interplay between heating rate and residence time determine the extent of polymer degradation and the occurrence of secondary reactions.

❖ Reactor Configurations

The reactor determines heat transfer efficiency and feedstock capability. Common classifications include:

- Batch/Semi-Batch: Simple and low-cost; ideal for lab-scale parameter control (Jahirul et al., 2022).
- Fixed Bed: Reliable but prone to poor heat transfer and char blockage (Al-Salem et al., 2017).
- Fluidized Bed (FBR): The industrial standard. Offers superior mixing and uniform heat for high yields, though feedstock shredding is required (Armenise et al., 2021).
- Conical Spouted Bed (CSBR): An FBR variant capable of handling irregular shapes to prevent defluidization.
- Auger: Continuous, compact, and mobile. Recent liquid-fed designs help prevent clogging (Kulas et al., 2022).
- Microwave: Offers rapid volumetric heating but faces high electrical costs and technical challenges (Jahirul et al., 2022).

❖ Temperature Range

Temperature is the most critical parameter influencing the cracking mechanism. The breakdown of C-C bonds requires specific thermal energy thresholds, which vary by polymer type.

- The literature consistently identifies 500°C–550°C as the optimal window for maximizing liquid oil production from mixed polyolefins (PE/PP) (Jahirul et al., 2022; Peng et al., 2022) (Figure 5).
- Low Temperatures (<400°C): Decomposition is often incomplete, leading to high yields of solid residues and heavy waxes, particularly for HDPE which produces significant wax fractions at lower temperatures (Jahirul et al., 2022; Kiran et al., 2000).
- High Temperatures (>600°C): Promotes "over-cracking" or secondary reactions where primary liquid vapors break down further into non-condensable gases (syngas) and char, reducing liquid yield (Peng et al., 2022).
- Polystyrene (PS) degrades at lower temperatures (~350°C) compared to PE and PP due to the stability of the benzylic radical (Gao, 2010). Conversely, removing chlorine from PVC requires a lower temperature step (~300°C) to prevent HCl from contaminating the oil produced at higher temperatures (Peng et al., 2022).

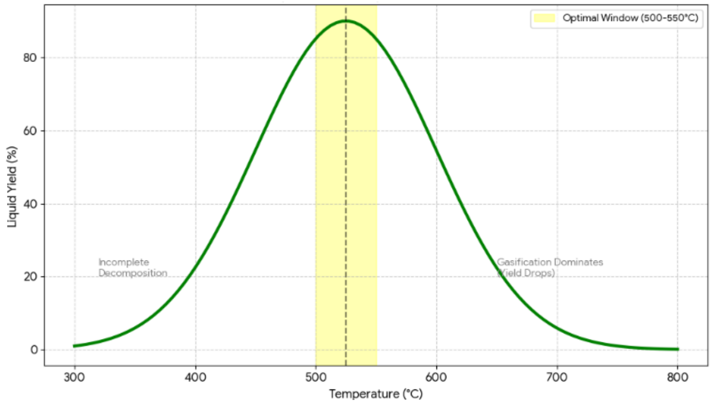


Figure 5. Optimal Temperature Window

❖ Residence Time and Heating Rate

Pyrolysis modes are defined by kinetics. Fast Pyrolysis (10-200°C/s, <2s residence) maximizes liquid oil yields by rapidly quenching vapors to prevent secondary cracking. In contrast, Slow Pyrolysis (5-10°C/min, minutes to hours) favors solid char production. As shown in Figure 6, residence time is critical; while longer times help crack heavy waxes into lighter oils, excessive exposure in the hot zone leads to "over-cracking," resulting in high gas yields and coke formation (Jahirul et al., 2022; Supriyanto et al., 2021; Supriyanto et al., 2021; Gao, 2010).

Table 2. Summary of Process Condition Effects

Reactor Type	**Key Characteristic**	**Effect on Product**
Batch / Semi-batch	Closed system, non-continuous	High residence time favors high conversion but inconsistent quality (Jahirul et al., 2022).
Fixed Bed	Static bed, poor heat transfer	Temperature gradients can lead to waxy oil or high char (Papuga et al., 2016).
Fluidized Bed	Excellent mixing, uniform heat	Maximizes liquid yield, ideal for industrial scale-up (Manos, 2017).
Auger	Mechanical transport	Good for continuous processing; enables "liquid-fed" modes (Kulas et al., 2022).
Process Variable	**Condition**	**Outcome**
Temperature	Low (<400°C)	High wax and solid residue (incomplete cracking) (Kiran et al., 2000).
	Optimal (500-550°C)	Maximum Liquid Oil Yield (Jahirul et al., 2022).
	High (>600°C)	High gas yield (secondary cracking) (Peng et al., 2022).
Residence Time	Short (<5 s)	Preserves primary liquid products (Fast Pyrolysis) (Supriyanto et al., 2021).
	Long (> min)	Promotes secondary reactions (Gas/Char increase) (Gao, 2010).

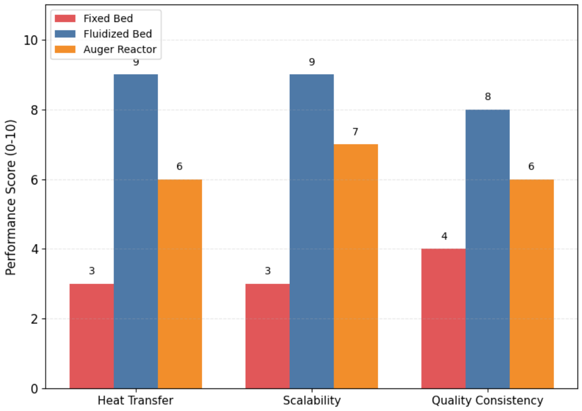


Figure 6. Comparative Assessment of Reactor Technologies.

3.3 Catalytic Influence in Plastic Pyrolysis

The introduction of catalysts into the pyrolysis process fundamentally alters the reaction mechanism from free-radical thermal cracking to carbo-cationic cracking. This shift lowers the activation energy, reduces the required reaction temperature, and significantly narrows the product distribution towards valuable fuel-range hydrocarbons.

Catalyst choice dictates reaction pathways through physical architecture and chemical acidity. Zeolites are dominant: HZSM-5 offers shape selectivity for light aromatics and coke suppression, while Y-Zeolite facilitates deep cracking of bulky polymers but deactivates rapidly. Spent FCC catalysts offer a cost-effective alternative, and basic oxides (CaO) are crucial for neutralizing HCl in PVC feedstocks. Performance relies on two factors: Pore Structure and Acidity. Microporous catalysts (<2nm) favor light olefins via shape selectivity, whereas mesoporous materials allow bulky chain diffusion. Chemically, Brønsted acid sites drive the primary C-C cracking (often increasing gas yield), while Lewis sites influence coke formation; a balanced distribution is essential for optimizing liquid fuel production. A summery was concluded in Table 3 and Figure 7.

Table 3. Catalytic Influence on Plastic Pyrolysis

Catalyst Property	**Variation**	**Impact on Pyrolysis Process**	**Reference**
Catalyst Type	ZSM-5	High aromatics, low coke, high gas yield.	(Dong et al., 2022)
	Y-Zeolite	High conversion of heavy waxes, faster deactivation.	(Miandad et al., 2016)
	FCC	Cost-effective, moderate liquid yield, higher coke.	(Mangesh et al., 2019)
	Basic (CaO)	Neutralizes HCl (from PVC), low cracking activity.	(Peng et al., 2022)
Pore Structure	Microporous	Shape selective for light olefins/aromatics.	(Al-Salem et al., 2017)
	Mesoporous	Better diffusion for bulky polymers, higher liquid yield.	(Peng et al., 2022)
Acidity	High Acidity	Intense cracking ➔ High Gas, Low Liquid.	(Miandad et al., 2019)
	Mild Acidity	Moderate cracking ➔High Liquid (Diesel range).	(Lopez-Urionabarrenechea, 2011)

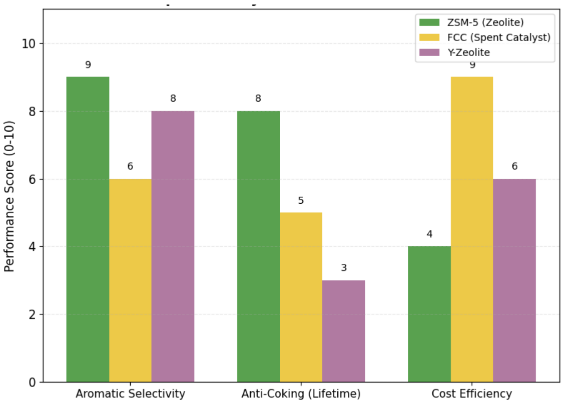


Figure 7. Catalyst Performance Trade-offs.

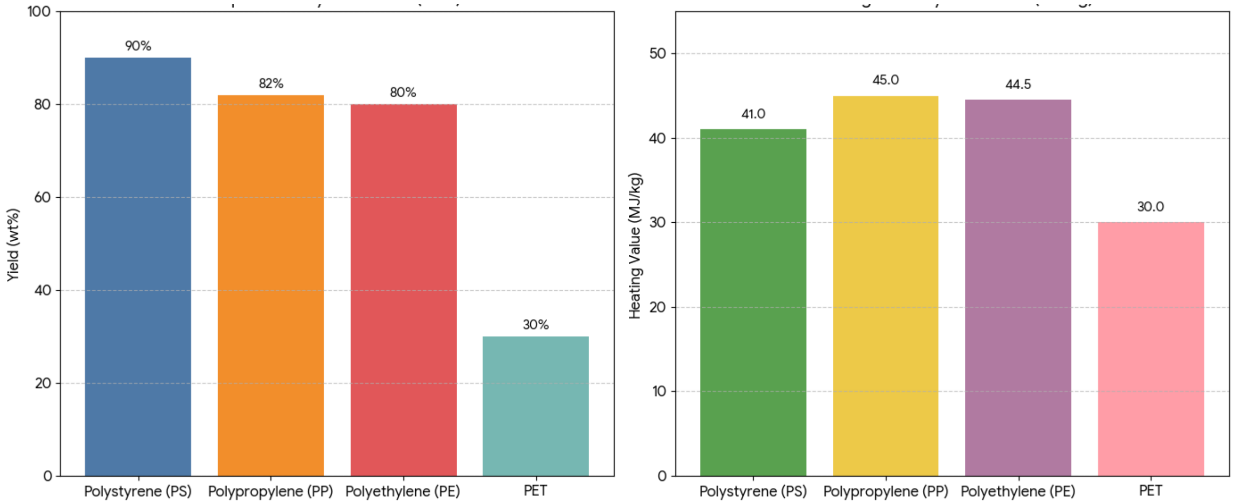
3.4 Output Characteristics in Plastic Pyrolysis

The commercial viability of plastic pyrolysis is fundamentally determined by the quantity and quality of its output. The distribution of products specifically the liquid oil yield, its chemical composition (aromatic vs. aliphatic balance), and its energy density (heating value) varies significantly based on the plastic feedstock and the specific process conditions employed (Figure 8).

- **Liquid Yield:**
  - **Polystyrene (PS):** Highest efficiency (>90% yield) due to easy depolymerization into monomers (Miandad, 2017).
  - **Polyolefins (PE, PP):** High yields (80–90%). PP cracks easily; PE tends to form solid waxes requiring catalytic upgrading (Jahirul, 2022).
  - **PET:** Poor fuel source (<40% liquid), yielding mostly gas/char and clogging systems with benzoic acid.
- **Chemical Composition:**
  - **Thermal Mode:** PE/PP produce aliphatic chains (waxes/alkanes), while PS produces aromatics (styrene).
  - **Catalytic Mode:** Catalysts like ZSM-5 significantly shift products toward aromatics (BTX), reducing wax and increasing fuel octane (Dong et al., 2022).
- **Heating Value (HHV):**
  - **High Quality:** PP (~46 MJ/kg) and PS (~40-42 MJ/kg) are comparable to commercial diesel/gasoline.
  - **Low Quality:** PET and PVC are inferior (<30 MJ/kg) due to high oxygen and chlorine content.

Table 4. Comparison of Output Characteristics in Plastic Pyrolysis

Feedstock	**Liquid Yield (wt%)**	**Primary Chemical Composition**	**Heating Value (MJ/kg)**	**Reference**
Polystyrene (PS)	> 90%	Aromatic (Styrene monomer)	~ 40 - 42	(Miandad et al., 2017; Jahirul et al., 2022)
Polyethylene (PE)	~ 80% (High Wax)	Aliphatic (Alkanes/Alkenes)	~ 43 - 46	(Jahirul et al., 2022; Supriyanto et al., 2021)
Polypropylene (PP)	~ 82%	Aliphatic (Branched)	~ 44 - 46	(Mangesh et al., 2019; Jahirul et al., 2022)
PET	< 30%	Oxygenated (Benzoic acid)	< 30	(Peng et al., 2022; Jahirul et al., 2022)
PVC	Low liquid	Chlorinated hydrocarbons	Low	(Peng et al., 2022)
Catalytic PE/PP	Lower liquid, higher gas	Increased Aromatics (BTX)	High	(Dong et al., 2022; Miandad et al., 2016)



(a) (b)

Figure 8. Comparison of (a) Liquid Yield & (b)Heating Value.

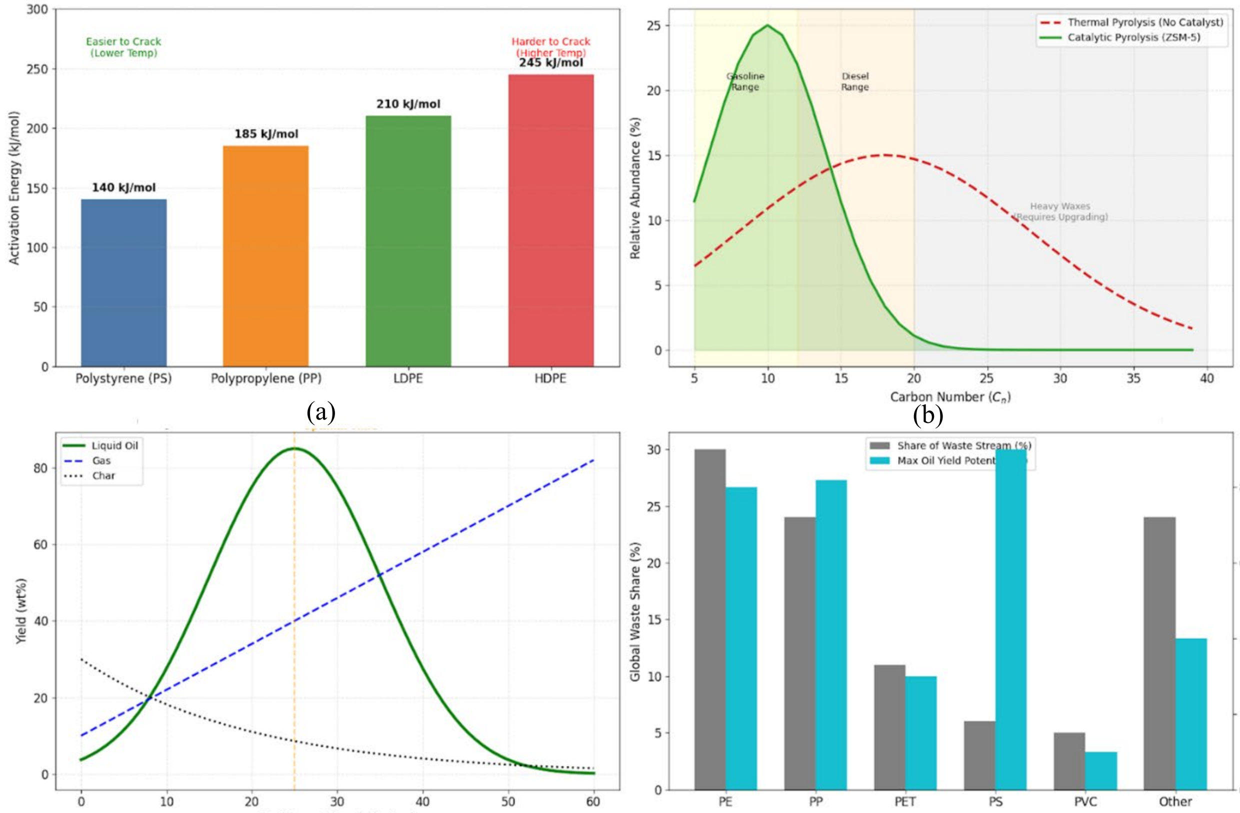
3.5 Engine Performance Indicators in Plastic Pyrolysis

Engine performance indicators, such as ignition delay, heat release rate, and emission characteristics, are critical factors for evaluating the combustibility and efficiency of pyrolysis-derived fuels.

- **Ignition Delay:**
  - **Aromatic (PS/PET):** Exhibit long ignition delays due to the high activation energy required to break stable aromatic bonds (Saxena, 2024).
  - **Aliphatic (PE/PP):** Ignite rapidly (short delay) due to simpler alkane structures, making them compatible with standard ignition systems (Armenise et al., 2021).
- **Heat Release Rate (HRR):**
  - **Aromatic:** Produces high peak HRR for increased power, but rapid energy release risks engine knock and thermal damage.
  - **Aliphatic:** Offers a lower, more stable HRR, ensuring smooth combustion and efficiency under continuous operation (Jha & Kannan, 2020).
- **Emissions:**
  - **Aromatic:** High production of CO, Unburned Hydrocarbons (UHC), and NOx due to incomplete combustion and high peak temperatures.
  - **Aliphatic:** significantly cleaner combustion with lower CO and UHC, though NOx may still form at high loads (Saxena, 2024).

Table 5. Comparison of Engine Performance Indicators for Plastic Pyrolysis Fuels

Performance Indicator	Aromatic Polymers (PS, PET)	Aliphatic Polymers (PE, PP)	Reference
Ignition Delay	Longer delay due to aromatic content	Shorter delay, simpler structure	Kiran et al., 2000; Saxena, 2024
Heat Release Rate (HRR)	Higher HRR, rapid energy release	Lower HRR, stable combustion	Jha & Kannan, 2020; Armemise et al., 2021
Emission Characteristics	Higher CO, UHC, and NOx emissions	Lower CO, UHC, and NOx emissions	Saxena, 2024; Jha & Kannan, 2020



(a) (b)

(c) (d)

Figure 9 (a) Activation Energy, E_a Requirements, (b) Carbon Number Distribution (Fuel Quality), (c) Effect of Residence Time on Yield, (d) Waste Availability vs. Conversion Efficiency

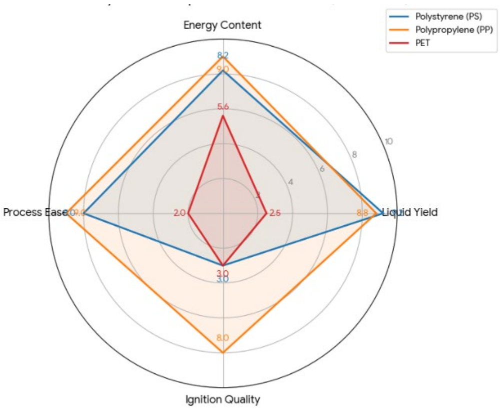
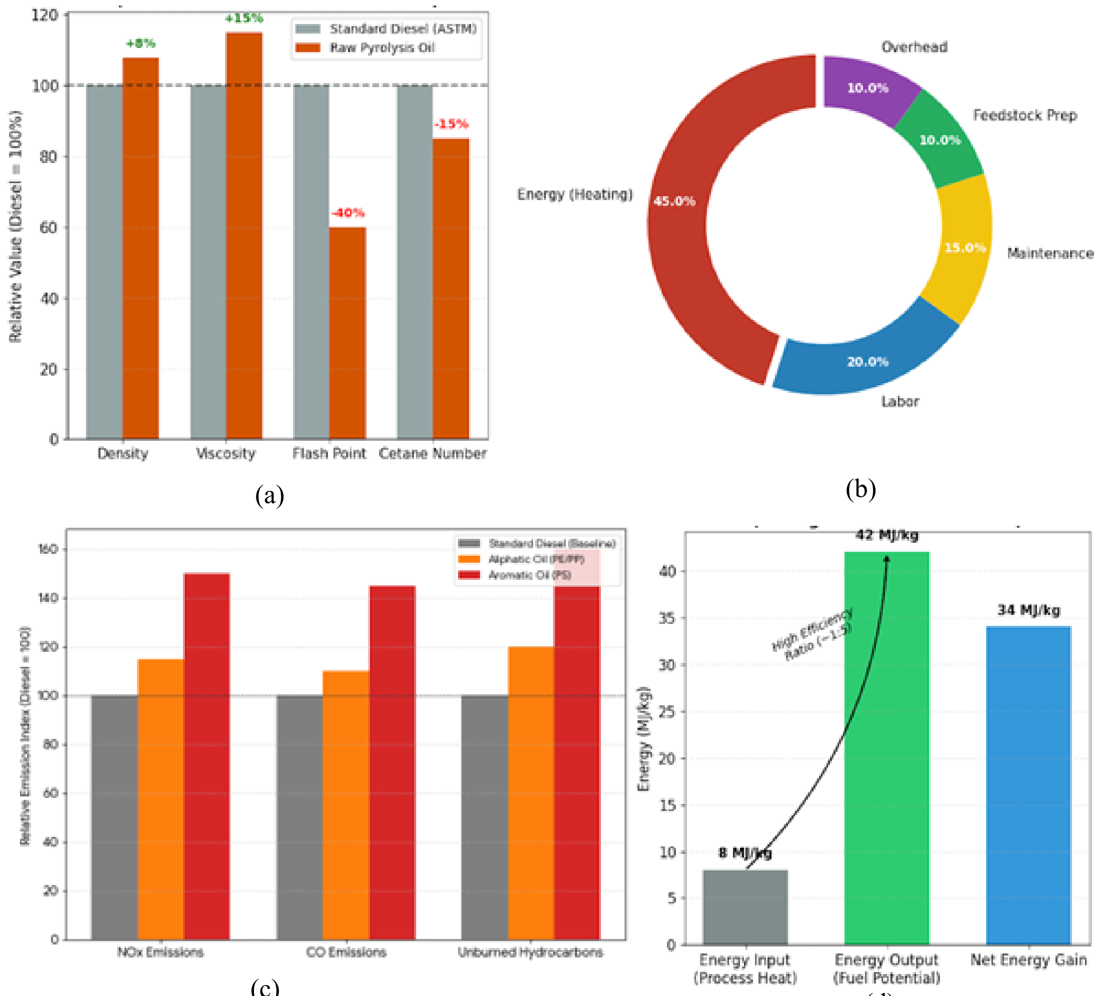


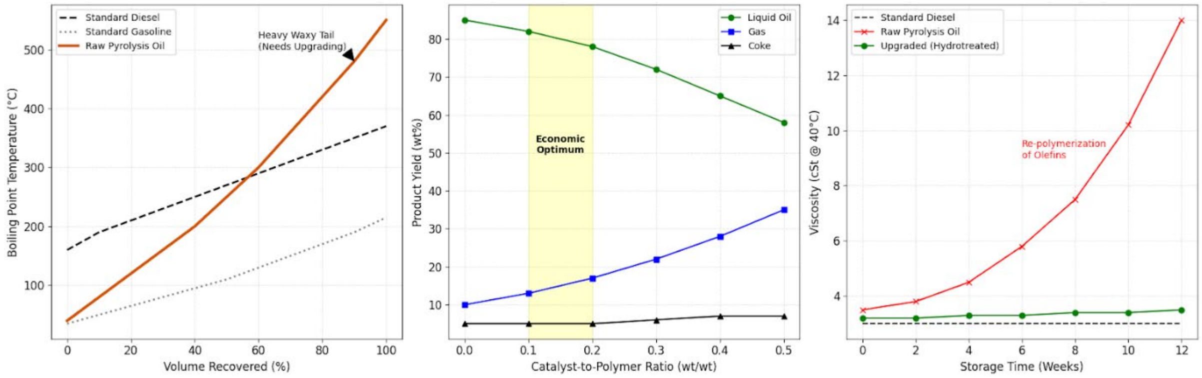
Figure 10. Fuel Viability Index



(a) (b)

(c) (d)

Figure 11. (a) Physicochemical Properties (Quality Check), (b) Operational Cost Distribution (Economics), (c) Relative Emission Profile, (d) Process Energy Balance (Efficiency).



(a) (b) (c)

Figure 12. (a) Distillation Curve (ASTM D86 Comparison), (b) Impact of Catalyst-to-Polymer (C/P) Ratio,(c) Fuel Stability (Aging Effect)

Figure 9 illustrates the critical kinetic relationship between the duration vapors spend in the reactor and the final product distribution. The graph demonstrates a clear "optimal window" around 25 minutes where liquid oil production peaks. Beyond this point, the curve reveals a sharp decline in liquid yield accompanied by a simultaneous spike in gas production. This phenomenon is scientifically attributed to "secondary cracking," where valuable long-chain oil molecules, if left exposed to heat for too long, thermally decompose further into non-condensable gases like methane and ethane. Therefore, the Figure 9 underscores the necessity of precise time management to maximize fuel output and prevent over-cracking. Figure 10 compares the market reality of plastic waste against the technical reality of fuel potential. It highlights a strategic disconnect: while Polystyrene (PS) offers the highest individual conversion efficiency (exceeding 90% liquid yield), it represents a very small fraction of the global waste stream (~6%). In contrast, Polyethylene (PE) dominates the waste stream (~30%) while still maintaining a high oil yield potential (~80%). The Figure leads to the conclusion that commercial scalability depends on optimizing the process for PE, the "workhorse" feedstock, rather than chasing the higher yields of the scarcer PS, while also illustrating that ubiquitous plastics like PET are largely unsuitable for pyrolysis due to their low oil potential (<30%).

Figure 11 benchmarks raw pyrolysis oil against standard commercial diesel, visualizing the quality gap that exists before upgrading. The data indicates that raw pyrolysis oil significantly deviates from the diesel baseline (set at 100%), specifically showing higher density and viscosity, which can strain fuel injection systems. Most critically, the Figure 11 highlights a dangerously low Flash Point (~60% of diesel's value), indicating that the raw oil is far more volatile and presents a higher fire risk during storage. This visual comparison confirms that raw pyrolysis oil is not a direct "drop-in" fuel and requires post-processing or blending to correct these stability and safety parameters. Figure 12 reveals the financial structure of a pyrolysis plant, identifying energy consumption as the dominant operational expenditure (OpEx). The chart shows that approximately 45% of running costs are attributed solely to heating the reactor to 500°C. This visualization provides a crucial economic insight: for a plant to be profitable, it cannot rely on purchased electricity or natural gas for heat. Instead, the facility must be designed to be self-sustaining, capturing the non-condensable gas by-product shown in Figure 9 and recirculating it to fuel the furnace, thereby offsetting the largest cost driver.

4. Conclusion

This study confirms that thermal and catalytic pyrolysis is a viable techno-economic solution for converting waste plastic into high-energy liquid fuel. The comparative analysis identifies Polypropylene (PP) and Polystyrene (PS) as optimal feedstocks; PS yields the highest liquid conversion (>90 wt%), while PP produces fuel with an energy density (~46 MJ/kg) surpassing commercial diesel. Conversely, PET and PVC are deemed unsuitable due to low yields and hazardous contaminants. Process optimization analysis establishes that maintaining reactor temperatures between 500°C and 550°C, alongside precise residence time management, is critical to maximizing yield and preventing secondary cracking. Furthermore, catalytic upgrading with ZSM-5 is essential to refine the hydrocarbon structure, reducing wax content and improving engine compatibility. However, raw pyrolysis oil exhibits limitations, including high viscosity and a low flash point (~60% of diesel), necessitating blending with standard diesel or hydrotreating to meet safety standards. Economically, the study reveals that reactor heating accounts for ~45% of operational costs. Consequently, commercial viability depends on adopting a self-sustaining model that recirculates non-condensable gas by-products to fuel the system, thereby offsetting the primary energy expenditure.

Funding Statement

This project did not receive any external financial support; it was fully funded by the authors.

References

Ahmad, I., Khan, M. I., Khan, H., Ishaq, M., Tariq, R., Gul, K. and Ahmad, W., Pyrolysis study of polypropylene and polyethylene into premium oil products, International Journal of Green Energy, vol. 12, no. 7, pp. 663-671, 2015.

Al-Salem, S. M., Antelava, A., Constantinou, A., Manos, G. and Dutta, A., A Review on Thermal and Catalytic Pyrolysis of Plastic Solid Waste (PSW), Journal of Environmental Management, vol. 197, pp. 177-198, 2017.

Armenise, S., Wong, S. L., Ramírez-Velásquez, J. M., Launay, F., Wuebben, D., Ngadi, N., Rams, J. and Muñoz, M., Plastic waste recycling via pyrolysis: A bibliometric survey and literature review, Journal of Analytical and Applied Pyrolysis, vol. 158, no. 105265, 2021.

Armenise, S., Wong, S., Ramírez-Velásquez, J. M., Launay, F., Wuebben, D., Nyakuma, B. B., Rams, J. and Muñoz, M., Application of computational approach in plastic pyrolysis kinetic modelling: a review, Reaction Kinetics, Mechanisms and Catalysis, vol. 132, pp. 591-614, 2021.

Bockhorn, H., Hentschel, J., Hornung, A. and Hornung, U., Environmental engineering: Stepwise pyrolysis of plastic waste, Chemical Engineering Science, vol. 54, no. 15-16, pp. 3043-3051, 1999.

Burra, K. G. and Gupta, A. K., Kinetics of synergistic effects in co-pyrolysis of biomass with plastic wastes, Applied Energy, vol. 220, pp. 408-418, 2018.

Çepelioğullar, Ö. and Pütün, A. E., Thermal and kinetic behaviors of biomass and plastic wastes in co-pyrolysis, Energy Conversion and Management, vol. 75, pp. 263-270, 2013.

Cunliffe, A. M., Jones, N. and Williams, P. T., Pyrolysis of composite plastic waste, Environmental Technology, vol. 24, no. 5, pp. 653-663, 2003.

Dai, L., Zhou, N., Lv, Y., Cheng, Y., Wang, Y., Liu, Y., Cobb, K., Chen, P., Lei, H. and Ruan, R., Pyrolysis technology for plastic waste recycling: A state-of-the-art review, Progress in Energy and Combustion Science, vol. 93, no. 101021, 2022.

Dong et al., S., Li, H., Bloede, I. K., Al Abdulghani, A. J., Lebrón-Rodríguez, E. A., Huber, G. W. and Hermans, I., Catalytic Conversion of Model Compounds of Plastic Pyrolysis Oil over ZSM-5, Journal of Catalysis, vol. 405, pp. 10-23, 2022.

Encinar, J. M. and González, J. F., Pyrolysis of synthetic polymers and plastic wastes. Kinetic study, Fuel Processing Technology, vol. 89, no. 7, pp. 678-686, 2008.

Ephraim, A., Pham Minh, D., Lebonnois, D., Peregrina, C., Sharrock, P. and Nzihou, A., Co-pyrolysis of wood and plastics: Influence of plastic type and content on product yield, gas composition and quality, Fuel, vol. 231, pp. 110-117, 2018.

Gao, F., Pyrolysis of Waste Plastics into Fuels, PhD Thesis, University of Canterbury, New Zealand, 2010.

Gracida-Alvarez, U. R., Benavides, P. T., Lee, U. and Wang, M., Life-cycle analysis of recycling of post-use plastic to plastic via pyrolysis, Journal of Cleaner Production, vol. 415, no. 138867, 2023.

Hartulistiyoso, E., Sigiro, F. A. and Yulianto, M., Temperature distribution of the plastics Pyrolysis process to produce fuel at 450°C, Procedia Environmental Sciences, vol. 28, pp. 234-241, 2015.

Jahirul, M. I., Rasul, M. G., Schaller, D., Khan, M. M. K., Hasan, M. M. and Hazrat, M. A., Transport fuel from waste plastics pyrolysis - A review on technologies, challenges and opportunities, Energy Conversion and Management, vol. 258, no. 115451, 2022.

Jha, K. K. and Kannan, T. T. M., Recycling of plastic waste into fuel by pyrolysis – a review, Materials Today: Proceedings, vol. 37, no. 2, pp. 3132-3135, 2021.

Kalargaris, I., Tian, G. and Gu, S., Combustion, performance and emission analysis of a DI diesel engine using plastic pyrolysis oil, Fuel Processing Technology, vol. 157, pp. 108-115, 2017.

Kim, D., Han, M., Kim, N., Kim, J. and Jung, S. P., Waste Plastic Pyrolysis Industry: Current Status and Prospects, Journal of Korean Society of Environmental Engineers, vol. 46, no. 1, pp. 395-407, 2024.

Kiran, N., Ekinci, E. and Snape, C. E., Recyling of plastic wastes via pyrolysis, Resources, Conservation and Recycling, vol. 29, no. 4, pp. 273-283, 2000.

Kulas, D. G., Zolghadr, A., Chaudhari, U. S. and Shonnard, D. R., Economic and Environmental Analysis of Plastics Pyrolysis After Secondary Sortation of Mixed Plastic Waste, Journal of Cleaner Production, vol. 369, no. 131442, 2022.

Kumagai, S. and Yoshioka, T., Feedstock Recycling via Waste Plastic Pyrolysis, Journal of the Japan Petroleum Institute, vol. 59, no. 6, pp. 243-253, 2016.

López Urionabarrenechea, A., Chemical Recycling of Municipal Packaging Waste by Pyrolysis, PhD Thesis, University of the Basque Country, Spain, 2011.

Mangesh, V. L., Padmanabhan, S., Tamizhdurai, P. and Ramesh, A., Experimental investigation to identify the type of waste plastic pyrolysis oil suitable for conversion to diesel engine fuel, Journal of Cleaner Production, vol. 246, no. 119066, 2020.

Miandad, R., Barakat, M. A., Aburiazaiza, A. S., Rehan, M. and Nizami, A. S., Catalytic pyrolysis of plastic waste: A review, Process Safety and Environmental Protection, vol. 102, pp. 822-838, 2016.

Miandad, R., Barakat, M. A., Aburiazaiza, A. S., Rehan, M., Ismail, I. M. I. and Nizami, A. S., Effect of plastic waste types on pyrolysis liquid oil, International Biodeterioration & Biodegradation, vol. 119, pp. 239-252, 2017.

Miandad, R., Rehan, M., Barakat, M. A., Aburiazaiza, A. S., Khan, H., Ismail, I. M. I., Dhavamani, J., Gardy, J., Hassanpour, A. and Nizami, A. S., Catalytic Pyrolysis of Plastic Waste: Moving Toward Pyrolysis Based Biorefineries, Frontiers in Energy Research, vol. 7, no. 27, 2019.

Papuga, S. V., Gvero, P. M. and Vukić, L. M., Temperature and time influence on the waste plastics pyrolysis in the fixed bed reactor, Thermal Science, vol. 20, no. 2, pp. 731-741, 2016.

Paradela, F., Pinto, F., Gulyurtlu, I., Cabrita, I. and Lapa, N., Study of the co-pyrolysis of biomass and plastic wastes, Clean Technologies and Environmental Policy, vol. 11, pp. 115-122, 2009.

Peng, Y., Wang, Y., Ke, L., Dai, L., Wu, Q., Cobb, K., Zeng, Y., Zou, R., Liu, Y. and Ruan, R., A review on catalytic pyrolysis of plastic wastes to high-value products, Energy Conversion and Management, vol. 254, no. 115243, 2022.

Qureshi, M. S., Oasmaa, A., Pihkola, H., Deviatkin, I., Tenhunen, A., Mannila, J., Minkkinen, H., Pohjakallio, M. and Laine-Ylijoki, J., Pyrolysis of plastic waste: Opportunities and challenges, Journal of Analytical and Applied Pyrolysis, vol. 152, no. 104804, 2020.

Saxena, S., Pyrolysis and beyond: Sustainable valorization of plastic waste, Applications in Energy and Combustion Science, vol. 18, no. 100311, 2025.

Seah, C. C., Tan, C. H., Arifin, N. A., Hafriz, R. S. R. M., Salmiaton, A., Nomanbhay, S. and Shamsuddin, A. H., Co-pyrolysis of biomass and plastic: Circularity of wastes and comprehensive review of synergistic mechanism, Results in Engineering, vol. 20, no. 100989, 2023.

Shah, H. H., Amin, M., Iqbal, A., Nadeem, I., Kalin, M., Soomar, A. M. and Galal, A. M., A review on gasification and pyrolysis of waste plastics, Frontiers in Chemistry, vol. 11, no. 960894, 2023.

Sogancioglu, M., Ahmetli, G. and Yel, E., A Comparative Study on Waste Plastics Pyrolysis Liquid Products Quantity and Energy Recovery Potential, Energy Procedia, vol. 118, pp. 221-226, 2017.

Sophonrat, N., Sandström, L., Zaini, I. N. and Yang, W., Stepwise pyrolysis of mixed plastics and paper for separation of oxygenated and hydrocarbon condensates, Applied Energy, vol. 229, pp. 314-325, 2018.

Supriyanto, Ylitervo, P. and Richards, T., Gaseous products from primary reactions of fast plastic pyrolysis, Journal of Analytical and Applied Pyrolysis, vol. 157, no. 105248, 2021.

Williams, E. A. and Williams, P. T., The Pyrolysis of Individual Plastics and a Plastic Mixture in a Fixed Bed Reactor, Journal of Chemical Technology and Biotechnology, vol. 70, no. 1, pp. 9-20, 1997.

Wu, C. and Williams, P. T., Pyrolysis-gasification of plastics, mixed plastics and real-world plastic waste with and without Ni-Mg-Al catalyst, Fuel, vol. 89, no. 10, pp. 3022-3032, 2010.

Biographies

Khalid Mahmud Saifullah received his B.Sc. in Mechanical Engineering from Khulna University of Engineering and Technology (KUET), Khulna, Bangladesh. He is presently enrolled in the M.Sc. program in Mechanical Engineering at Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh. His research interests include heat transfer, thermal management in electronics, and simulation of complex fluid systems.

Aniruddha Roy Protya completed his B.Sc. in Mechanical Engineering from Khulna University of Engineering and Technology (KUET), Khulna, Bangladesh. He is currently pursuing his Master of Science (M.Sc.) in Mechanical Engineering at Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh. His research focuses on thermal systems, renewable energy, energy efficiency, and fluid flow analysis using CFD techniques.

Md Ashfak Hossain obtained his B.Sc. in Mechanical Engineering from Khulna University of Engineering and Technology (KUET), Khulna, Bangladesh. He is currently a graduate student in the M.Sc. Mechanical Engineering program at Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh. His academic pursuits are centered on thermal engineering, porous media flows, and advanced cooling technologies.

MD. Alifur Rahman earned his Bachelor of Science (B.Sc.) degree in Electrical and Electronic Engineering from Khulna University of Engineering and Technology (KUET), Khulna, Bangladesh. Currently he is working as Customer Service Engineer at GE Healthcare. His research interests include solar PV system, renewable energy and energy conversion.