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PLASTOFUEL: Converting Plastic Waste into Petrol via Pyrolysis

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Abstract: *The escalating accumulation of plastic waste poses a pressing environmental and resource challenge, prompting the need for sustainable conversion technologies. Pyrolysis has emerged as a promising thermochemical route for transforming waste plastics into liquid fuels with potential to partially replace conventional fossil-derived fuels. This research synthesis provides a comprehensive investigation of the latest advances in thermo-catalytic pyrolysis of plastic waste for liquid fuel generation, with emphasis on process parameters, catalyst development, and fuel quality characteristics. The analysis of 30+ recent studies reveals that catalytic pyrolysis consistently delivers higher-quality liquid fuels, with yield improvements exceeding 20% over non-catalytic processes. The optimal pyrolysis temperature ranges from 300-380°C, and the resulting fuels exhibit physico-chemical properties comparable to conventional petrol and diesel. This paper offers valuable insights into the potential of thermo-catalytic pyrolysis as an emerging strategy for plastic waste management and sustainable fuel production.*

Keywords: plastic waste, pyrolysis, petrol conversion, catalysts, thermochemical conversion, fuel production, waste-to-energy

I. INTRODUCTION

1.1 Background and Problem Statement

Plastic consumption and production have been increasing exponentially since the first commercial production in the 1950s. Currently, over 100 million tons of plastics are produced annually worldwide, with approximately 4% of global oil and gas production being used as feedstock for plastics and 3-4% used to provide energy for their manufacture (Kabeyi & Olanrewaju, 2023). This massive production has led to unprecedented accumulation of plastic waste in landfills, oceans, and ecosystems globally, creating a severe environmental crisis.

The widespread use of plastics has led to increased consumption of fossil fuels and worsened pollution, especially in marine environments (Marhaini et al., 2024). Common waste management methods like landfills and incinerators present significant environmental challenges. For instance, incineration releases harmful gases such as carbon monoxide (CO), carbon dioxide (CO_2), ammonia (NH_3), nitrous oxide (N_2O), and nitrogen oxides (NO_x), significantly contributing to greenhouse gas emissions. Burning one ton of waste can produce at least 700 kg of CO_2 (Marhaini et al., 2024).

1.2 The Pyrolysis Solution

Pyrolysis—the thermal decomposition of organic compounds through intense heating in a minimum oxygen environment—presents a technically and economically feasible alternative for waste plastic recycling (Kabeyi & Olanrewaju, 2023). Unlike incineration, pyrolysis converts plastic waste into valuable products without producing hazardous emissions. The process offers a dual solution: addressing the twin problem of plastic waste disposal while simultaneously producing alternative fuels to address the depletion of fossil fuel reserves.

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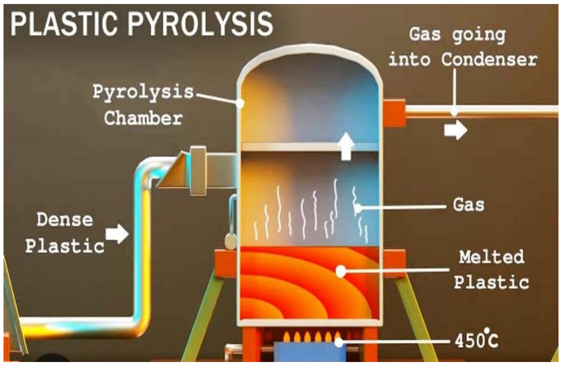

1.3 Research Objectives

This comprehensive review synthesizes recent research advances to:

Examine the fundamental mechanisms and technical parameters of plastic waste pyrolysis
Analyze the role and effectiveness of various catalysts
Evaluate fuel quality characteristics and engine compatibility
Assess environmental and economic sustainability
Identify challenges and future research directions

II. PYROLYSIS PROCESS FUNDAMENTALS

2.1 Process Definition and Mechanism

Pyrolysis is a thermochemical process that converts plastic polymers into simpler compounds in the absence of oxygen (Sugiarto et al., 2020). The process breaks down long-chain polymer molecules through thermal cracking at high temperatures, resulting in liquid, gaseous, and solid products. The calorific value of plastic is almost identical to that of hydrocarbon fuel, making this option an attractive alternative for energy recovery (Kabeyi & Olanrewaju, 2023).

2.2 Operating Parameters

The pyrolysis process is influenced by multiple critical parameters that significantly impact feed reactivity, product yield, and carbon number distribution (Valizadeh et al., 2024):

Temperature: Temperature is the most critical parameter affecting pyrolysis efficiency. Research indicates that the optimal pyrolysis temperature typically ranges from 300-380°C (Tambunan et al., 2024), (Yulistianto et al., 2025). However, different plastic types exhibit varying optimal temperatures. For polypropylene (PP), the fastest oil production was achieved at 450°C in 300 minutes, while high-density polyethylene (HDPE) reached optimal oil yield at 330°C in 330 minutes (Herraprastanti et al., 2024).

Residence Time: The duration of residence time in the reactor significantly affects product composition and yield. Longer residence times generally increase oil production up to an optimal point, beyond which increased residence time provides minimal yield improvements (Valizadeh et al., 2024).

Heating Rate: The rate at which temperature increases affects the degradation pathway and product selectivity. Controlled heating rates can optimize the production of desired fuel fractions (Valizadeh et al., 2024).

Reactor Type and Design: Different reactor configurations—batch, continuous, fluidized bed—influence heat transfer efficiency and product distribution. Reactor design innovations, including adsorbents such as lime ($CaCO_3$) and iron fiber (Fe_2O_3), can improve liquid fuel yields up to 86.40% (Aswan et al., 2020).

Pyrolysis Medium: The atmospheric conditions during pyrolysis, including the use of inert gases and vacuum conditions, can optimize product yields and quality (Valizadeh et al., 2024).

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2.3 Thermal vs. Catalytic Pyrolysis

Research comparing thermal and catalytic pyrolysis demonstrates significant differences in efficiency and product quality. In thermal pyrolysis without catalysts, polypropylene waste produced 83.10 cm^3 of oil (41.55% yield) at 300°C and 3 hours reaction time (Ezeokolie et al., 2025). When the same process was conducted using aluminum chloride on activated carbon catalyst, oil production increased to 108.46 cm^3 (54.23% yield) at 300°C but requiring only 2 hours reaction time.

This enhancement occurs because catalytic pyrolysis shifts the pyrolysis mechanism from the conventional free radical mechanism towards the carbonium ion mechanism, altering kinetics and pathways (Valizadeh et al., 2024). The introduction of either acid or base catalysts fundamentally changes how plastic polymers break down, resulting in higher liquid fuel yields with improved quality.

III. PLASTIC FEEDSTOCK CHARACTERISTICS

3.1 Types of Plastics Studied

Research has focused primarily on the most commonly generated plastics:

Polyethylene (PE): Both low-density polyethylene (LDPE) and high-density polyethylene (HDPE) have been extensively studied. LDPE pyrolysis using titanium dioxide catalyst at 350°C with 37.5g catalyst produced fuel with calorific value of 36.1698 MJ/kg and flash point of 34°C (Marhaini et al., 2024). The gas chromatography analysis showed the fuel consisted of 49.41% gasoline, 10.56% kerosene-diesel, and 40.03% fatty acids.

Polypropylene (PP): This plastic type has demonstrated excellent conversion characteristics. PP waste converted through pyrolysis produces oil with properties similar to diesel, including comparable cetane numbers and viscosity characteristics (Banurea et al., 2024).

Mixed Plastic Waste: Most practical applications involve mixed plastic waste streams. A study using mixed plastic composition of 30% PP and 70% LDPE with kaolin catalyst addition produced oil equivalent to gasoline with an octane rating of 88 (Yulistianto et al., 2025).

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3.2 Feedstock Preprocessing

Most research indicates that plastic waste can be directly fed to pyrolysis reactors without extensive pretreatment (Kabeyi & Olanrewaju, 2023). However, optimal results are achieved when plastic waste is shredded to appropriate sizes (4-9 cm^2) to facilitate efficient heating and decomposition (Sugiarto et al., 2020).

IV. CATALYST DEVELOPMENT AND MECHANISMS

4.1 Catalytic Materials

Recent research has identified and tested numerous catalytic materials for enhanced pyrolysis performance:

Zeolite Catalysts: ZSM-5 zeolite catalysts have proven particularly effective. The synthesized ZSM-5 zeolite catalyst produced a maximum oil output of 70% and corresponding gas and char of 16% and 14% for LDPE plastic (Sivagami et al., 2022). The strong acidic properties and microporous crystalline structure of ZSM-5 enables increased cracking and isomerization, leading to breakup of larger molecules into smaller molecules, forming more oil yield.

Commercial ZSM-5 was compared with lab-synthesized versions, and Philippine natural zeolite (PNZ) containing clinoptilolite, mordenite, and heulandite also proved viable. Non-catalytic pyrolysis of PP yielded an average of 75.03% liquid oil, but catalytic pyrolysis with PNZ produced higher yields of 86.39% liquid oil (Bautista et al., 2024).

Metal Oxide Catalysts: Titanium dioxide (TiO_2) catalysts derived from minerals like ilmenite, rutile, and anatase have shown promise in enhancing LDPE pyrolysis. TiO_2 helps stabilize heterogeneous catalysts and improves efficiency of plastic degradation while reducing necessary temperatures (Marhaini et al., 2024).

Composite Catalysts: Nickel-Calcium oxide (Ni-CaO) catalysts have been applied in co-pyrolysis studies. Bio-oil obtained from oil palm frond pretreated with 70% formic acid, with 50:50 oil palm frond to LDPE ratio, and 15% Ni-CaO catalyst addition yielded 49.6% with calorific value of 31.732 MJ/kg (Sunarno et al., 2024).

4.2 Catalyst Performance and Mechanisms

Analysis of research reveals that catalytic pyrolysis consistently delivers higher-quality liquid fuels, with several studies reporting yield improvements exceeding 20% over non-catalytic processes (Muhammad & Mohamad, 2025). The mechanisms underlying this improvement include:

Enhanced Cracking: Catalysts facilitate the breaking of C-C bonds in long polymer chains

Isomerization: Catalysts promote molecular rearrangement for optimal fuel properties

Reduced Coking: Catalysts minimize undesirable char formation

Lower Temperature Requirements: Catalytic processes achieve equivalent results at lower temperatures than thermal-only approaches

V. FUEL PRODUCTION AND YIELD OPTIMIZATION

5.1 Yield Performance

The yield of liquid fuel from plastic waste pyrolysis varies based on operating conditions and plastic feedstock composition. Key findings include:

Optimal Temperature Performance: Research testing at multiple temperature intervals (200-400°C) found that 300°C represents an optimal balance, producing maximum oil yield with minimal temperature increase afterward (Tambunan et al., 2024). However, other studies suggest that 350°C (Aswan et al., 2020) and 380°C (Yulistianto et al., 2025) may provide superior yields with enhanced fuel quality.

Fuel Separation: After pyrolysis, distillation of the crude oil product effectively separates different fuel fractions. One study distilled 2000 grams of pyrolysis oil by gradually increasing temperature from 100 to 300°C, resulting in 1520 grams (79.17%) gasoline equivalent fraction, 320 grams (16.67%) diesel fraction, and 80 grams (4.17%) residual oil (Tambunan et al., 2024).

Waste Reduction: Pyrolysis processes can reduce waste volume by up to 90% while creating an alternative fuel with high economic value (Yulistianto et al., 2025).

5.2 Fuel Quality Characteristics

The resulting pyrolysis oil demonstrates physico-chemical properties comparable to conventional fossil fuels:

Gasoline-Equivalent Fuel: Distilled waste plastic pyrolysis oil produced from clay catalyst exhibited kinematic-viscosity of 6.4 × 10^{-7} m²/s and caloric-value of 47.82 MJ/kg, with chemical composition closely resembling pure gasoline, particularly in the temperature range of 90°C-180°C (Musongwa et al., 2024).

Diesel-Equivalent Fuel: Distilled plastic fuel from non-catalytic pyrolysis demonstrated heating values of approximately 43.362 to 44.364 MJ/kg, with chemical properties and composition similar to diesel fuel (Daryanto et al., 2024).

Viscosity Characteristics: Pyrolyzed PP oil exhibits average viscosity of approximately 4.25 cSt compared to diesel, while HDPE oil averages about 3.3725 cSt (Banurea et al., 2024). Compared to gasoline, average viscosity values are 0.603 cSt for PP and 0.5965 cSt for HDPE, suggesting that both oils have viscosities similar to petrol.

VI. ENGINE PERFORMANCE AND APPLICATION

6.1 Internal Combustion Engine Compatibility

Extensive research has evaluated the performance of engines using pyrolysis-derived fuels. Key findings demonstrate practical viability:

Gasoline Engine Performance: A 50% distilled waste plastic pyrolysis oil and 50% gasoline blend (D50WPPO) significantly improved brake power and brake thermal efficiency while reducing brake specific fuel consumption (Musongwa et al., 2024). Unburned hydrocarbon emissions were reduced by 40% when engines were fueled with D50WPPO.

Diesel Engine Performance: Using a 50% diesel, 45% biodiesel from waste cooking oil, and 5% plastic pyrolysis oil blend (DW50P5), engines achieved superior performance at 1000 RPM with torque of 5.36 N·m and thermal efficiency of 14.75%, compared to pure diesel (B0) which showed torque of 2.53 N·m and thermal efficiency of 8.49% (Suardi et al., 2025).

Emission Characteristics: The optimal fuel mixture of 20% plastic pyrolysis fuel with 80% RON 90 provided best performance at medium to high engine speeds (3000–6000 rpm) with low CO emissions (Susilo et al., 2024). The PE-RON 90 30:70 blend showed the lowest CO at 0.78% at 6000 rpm and consistently reduced HC emissions across the rpm range.

6.2 Engine Modification Requirements

A significant finding is that distilled waste plastic pyrolysis oil can potentially be employed as a substitute for conventional gasoline without any engine modifications (Musongwa et al., 2024). This substantially reduces implementation barriers for practical adoption.

VII. ENVIRONMENTAL AND ECONOMIC ASSESSMENT

7.1 Environmental Benefits

The conversion of plastic waste to fuel offers substantial environmental benefits:

Greenhouse Gas Emission Reduction: In a comprehensive Ukrainian study, it was found that from an average of 1,444 thousand tons/year of plastic waste generated annually, approximately 838 thousand tons/year of alternative fuel can be obtained through pyrolysis (Boichenko et al., 2025). Direct CO_2 emissions from the pyrolysis process are 361 thousand tons/year. Critically, in a substitution scenario where pyrolysis replaces incineration, it is possible to avoid 21,154.2 thousand tons of CO_2-eq./year, and replacing landfilling could avoid 19,623.6 thousand tons of CO_2-eq./year.

Waste Volume Reduction: Pyrolysis can reduce waste plastic volume by up to 90%, substantially decreasing landfill burden and environmental pollution (Yulistianto et al., 2025).

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Avoided Incineration Emissions: Traditional incineration of one ton of plastic waste produces at least 700 kg of CO_2, along with harmful pollutants like CO, NH_3, N_2O, and NO_x (Marhaini et al., 2024). Pyrolysis avoids these hazardous emissions.

7.2 Economic Sustainability

Energy Substitution Potential: The produced pyrolysis fuel can replace approximately 13% of annual diesel fuel consumption in regions with high plastic waste generation (Boichenko et al., 2025), significantly reducing energy import dependence.

Return on Investment: Analysis of plastic waste to diesel conversion demonstrates economic viability, with projects showing return on investment potential, though varying by location and scale (Raharjo et al., 2025).

Value-Added Product Creation: Converting waste plastics into fuel transforms a disposal problem into an opportunity for wealth creation. The process creates value-added fuels such as petrol, kerosene, diesel, and lubricating oils (Yakoob et al., 2024).

Cost Efficiency: Compared to other waste management options and alternative fuel production methods, pyrolysis offers competitive cost-effectiveness due to simpler technology compared to alternatives like gasification (Tambunan et al., 2024).

VIII. PROCESS OPTIMIZATION AND CRITICAL FACTORS

8.1 Machine Learning Applications

Recent advances have integrated machine learning into pyrolysis optimization. Research indicates that machine learning methods have been frequently applied to predict, interpret, and optimize plastic waste pyrolysis (Li et al., 2023). These applications include:

Feedstock Classification: Deep learning and computer vision enable precise plastic waste sorting

Process Parameter Optimization: Machine learning predicts optimal pyrolysis conditions for different plastic combinations

Yield Prediction: Algorithms forecast product yields under varying conditions

Reactor Control: Reinforcement learning optimizes process parameters dynamically

8.2 Critical Process Factors

A systematic review identified three key thematic domains for optimization (Muhammad & Mohamad, 2025):

Catalyst Development and Catalytic Mechanisms: Advances in catalyst formulation, active site engineering, and reaction pathway elucidation for enhanced product selectivity

Process Optimization, Kinetics, and Mechanistic Studies: Impact of operating parameters, reactor configurations, and kinetic modeling on maximizing liquid fuel yields and process efficiency

Fuel Production, Engine Application, and Environmental Assessment: Evaluation of fuel quality upgrades, engine performance compatibility, and potential environmental benefits

8.3 Technical Challenges and Solutions

Temperature Control: Consistent temperature maintenance is essential for optimal yields. Solutions include enhanced reactor design with improved insulation and temperature monitoring systems.

Impurity Management: Pyrolysis oil contains impurities requiring purification, esterification, and filtration stages (Susanto et al., 2024).

Catalyst Deactivation: Long-term catalyst performance requires investigation of deactivation mechanisms and catalyst regeneration strategies (Li et al., 2023).

Reactor Scaling: Design of renewable energy supply systems for commercial-scale pyrolysis plants remains an active research area (Li et al., 2023).

IX. CO-PYROLYSIS APPROACHES

9.1 Plastic Waste and Biomass Co-pyrolysis

Combining plastic waste with biomass has demonstrated synergistic effects. Co-pyrolysis of plastic waste and eucalyptus wood waste with molasses binder produced biofuel pellets with enhanced mechanical properties (Samal et al., 2024). The optimized formulation used 16.96% molasses with 28% waste LDPE proportion, achieving improved structural integrity and stable combustion profiles.

9.2 Municipal Waste Integration

Co-pyrolysis integrating municipal and plastic waste demonstrates synergistic advantages, enabling synthesis of renewable fuels and valuable chemical intermediates with optimized product distribution (Razzak, 2024).

X. GLOBAL IMPLEMENTATION AND REGIONAL PERSPECTIVES

10.1 African Context

Africa, with an estimated 25–33% of daily waste composition made up of plastic, faces unique waste management challenges. Pyrolysis offers a promising solution aligned with the African Union's plastic waste recycling goals (Dennison et al., 2025). Case studies from South Africa and Nigeria demonstrate the potential for scaling up pyrolysis to address waste management issues while generating energy and job opportunities. However, the continent faces significant barriers including infrastructural, economic, and social difficulties requiring investment, regulatory support, and public awareness.

10.2 Asian Implementation

Studies from Indonesia demonstrate practical implementation of pyrolysis technology using locally available resources. One project utilized rice husk briquette gasification to provide combustion heat for plastic waste pyrolysis, producing 1.29 liters of fuel oil from 3000g of shredded PP waste with thermal efficiency of 38.60% (Wijianto & Hayatullah, 2024).

10.3 Economic Context: Energy Security

In Ukraine, plastic waste pyrolysis was identified as a strategic solution for reducing fuel import dependence and increasing energy security during challenging times. The analysis demonstrated that domestic plastic waste could provide significant fuel substitution while simultaneously reducing greenhouse gas emissions (Boichenko et al., 2025).

XI. CHALLENGES AND FUTURE DIRECTIONS

11.1 Technical Challenges

Data and Model Development: More efforts are needed in enlarging machine learning datasets, improving model interpretability, and exploring innovative applications of machine learning in pyrolysis optimization (Li et al., 2023).

Catalyst Innovation: Future research should emphasize catalyst synthesis improvements, selection of co-pyrolysis additives, and investigation of catalyst deactivation mechanisms (Li et al., 2023).

Scalability: Designing renewable energy supply systems for commercial-scale pyrolysis plants and achieving economically viable production at scale remain critical challenges.

Product Consistency: Achieving consistent fuel quality and narrow product distribution remains challenging due to variations in feedstock composition (Li et al., 2023).

11.2 Environmental Considerations

Future research should conduct comprehensive life cycle assessments (LCA) and environmental impact evaluations to fully quantify the sustainability benefits of pyrolysis compared to alternative waste management methods (Razzak, 2024).

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Recommended Future Research Directions

Integrative Approaches: Link catalyst innovation, process optimization, and real-world application to achieve scalable, economically viable, and environmentally responsible solutions (Muhammad & Mohamad, 2025)

Diverse Waste Streams: Extend research to waste tires, waste vegetable oils, and animal waste for multi-waste valorization (Boichenko et al., 2025)

AI-Powered Solutions: Develop multi-modal artificial intelligence frameworks to maximize sustainability and commercial viability (Ogundolie et al., 2025)

Circular Economy Integration: Integrate pyrolysis with other waste management techniques and renewable energy sources for comprehensive circular economy implementation (Razzak, 2024)

Policy Development: Establish regulatory frameworks and economic incentives to support commercial deployment of pyrolysis technology globally

XII. CONCLUSION

Pyrolysis has emerged as a highly promising technology for converting plastic waste into valuable liquid fuels with properties comparable to conventional petrol and diesel. Extensive recent research demonstrates that thermo-catalytic pyrolysis, operating at optimal temperatures of 300-380°C with appropriate catalysts, can achieve liquid fuel yields exceeding 70-80%, with significant reductions in waste volume and greenhouse gas emissions.

The research synthesis reveals that catalytic pyrolysis consistently outperforms non-catalytic approaches, with yield improvements often exceeding 20%. The resulting fuels exhibit physico-chemical properties comparable to commercial petrol and diesel, with demonstrated compatibility for use in internal combustion engines, often without requiring engine modifications.

From an environmental perspective, pyrolysis offers substantial benefits, including avoiding 19,600-21,000 thousand tons of CO_2-eq. annually compared to landfilling or incineration alternatives. Economically, the technology can contribute to fuel security by producing alternative fuels from readily available waste streams.

However, challenges remain in scaling production capacity, maintaining product consistency, optimizing catalyst performance, and integrating renewable energy sources for sustainable commercial operations. Future research should emphasize integrative approaches combining catalyst innovation, process optimization, machine learning applications, and real-world implementation strategies.

Despite these challenges, the convergence of technical viability, environmental necessity, and economic potential positions pyrolysis-based plastic waste valorization as a critical technology for achieving circular economy goals and sustainable energy transition. With continued research advancement and policy support, plastofuel conversion technology has the potential to significantly address both plastic waste accumulation and fossil fuel depletion while contributing to global decarbonization objectives.

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