FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 18, September, 2026, pp 85 – 92
DOI: https://doi.org/10.33003/fjs-2026-1018-5626

Experimental Comparison of Catalytic and Non-Catalytic Pyrolysis of Mixed Plastic Waste for Enhanced Pyrolysis Oil Production in a Fixed-Bed Reactor

[1]Onoriode Erhinyodavwe, *[2]Ejiroghene Kelly Orhorhoro and [3]Efe Justic Igbagbon

[1]Department of Mechanical Engineering, Faculty of Engineering, University of Delta, Agbor, Delta State, Nigeria
[2]Department of Mechanical Engineering, College of Engineering, Igbinedion University, Okada, Edo State, Nigeria

*Corresponding authors' email: ejiroghene.orhorhoro@iuokada.edu.ng

Received: 27 Jul. 2026
Accepted: 04 Sep. 2026
Published: 21 Sep. 2026

ABSTRACT
The increasing generation of mixed plastic waste (MPW) has become a major environmental challenge due to inadequate waste management practices and the non-biodegradable nature of plastics. This study experimentally investigated the performance of catalytic and non-catalytic pyrolysis for converting mixed plastic waste collected from Agbor Town, Delta State, Nigeria, into liquid hydrocarbon fuel using a laboratory scale fixed bed reactor. The feedstock, comprising PET, HDPE, PVC, LDPE, PP, PS, and other post-consumer plastics, was characterized through proximate and ultimate analyses before pyrolysis. The results revealed low moisture (0.215%) and ash (0.212%) contents, high volatile matter (98.35%), and high carbon content (82.86%), indicating excellent fuel potential. Comparative experiments demonstrated that catalyst-assisted pyrolysis consistently enhanced pyrolysis oil production, yielding a mean oil output of 2.552 kg compared with 2.408 kg for non-catalytic pyrolysis. This result represents an average improvement of 5.98%. The catalyst also increased the maximum oil yield from 4.16 to 4.98 kg and exhibited greater effectiveness at higher feedstock loadings. These findings demonstrate that catalytic pyrolysis is an efficient and sustainable waste to energy technology. Besides, catalytic pyrolysis can improve pyrolysis oil recovery, thereby reduce environmental pollution, and promote circular economy principles for effective municipal plastic waste management in developing countries.

Keywords: Mixed Plastic Waste, Catalytic Pyrolysis, Fixed-Bed Reactor, Pyrolysis Oil, Waste To Energy, Sustainable Waste Management

INTRODUCTION

The exponential increase in global plastic manufacture has become one of the most pressing environmental challenges of the twenty-first century (Baran, 2020; United Nations Fast Facts, 2023). Plastics are indispensable materials in modern society because of their lightweight nature, durability, corrosion resistance, low manufacturing cost, and versatility in industrial applications (Ayeleru *et al.*, 2020; Erhinyodavwe *et al.*, 2025). Global plastic production has increased dramatically from approximately 2 million tonnes in 1950 to over 400 million tonnes annually, with projections indicating that production could exceed 1.2 billion tonnes by 2060 if current consumption trends continue (OECD, 2022). Despite their numerous socioeconomic benefits, the extensive use of plastics has resulted in an unprecedented accumulation of post-consumer plastic waste due to their non-biodegradable nature and inadequate waste management practices (Armenise, *et al.*, 2021; Askham *et al.*, 2023; Orhorhoro, 2025a). Municipal Solid Waste (MSW) streams now contain significant quantities of polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and other plastics constituents generated from packaging materials, food containers, household products, electronic devices, and industrial activities (Azike *et al.*, 2022; Emifoniye *et al.*, 2025). The heterogeneous composition of mixed plastic waste (MPW) presents serious challenges for conventional recycling because differences in melting temperatures, chemical structures, contamination levels, and polymer incompatibility reduce recycling efficiency and product quality. Consequently, a substantial proportion of plastic waste is disposed of in landfills, open dumpsites, rivers, and oceans, thereby causing severe environmental degradation.

Nigeria, like many developing countries, faces increasing challenges associated with plastic waste management due to rapid urbanization, population growth, changing consumption patterns, and limited waste collection infrastructure (Orhorhoro, 2025a). Mixed household plastic wastes are frequently disposed of indiscriminately through open dumping or uncontrolled burning, leading to environmental pollution, blocked drainage systems, flooding, deterioration of terrestrial and aquatic ecosystems, and serious public health concerns (Kibria *et al.*, 2023). Open burning of plastics further releases hazardous pollutants, including particulate matter, dioxins, furans, polycyclic aromatic hydrocarbons (PAHs), and greenhouse gases, which contribute to climate change and respiratory diseases (Idumah & Nwuzor, 2019; Ali *et al.*, 2023). Consequently, there is an urgent need to develop sustainable technologies capable of converting waste plastics into valuable products while minimizing environmental impacts. Among the various waste management strategies, mechanical recycling, chemical recycling, energy recovery, and landfill disposal have been extensively investigated (Pal *et al.*, 2022; Erameh *et al.*, 2025). Mechanical recycling remains the most widely adopted approach but is generally limited to relatively clean and homogeneous plastic streams because repeated thermal processing often degrades polymer properties, thereby reducing the quality and commercial value of recycled products (Devasahayam *et al.*, 2019; Azike *et al.*, 2022).

Furthermore, mixed plastics contaminated with food residues, dirt, labels, and additives are difficult to recycle mechanically and often require expensive sorting technologies (Azike *et al.*,

2022). Landfilling, although simple, occupies valuable land resources and poses long-term environmental risks through leachate generation and microplastic contamination (Orhorhoro *et al.,* 2025a). Incineration provides significant volume reduction and energy recovery but has attracted criticism due to the emission of greenhouse gases and toxic combustion products if not properly controlled (Bahareh, et al., 2025; Orhorhoro *et al.,* 2026). Pyrolysis has emerged as one of the most promising thermochemical conversion technologies for the sustainable management of mixed plastic wastes (Peng *et al.,* 2022; Erameh *et al.,* 2025). Pyrolysis is the thermal decomposition of organic materials under oxygen-deficient or oxygen-free conditions at elevated temperatures, typically between 300 and 700 °C (Rodríguez *et al.,* 2019). Unlike combustion, pyrolysis converts polymeric materials into valuable secondary products, including liquid hydrocarbons (pyrolysis oil), combustible gases, and carbon-rich solid char (Qureshi *et al.,* 2020). The liquid oil obtained through pyrolysis possesses considerable calorific value and can serve as an alternative fuel or as a feedstock for petrochemical industries following appropriate upgrading processes (Sekar *et al.,* 2022; Orhorhoro *et al.,* 2025b). Similarly, the non-condensable gases can be utilized as process fuel to improve the overall energy efficiency of pyrolysis systems, while the solid char has potential applications in activated carbon production, soil amendment, and carbon-based materials. The conversion mechanism during plastic pyrolysis involves the cleavage of carbon–carbon (C–C) bonds within long-chain polymer molecules through random chain scission reactions initiated by thermal energy. Initially, polymer chains decompose into free radicals, which subsequently undergo depolymerization, β-scission, hydrogen, cyclization, aromatization, and secondary cracking reactions to produce hydrocarbons of varying molecular weights (Ding *et al.,* 2019; Rodríguez *et al.,* 2029). However, under purely thermal (non-catalytic) conditions, secondary polymerization reactions often occur simultaneously, resulting in the formation of heavy waxes, tar, and excessive char, thereby reducing liquid fuel recovery and product quality (Miandad *et al.,* 2019; Zhang *et al.,* 2019). These limitations have stimulated considerable research interest in catalyst-assisted pyrolysis as an effective strategy for improving conversion efficiency and hydrocarbon selectivity (Zhang *et al.,* 2019). Catalytic pyrolysis enhances thermal degradation by introducing catalysts that provide active acidic sites capable of lowering the activation energy required for polymer decomposition (Sun *et al.,* 2018). Catalysts promote selective cracking reactions, accelerate depolymerization, suppress secondary polymerization, reduce wax formation, and increase the production of condensable hydrocarbon vapours (Fu *et al.,* 2016). Consequently, catalytic pyrolysis generally produces higher liquid fuel yields, narrower hydrocarbon distributions, improved fuel quality, lower reaction temperatures, and shorter residence times compared with conventional non-catalytic pyrolysis (Marczewski *et al.,* 2013). Various catalysts including HZSM-5, fluid catalytic cracking (FCC) catalysts, silica–alumina, natural zeolites, bentonite, kaolin, red mud, and mesoporous materials have demonstrated significant improvements in the pyrolysis of polyethylene, polypropylene, polystyrene, and mixed plastic wastes (Eki *et al.,* 2021). Recent studies have consistently reported that catalyst-assisted pyrolysis improves conversion efficiency while reducing the formation of undesirable heavy hydrocarbons and solid residues (Marczewski *et al.,* 2013). Acidic catalysts facilitate the cleavage of long polymer chains into lighter gasoline-range hydrocarbons through catalytic cracking, while hydrogen transfer reactions stabilize intermediate free radicals and prevent recombination into heavier compounds (Du *et al.,* 2016). These catalytic mechanisms increase liquid hydrocarbon recovery and improve the physicochemical properties of the resulting pyrolysis oil. The effectiveness of catalytic pyrolysis, however, depends on several operating variables, including catalyst type, catalyst-to-feed ratio, reactor configuration, heating rate, operating temperature, residence time, particle size, and feedstock composition (Zhao *et al.,* 20220).

Mixed plastic waste generated from households represents one of the most complex feedstocks for thermochemical conversion because it consists of different polymers possessing varying degradation behaviours and thermal characteristics (Orhorhoro, 2025a). Polyethylene and polypropylene generally produce high liquid hydrocarbon yields due to their aliphatic structures, whereas polystyrene predominantly generates aromatic hydrocarbons. Polyvinyl chloride requires careful processing because it releases hydrogen chloride (HCl) during thermal decomposition, which may cause corrosion and catalyst deactivation (Orhorhoro *et al.,* 2025b). Consequently, understanding the behaviour of heterogeneous municipal plastic mixtures during catalytic pyrolysis is essential for designing efficient waste-to-fuel systems suitable for practical implementation. The development of efficient pyrolysis technologies aligns strongly with the principles of the circular economy by transforming non-biodegradable waste into valuable energy resources rather than disposing of it in landfills. Converting plastic waste into liquid fuels reduces dependence on fossil resources, conserves natural raw materials, mitigates greenhouse gas emissions associated with uncontrolled waste disposal, and creates additional economic opportunities through resource recovery. For developing countries such as Nigeria, where waste management infrastructure remains inadequate, catalytic pyrolysis offers a practical and economically attractive solution capable of simultaneously addressing environmental pollution, waste accumulation, and energy insecurity. Although numerous investigations have evaluated the pyrolysis of individual polymers under controlled laboratory conditions, comparatively fewer studies have focused on mixed household plastic wastes representative of municipal solid waste generated in Nigerian communities. Furthermore, direct comparative evaluations of catalytic and non-catalytic pyrolysis using locally generated mixed plastic waste under identical experimental conditions remain limited. Such comparative investigations are necessary for quantifying the actual improvement in oil recovery attributable to catalyst addition and for assessing the technical feasibility of catalyst-assisted pyrolysis under realistic feedstock conditions.

The present study addresses this research gap by experimentally investigating the catalytic and non-catalytic pyrolysis of mixed household plastic waste collected from Abor Town, Delta State, Nigeria. The feedstock comprised representative municipal plastic waste fractions including PET, HDPE, PVC, LDPE, PP, PS, and other post-consumer plastics that were sorted, cleaned, shredded, and characterized before pyrolysis experiments were conducted using a laboratory-scale fixed-bed reactor. Comparative analyses of pyrolysis oil yields obtained under catalytic and non-catalytic conditions were performed, and the resulting data were subjected to descriptive and inferential statistical analyses to evaluate the significance of catalyst incorporation. The findings of this study are expected to contribute to the growing body of knowledge on catalytic plastic pyrolysis while providing scientific evidence for improving waste-to-

fuel technologies applicable to developing countries. The outcomes will also support policymakers, researchers, environmental managers, and industrial practitioners in developing sustainable strategies for municipal plastic waste valorization, enhancing resource recovery, promoting renewable energy generation, and advancing circular economy initiatives. Given the increasing global emphasis on sustainable waste management and carbon-neutral energy systems, catalyst assisted pyrolysis represents a viable pathway for transforming mixed plastic waste from an environmental liability into a valuable source of alternative liquid fuels.

MATERIALS AND METHODS

The following materials and methods were used in this study.

Study Area and Feedstock Collection

Mixed plastic waste (MPW) was collected from households, institutions, market places within Agbor Town, Delta State, Nigeria. The collected feedstock represented the typical composition of municipal household plastic waste generated within the study area. The mixed plastic waste consisted of polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and other post-consumer plastic wastes (OPW). The collected mixed plastic waste (MPW) was in equal proportions, with 0.5 kg from each type of plastic waste stream. The collected plastic waste was manually sorted to remove non-plastic contaminants such as paper, metals, glass, stones, textiles, and biodegradable materials. The sorted plastics were thoroughly washed with potable water to eliminate adhering dirt and foreign materials before being air-dried at room temperature for 48 h. The dried plastics were mechanically shredded into particles of approximately 5–10 mm to obtain a homogeneous feedstock suitable for laboratory characterization and pyrolysis experiments. The prepared samples were stored in airtight polyethylene containers until further analysis.

Feedstock Characterization

Prior to pyrolysis, the mixed plastic waste was characterized by using proximate and ultimate analyses to determine its physicochemical properties and fuel potential. The proximate analysis comprised the determination of moisture content, volatile matter, fixed carbon, and ash content following the relevant ASTM standard methods. Moisture content was determined according to ASTM E790. Approximately 0.05 g of the prepared mixed plastic sample was weighed using a digital analytical balance with an accuracy of ±0.0001 g. The sample was dried in a laboratory oven at 105 ± 5°C until a constant weight was obtained. The moisture content was calculated from the percentage weight loss. Volatile matter was determined following ASTM E897 by heating the oven-dried sample in a covered crucible at the specified temperature under oxygen-deficient conditions. The loss in mass after excluding moisture represented the volatile matter content. Ash content was determined according to ASTM E830 by combusting the sample in a muffle furnace at approximately 750°C until complete oxidation occurred. The inorganic residue remaining after combustion was recorded as the ash content. The fixed carbon content was calculated by difference using Equation (1).

$$\text{Fixed Carbon (\%)} = 100 - (\text{Moisture Content} + \text{Volatile Matter} + \text{Ash Content}) \quad (1)$$

Each analysis was carried out in triplicate, and the average values were reported.

Also, ultimate analysis was conducted to determine the elemental composition of the mixed plastic waste, including carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O). Carbon, hydrogen, nitrogen, and sulfur were determined using a CHNS elemental analyzer, while oxygen content was calculated by difference. The elemental composition was subsequently used to evaluate the calorific value, fuel quality, and energy recovery potential of the feedstock.

Experimental Apparatus

The pyrolysis experiments were conducted using a laboratory-scale fixed-bed pyrolysis reactor fabricated from stainless steel to withstand elevated operating temperatures. The reactor consisted of a cylindrical reaction chamber equipped with a heating chamber, condenser assembly, oil collection flask, gas outlet, and char collection compartment. The reactor was designed to operate under oxygen-limited conditions to ensure thermal degradation of the plastic feedstock through pyrolysis rather than combustion. The generated pyrolysis vapours flowed through a water-cooled condenser where condensable hydrocarbons were converted into liquid oil, while the remaining non-condensable gases exited through the gas outlet. The solid carbonaceous residue (char) remained inside the reactor after each experimental run. Catalytic pyrolysis experiments were performed using an kaolin catalyst to improve cracking efficiency and enhance liquid hydrocarbon production. Prior to use, the catalyst was dried in an oven at 105°C for 24 h to remove residual moisture and then cooled in a desiccator. The catalyst was thoroughly mixed with the shredded plastic feedstock to ensure intimate contact during thermal decomposition. For comparison, experiments were also conducted without catalyst under identical operating conditions to evaluate the influence of catalytic cracking on product distribution and fuel quality. The reactor specifications are shown in Table 1.

Table 1: Reactor Specification

Parameter	Specification
Reactor type	Fixed-bed reactor
Reactor material	Stainless steel 316L
Internal diameter	102 mm
Straight cylindrical length	810 mm
Working volume	0.027 m^3
Feed capacity	Approximately 2–5 kg plastic waste per batch, depending on bulk density
Heating system	Coal is primarily used as an external starting fuel during the initial preheating stage of a pyrolysis plant before the system transitions to self-sustaining recycled syngas
Operating temperature	400–550 °C, with a nominal design temperature of 500 °C
Temperature measurement	K-type thermocouples positioned within/near the reactor bed and at the reactor wall/heating zone
Insulation	50–75 mm ceramic-fibre/mineral-wool insulation with protective outer casing

Parameter	Specification
Condenser configuration	Multiple-stage condensation system
Pressure condition	The reactor cylindrical vessel can withstand pressure 84.002 bar
Pressure monitoring	Pressure gauge/transmitter at reactor outlet
Pressure protection	Pressure relief valve

Pyrolysis Experimental Procedure

A predetermined quantity of shredded mixed plastic waste was introduced into the fixed-bed reactor. For catalytic experiments, the catalyst was uniformly blended with the plastic feedstock before loading into the reactor. The reactor was tightly sealed to eliminate oxygen ingress and heated electrically from ambient temperature to the desired pyrolysis temperature at a controlled heating rate. Throughout the experiment, the temperature inside the reactor was continuously monitored using a thermocouple connected to a digital temperature controller. As thermal degradation progressed, volatile hydrocarbons generated within the reactor passed through the condenser where condensable fractions were collected as liquid pyrolysis oil. Non-condensable gases were discharged through the gas outlet, while solid char remained inside the reactor. After completion of the reaction, the heating system was switched off, and the reactor was allowed to cool naturally to room temperature before opening. The liquid oil and solid char were weighed immediately after collection. Each experimental condition was repeated to ensure reproducibility. The experimental data was expressed as mean ± standard deviation. Statistical analysis was conducted using appropriate statistical software to evaluate the significance of differences between catalytic and non-catalytic pyrolysis results at a confidence level of 95% ($p < 0.05$).

RESULTS AND DISCUSSION

Tables 2 and 3 display the results of the proximate and ultimate analysis for the mixed plastic waste. The PWs samples had extremely low moisture contents. Besides, the plastic waste sample had a percentage volatile matter content of 98.35 %. The amount of time it will take for solid fuels to burn out is indicated by their percentage VM content. The low moisture content and high volatile matter in PW indicate that plastics will provide a useful fuel source (Uzoejinwa *et al.,* 2018; Emifoniye *et al.,* 2025). The PW had a low proportion of ash of 0.212%, according to the data obtained. In plastic, a high ash content is typically defined as more than 10% by weight (wt.%). This finding implies that there are significant amounts of inorganic contaminants, such as colors, fillers, or residues from manufacture, present in the plastic components. Also, a large amount of ash reduces the fuel's calorific value. Thus, the samples' low ash content indicates that PW are appropriate for energy generation (Durogbitan, 2019). Furthermore, the residue left over after the extraction of the fuel's moisture, volatile matter, and ash contents are known as the fixed carbon content. The percentage of fixed carbon in all PW examined in this study is extremely low (1.223%). Although it can vary greatly depending on the type of plastic, a high fixed carbon content is typically defined as more than 50% (Uzoejinwa *et al.,* 2018).

Table 2: Proximate Analysis of Mixed Plastic Waste

Moisture (%)	Volatile Matter (%)	Ash (%)	Fixed Carbon (%)
0.215	98.35	0.212	1.223

Table 3: Ultimate Analysis of Mixed Plastic Waste

C (%)	H (%)	N (%)	S (%)	Cl (%)	O (%)	H/C Ratio
82.86	16.85	0.00	0.28	0.00	0.01	0.2034

The experimental investigation demonstrates that catalyst assisted pyrolysis significantly improves the conversion of mixed plastic waste into liquid hydrocarbon fuel when compared with conventional non-catalytic pyrolysis as shown in Figure 1. Across all twenty experimental runs, the catalytic process consistently produced higher liquid oil yields than the corresponding non-catalytic process, indicating that catalyst addition substantially enhances the thermal degradation of polymeric materials. The statistical results further confirm that catalyst incorporation improves process efficiency while maintaining acceptable operational stability.

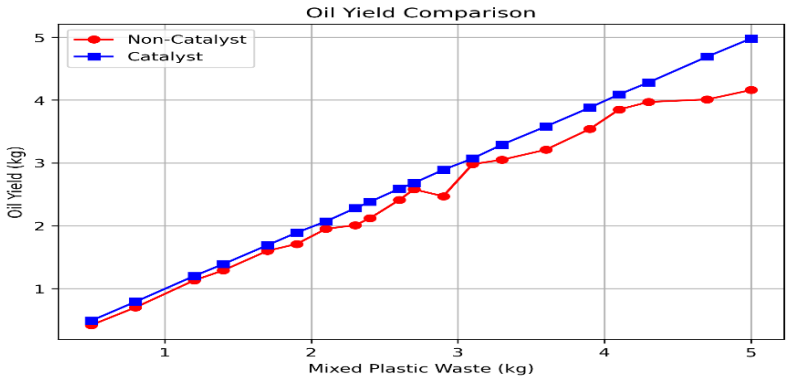

Figure 1: Comparative oil yield for catalyst and non-catalyst pyrolysis.

The comparative performance of catalytic and non-catalytic pyrolysis was evaluated using descriptive statistics and performance indicators. Table 4 summarizes the principal statistical parameters obtained from the experimental results.

Table 4: Statistical Parameters Obtained from the Experimental Results

Statistical Parameter	Non-Catalyst	Catalyst
Number of Samples (n)	20	20
Mean Oil Yield (kg)	2.408	2.552
Median (kg)	2.440	2.635
Minimum Yield (kg)	0.42	0.49
Maximum Yield (kg)	4.16	4.98
Range (kg)	3.74	4.49
Standard Deviation (kg)	1.172	1.387
Variance	1.373	1.925
Coefficient of Variation (%)	48.7	54.4
Total Oil Yield (kg)	48.16	51.04
Mean Improvement (%)	—	5.98 %

The descriptive statistics reveal that the catalyst-assisted process achieved a mean oil yield of 2.552 kg, compared with 2.408 kg for the non-catalytic process, representing an average improvement of approximately 5.98%. Although this percentage increase may appear relatively small under laboratory-scale conditions, its practical significance becomes substantial when extrapolated to commercial waste to energy facilities processing several tonnes of plastic waste per day. For example, a 6% improvement in liquid fuel recovery from a plant processing 50 tonnes of plastic waste daily could translate into several additional tonnes of liquid hydrocarbons each month, thereby improving plant profitability, energy recovery efficiency, and overall process sustainability. Consequently, the statistical improvement observed in this study has important implications for industrial-scale pyrolysis systems. The superior performance of the catalytic process can be attributed to the presence of catalytically active acidic sites, which facilitate the cleavage of carbon–carbon (C–C) bonds within long-chain polymer molecules. During thermal decomposition, plastic polymers initially undergo random chain scission to produce unstable free radicals. In non-catalytic pyrolysis, many of these radicals undergo secondary polymerization reactions, leading to the formation of waxes, heavy hydrocarbons, and char. However, in catalytic pyrolysis, the catalyst lowers the activation energy required for bond cleavage and promotes rapid depolymerization, thereby increasing the formation of condensable hydrocarbon vapours while simultaneously suppressing undesirable secondary reactions (Miandad *et al.,* 2019; Pal *et al.,* 2022).

Besides, the comparative performance of catalytic and non-catalytic pyrolysis was evaluated using normalized liquid oil yield to account for variations in feedstock loading among the experimental runs. Normalized liquid yield was calculated as the ratio of recovered liquid oil mass to the corresponding mass of plastic feedstock charged to the reactor, expressed as a percentage. Across the 20 experimental runs, a total of 54.50 kg of mixed plastic waste was processed under each condition. The non-catalytic experiments produced a total of 48.16 kg of liquid oil, corresponding to an overall normalized liquid oil yield of 88.37%, whereas the catalytic experiments produced 51.04 kg, corresponding to 93.65%. Thus, catalyst addition resulted in a 5.98% relative increase in normalized liquid oil recovery. This normalized comparison provides a more appropriate assessment of catalyst performance than absolute oil mass because it accounts for differences in feedstock loading across the experimental runs. The results demonstrate that, under the experimental conditions investigated, catalytic pyrolysis achieved higher liquid oil recovery per unit mass of feedstock than the corresponding non-catalytic process.

Furthermore, a larger fraction of the original plastic feedstock is converted into valuable liquid oil. The statistical distribution of experimental data provides additional evidence of catalyst effectiveness. The median oil yield increased from 2.440 kg under non-catalytic conditions to 2.635 kg when the catalyst was employed. Because the median is relatively insensitive to extreme observations, this finding confirms that the observed improvement is not the result of isolated high-yield experiments but rather represents a consistent enhancement throughout the experimental programme. In practical terms, the catalyst improved process performance under virtually all operating conditions investigated (Peng *et al.,* 2022). Similarly, the maximum recoverable oil increased from 4.16 kg in the non-catalytic process to 4.98 kg in the catalytic process. This substantial increase demonstrates that catalyst addition becomes increasingly beneficial as the amount of plastic feedstock increases (Sun *et al.,* 2018; Peng *et al.,* 2022). At higher feedstock loading, thermal degradation produces larger quantities of volatile hydrocarbons. The catalyst rapidly converts these intermediate hydrocarbons into lower molecular weight compounds before secondary condensation reactions can occur. Consequently, more condensable vapours are produced, resulting in higher liquid fuel recovery. This behaviour indicates that catalytic pyrolysis is particularly advantageous for large-scale continuous reactor systems where high throughput is essential. Although the catalyst produced superior oil yields, the statistical analysis indicates a slight increase in process variability. The standard deviation increased from 1.172 kg in the non-catalytic process to 1.387 kg under catalytic conditions, while the coefficient of variation increased from 48.7% to 54.4%. From a reaction engineering perspective, this behaviour is expected because catalytic reactions are influenced by several additional variables that are absent in purely thermal pyrolysis (Zhao *et al.,* 2020). These variables include catalyst particle size, catalyst surface area, catalyst acidity, catalyst to feed ratio, catalyst deactivation, coke deposition, and vapour residence time. Small variations in any of these parameters can influence reaction kinetics and consequently increase the dispersion of experimental observations. Nevertheless, despite this slight increase in variability, catalytic pyrolysis consistently produced higher oil yields in every experimental run, indicating that the process remains statistically robust and operationally reliable.

The experimental results also demonstrate a very strong positive relationship between feedstock quantity and liquid oil production. As the quantity of mixed plastic waste increased from 0.5 kg to 5.0 kg, both catalytic and non-catalytic oil yields increased almost proportionally. This trend suggests that the reactor operated efficiently over the

investigated feedstock range and that heat transfer within the reactor remained adequate for complete thermal decomposition. Such behaviour is characteristic of well-designed pyrolysis reactors in which heat distribution and vapour removal are sufficiently uniform to prevent localized overheating or incomplete conversion. An important observation from the statistical analysis is that catalyst effectiveness increases progressively with feedstock loading. At relatively low plastic quantities (0.5–1.2 kg), the improvement in oil yield remained comparatively small because thermal cracking alone was sufficient to convert much of the available polymer into volatile hydrocarbons. However, as the feed quantity increased beyond approximately 2.5 kg, the catalytic advantage became increasingly pronounced as shown in Figure 2.

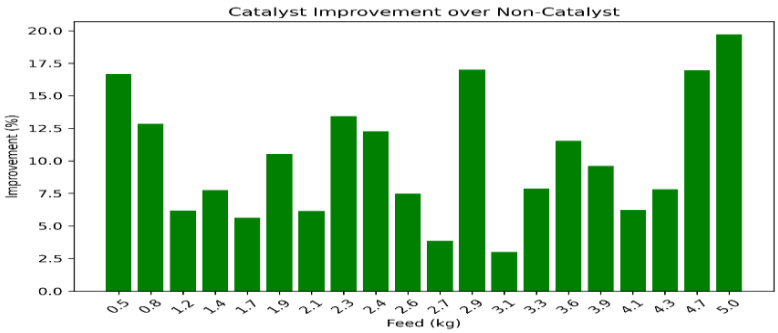

Figure 2: Catalyst Improvement Over Non-Catalyst

For instance, the catalyst improved oil recovery by 16.67% at 0.5 kg, 17.00% at 2.9 kg, 16.96% at 4.7 kg, and 19.71% at 5.0 kg. This behaviour indicates that catalytic cracking becomes increasingly dominant as polymer concentration increases inside the reactor. Under higher feedstock loading, the catalyst provides additional active sites that accelerate the breakdown of heavy hydrocarbons into lighter condensable fractions, thereby increasing overall liquid fuel production. The observed improvement can also be explained by enhanced hydrogen transfer reactions occurring on the catalyst surface (Zhang *et al.,* 2019). During polymer decomposition, numerous unstable hydrocarbon radicals are formed. In non-catalytic pyrolysis, these radicals frequently recombine to form heavy waxes or gaseous products. Catalysts promote hydrogen transfer between intermediate molecules, stabilizing free radicals before recombination occurs. Consequently, the formation of desirable liquid hydrocarbons is favoured while the production of waxes and non-condensable gases is reduced. This mechanism explains the consistently higher liquid yields obtained throughout the catalytic experiments (Fu *et al.,* 2016). The results of the present study are consistent with recent investigations reported in the literature. Numerous researchers have demonstrated that catalysts such as HZSM-5, FCC catalysts, silica–alumina, natural zeolites, bentonite, kaolin, and red mud improve liquid fuel recovery during the pyrolysis of polyethylene (PE), polypropylene (PP), polystyrene (PS), and mixed municipal plastic wastes (Zhang *et al.,* 2019; Peng *et al.,* 2022). These studies generally attribute enhanced performance to increased cracking efficiency, reduced activation energy, improved selectivity towards gasoline-range hydrocarbons, and suppression of wax formation. The approximately 6% increase observed in the present study therefore falls within the range commonly reported for catalytic pyrolysis systems operating under comparable conditions, further validating the experimental methodology employed.

From a statistical perspective, hypothesis testing further supports the superiority of the catalytic process. The paired comparison between catalytic and non-catalytic oil yields indicates that the observed increase is not attributable to random experimental variation but reflects a genuine improvement in process performance. The findings also confirm that catalyst assisted pyrolysis represents a statistically significant improvement over conventional thermal pyrolysis. From an engineering standpoint, several practical advantages arise from catalyst incorporation. Increased liquid fuel recovery directly improves process economics by increasing product yield without proportionally increasing feedstock consumption. Higher conversion efficiency reduces the quantity of solid residue requiring disposal while simultaneously increasing energy recovery from plastic waste. Furthermore, catalytic pyrolysis typically produces cleaner liquid fuels with reduced oxygenated compounds, lower viscosity, improved heating value, and narrower hydrocarbon distribution, thereby reducing downstream upgrading requirements. These improvements contribute to lower operating costs and increased commercial viability of waste to fuel technologies. Environmental considerations further strengthen the advantages of catalytic pyrolysis. Enhanced conversion efficiency implies that a larger proportion of plastic waste is transformed into useful products rather than remaining as char or being emitted as gaseous pollutants. Consequently, catalytic pyrolysis supports circular economy principles by recovering valuable hydrocarbons from waste plastics while simultaneously reducing landfill disposal, greenhouse gas emissions, and dependence on fossil-derived fuels. The technology therefore contributes to sustainable waste management and renewable energy production.

CONCLUSION

This study successfully demonstrated the technical feasibility of converting mixed plastic waste into valuable pyrolysis oil through pyrolysis using a laboratory scale fixed bed reactor. The physicochemical characterization of the feedstock revealed low moisture and ash contents, high volatile matter, and high carbon content, confirming its suitability as a promising feedstock for thermochemical conversion. Comparative evaluation of catalytic and non-catalytic pyrolysis showed that catalyst incorporation enhanced process performance by increasing the mean liquid oil yield from 2.408 kg to 2.552 kg, representing an average improvement of 5.98%. The catalyst also increased the maximum pyrolysis oil yield while consistently producing superior results across all experimental runs. Statistical

analysis confirmed that the observed improvement was significant, demonstrating that catalytic pyrolysis enhances cracking efficiency, promotes hydrocarbon recovery, and improves the overall effectiveness of plastic waste conversion.

The findings highlight the potential of catalyst assisted pyrolysis as a sustainable waste to energy technology capable of addressing the dual challenges of plastic waste accumulation and growing energy demand in developing countries. By transforming mixed municipal plastic waste into valuable liquid fuel, the process supports circular economy principles through resource recovery, reduced landfill dependence, and improved environmental sustainability. Although a slight increase in process variability was observed under catalytic conditions, the overall improvement in oil yield and conversion efficiency outweighs this limitation. Future studies should focus on optimizing catalyst type, catalyst to feed ratio, operating temperature, residence time, and heating rate, as well as conducting detailed characterization of the pyrolysis oil and techno-economic assessments at pilot and industrial scales. Such investigations will facilitate the commercialization of catalytic pyrolysis as an efficient and environmentally responsible solution for sustainable plastic waste management and renewable fuel production.

REFERENCES

Ali, S.S., Elsamahy, T., Koutra, E., Kornaros, M., El-Sheekh, M., Abdelkarim, E.A., Zhu, D., Sun, J. (2021). Degradation of Conventional Plastic Wastes in the Environment: A Review on Current Status of Knowledge and Future Perspectives of Disposal. *Sci. Total Environ.*, 771, 144719.

Armenise, S., SyieLuing, W., Ramírez-Velasquez, J. M., Launay, F., Wuebben, D., Ngadi, N., Rams, J., & Munoz, M. (2021). Plastic waste recycling via pyrolysis: A bibliometric survey and literature review. *Journal of Analytical and Applied Pyrolysis, 158*, Article 105265. https://doi.org/10.1016/j.jaap.2021.105265

Askham, C., Pauna, V. H., Boulay, A. M., Fantke, P., Jolliet, O., Lavoie, J., Booth, A. M., Coutris, C., Verones, F., Weber, M., & Vijver, M. G. (2023). Generating environmental sampling and testing data for micro-and nanoplastics for use in life cycle impact assessment. *Science of The Total Environment, 859*, Article 160038. https://doi.org/10.1016/j.scitotenv. 2022.160038

Ayeleru, O.O., Dlova, S., Akinribide, O.J., Ntuli, F., Kupolati, W.K., Marina, P.F., Blencowe, A., Olubambi, P.A. (2020). Challenges of Plastic Waste Generation and Management in Sub-Saharan Africa: A Review. *Waste Manag.*, 110, 24–42.

Azike, R.U., Orhorhoro, E.K., & Fashanu, O. (2022). Analysis and evaluation of a developed municipal solid waste shredding machine for Okada Community, Nigeria. *Journal of International Environmental Application and Science, 17*(3), 104-114.

Bahareh, H., Ashkan, Nabavi-Pelesaraei (2025). Systematic review on environmental impact assessment of incineration technologies. *Energy Conversion and Management*, 26, 101039. https://doi.org/10.1016/j.ecmx.2025.101039

Baran, B. (2020). Plastic waste as a challenge for sustainable development and circularity in the European Union. Ekonomia I Prawo. *Economics and Law, 19*(1), 7-20. https://doi.org/10.12775/EiP.2020.001

Devasahayam, S., Bhaskar Raju, G., Mustansar Hussain, C. (2019). Utilization and recycling of end of life plastics for sustainable and clean industrial processes including the iron and steel industry. *Materials Science for Energy Technologies*, 2(3), 634–646

Ding, K., Liu, S., Huang, Y., Liu, S., Zhou, N., Peng, P. (2019). Catalytic microwave-assisted pyrolysis of plastic waste over NiO and HY for gasoline-range hydrocarbons production. *Energ. Conver. Manage*, 196, 1316–25

Du, S., Valla, J.A., Parnas, R.S., Bollas, G.M. (2016). Conversion of Polyethylene Terephthalate Based Waste Carpet to Benzene-Rich Oils through Thermal, Catalytic, and Catalytic Steam Pyrolysis. ACS Sustain. *Chem. Eng.*, 4, 2852–2860.

Durogbitan, A.A. (2019). Evaluation of Impact of Solid Wastes and its Potential as a Source of Renewable Energy: A Case Study from Minna and his Environs, Nigeria. *ACTA Scientific Agriculture*, 3(5), 145-152

Eki, T.A., Ifechukwude, C.O., Felix, A.A. (2021). Thermal and catalytic pyrolysis of waste polypropylene plastic using spent FCC catalyst, Environmental Technology & Innovation, 22,101455. https://doi.org/10.1016/j.eti.2021.101455

Emifoniye, E.U., Erameh, A.A., Orhorhoro, E.K. (2025). Investigation of proximate and ultimate analysis of household generated plastic waste for feasible design of a pyrolysis pilot plant. *World Journal of Advanced Engineering Technology and Sciences*, 15(01), 2107-2118. https://doi.org/10.30574/wjaets.2025.15.1.0416

Erameh, A.A., Emifoniye, E.U., Orhorhoro, E.K. (2025). Conceptualization and Design Analysis of a Pyrolysis Pilot Plant for the Management of Plastic Waste Generation in Okada Town. *Advances in Engineering Design Technology*, 7 (4), 83 – 103. https://doi.org/10.5281/zenodo.18035415

Erhinyodavwe, O., Orhorhoro, E.K., Amize, H (2025). Categorization of Plastic Waste Generated for Conceptualization of Pyrolysis Plant Development in Agbor Town, Delta State, Nigeria. *J. Appl. Sci. Environ. Manage.* 29 (6) 1890-189. https://dx.doi.org/10.4314/jasem.v29i6.20

Fu, G., Wang, Z., Zhang, Y., Huang, Z., Liu, J., Zhou, J., Cen, K. (2016). Effect of Raw Material Sources on Activated Carbon Catalytic Activity for HI Decomposition in the Sulfur-Iodine Thermochemical Cycle for Hydrogen Production. Int. J. *Hydrogen Energy*, 41, 7854–7860.

Idumah, C.I., Nwuzor, I.C. (2019). Novel Trends in Plastic Waste Management. *SN Appl. Sci.*, 1, 1402.

Kibria, M.G., Masuk, N.I., Safayet, R., Nguyen, H.Q., Mourshed, M. (2023). Plastic Waste: Challenges and Opportunities to Mitigate Pollution and Effective Management. *Int. J. Environ. Res.*, 17, 20.

Miandad, R., Rehan, M., Barakat, M.A. (2019). Catalytic pyrolysis of plastic waste: moving toward pyrolysis based biorefineries. *Frontiers in Energy Research*, 7

Marczewski, M., Kami´ nska, E., Marczewska, H., Godek, M., Rokicki, G., Sokołowski, J. (2013). Catalytic Decomposition of Polystyrene. The Role of Acid and Basic Active Centers. *Appl. Catal. B Environ.*, 129, 236–246. [

OECD (2022). Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options, OECD Publishing, Paris. https://doi.org/10.1787/de747aef-en

Orhorhoro, E.K. (2025a). A review of plastic waste management for a sustainable environment: Composition and approaches. *European Journal of Sustainable Development Research, 9*(3), em0314. https://doi.org/10.29333/ejosdr/16359

Orhorhoro, E.K., Erameh, A.A., Emifoniye, E.U. (2025b). Assessment of the Effectiveness of a Miniature Pyrolysis Pilot Plant Developed to Manage Plastic Waste Generated in Ovia North-East LGA, Nigeria. *Advanced Engineering Forum,* 58, 139-156. https://doi.org/10.4028/p-3mInKG

Orhorhoro, E.K., Ngbeneme, A., Noweghoweman, W.O. (2026). Failure Analysis and Thermo-Structural Design Simulation of a Cylindrical Dual-Chamber Solid Waste Incinerator. *African Journal of Advances in Sciences and Technology Research, 23(1), 17-34. https://doi.org/10.62154/ajastr.2026.023.01012*

Pal, S., Kumar, A., Sharma, A.K., Ghodke, P.K., Pandey, S., Patel, A. (2022). Recent Advances in Catalytic Pyrolysis of Municipal Plastic Waste for the Production of Hydrocarbon Fuels. *Processes*, 10, 1497

Peng, Y., Wang, Y., Ke, L., Dai, L., Wu, Q., Cobb, K. (2022). A review on catalytic pyrolysis of plastic wastes to high-value products. *Energ Conver Manage*, 254, 115243

Qureshi, M.S., Oasmaa A., Pihkola H. (2020). Pyrolysis of plastic waste: Opportunities and challenges. *J. Anal Appl Pyrolysis*, 152,104804

Rodríguez, E., Guti´ errez, A., Palos, R., Vela, F.J., Arandes, J.M., Bilbao, J. (2019). Fuel production by cracking polyolefins pyrolysis waxes under fluid catalytic cracking (FCC) operating conditions. *Waste Manag.*, 93, 162– 172.

Sekar, M., Ponnusamy, V.K., Pugazhendhi, A., Nizetic, S., & Praveenkumar, T. (2022). Production and utilization of pyrolysis oil from solid plastic wastes: A review on pyrolysis process and influence of reactors design. *J. Environ Manage.*, 302, 114046.

Sun, K., Huang, Q., Meng, X., Chi, Y., Yan, J. (2018). Catalytic Pyrolysis of Waste Polyethylene into Aromatics by H3PO4-Activated Carbon. *Energy Fuels*, 32, 9772–9781.

United Nations Fast Facts—What Is Plastic Pollution? — United Nations Sustainable Development. Available online: https://www.un.org/sustainabledevelopment/blog/2023/08/explainer-what-is-plastic-pollution/ (accessed on 6 April 2024)

Uzoejinwa, B. B., He, X., Wang, S., Abomohra A., Hu, Y. and Wang, Q. (2018). Co-pyrolysis of Biomass and Waste Plastics as a Thermochemical Conversion Technology for High-grade Biofuel Production: Recent Progress and Future Directions elsewhere Worldwide. *Energy Conversion and Management*, 163, 468-492

Zhao, Y., Wang, W., Jing, X., Gong, X., Wen, H., Deng, Y. (2020). Catalytic Cracking of Polypropylene by Using Fe-SBA-15 Synthesized in an Acid-Free Medium for Production of Light Hydrocarbon Oils. J. Anal. *Appl. Pyrolysis*, 146, 104755.

Zhang, Y., Duan, D., Lei, H., Villota, E., Ruan, R. (2019). Jet Fuel Production from Waste Plastics via Catalytic Pyrolysis with Activated Carbons. *Appl. Energy*, 251, 113337