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# Development of a Waste Plastic-to-Fuel Conversion System for Sustainable Energy Generation in Urban Nigeria

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***Abstract***. Plastic waste pollution has emerged as a critical environmental and public health concern in Nigeria's rapidly urbanising regions, where improper disposal and inefficient waste management systems persist. In parallel, the country faces acute energy insecurity, largely driven by erratic diesel supply and rising fossil fuel costs. This study presents the design, optimisation, and techno-environmental evaluation of a decentralised pyrolysis-based conversion system for transforming plastic waste into liquid fuel. Polypropylene (PP), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polystyrene (PS) were thermally degraded at controlled temperatures between 350°C and 500°C under inert conditions. Experimental trials revealed that oil yield increased with temperature, peaking at 450°C for all polymers. PP demonstrated the highest yield (65.1%) followed by PS (63.0%), HDPE (62.5%), and LDPE (60.4%). Fuel characterisation showed calorific values of up to 42.7 MJ/kg and physicochemical properties within acceptable diesel standards. Emissions analysis using flue gas monitoring confirmed low outputs of CO, NOx, and $SO_2$, all within Euro VI regulatory limits. Energy efficiency was highest for PP-derived fuel at 71.4%. Techno-economic modelling, based on a 10-year operational horizon, produced a net present value of ₦11.8 million, an internal rate of return of 28.4%, and a break-even fuel price of ₦290/litre. Statistical modelling further validated temperature and polymer type as primary determinants of yield performance. The findings demonstrate that decentralised plastic pyrolysis systems can simultaneously address urban waste accumulation, reduce environmental emissions, and provide affordable alternative fuels, making them suitable for integration into Nigeria's circular economy and energy access strategies.

***Keywords -*** Plastic pyrolysis, Decentralised energy, Fuel recovery, Waste valorisation, Urban sustainability, Techno-economic viability

## INTRODUCTION

The challenge of managing increasing volumes of plastic waste while addressing persistent energy shortages has become a pressing issue in rapidly urbanising regions of Nigeria. As of 2023, Nigeria generates over 2.5 million metric tonnes of plastic waste annually, with an estimated 88% of this waste not formally collected or recycled [1]. Urban centres such as Lagos, Abuja, and Port Harcourt bear the brunt of this crisis, where plastic waste clogs drainage systems, pollutes inland waterways, and contributes to urban flooding [2]. Simultaneously, over 43% of urban residents still lack reliable access to grid electricity, with widespread dependence on diesel and petrol generators, which emit greenhouse gases and exacerbate environmental degradation [3].

Recent advances in thermochemical technologies such as pyrolysis, gasification, and catalytic cracking provide promising pathways to convert non-recyclable plastic waste into valuable fuel products [4]. Pyrolysis, in particular, has gained significant attention due to its adaptability to mixed plastic streams and its potential to produce high-yield liquid fuels compatible with diesel engines [5]. These systems offer decentralised solutions, especially suited to resource-constrained environments like urban Nigeria, where centralised waste management and energy distribution infrastructures are weak or overburdened [6]. The integration of plastic-to-fuel technologies into the Nigerian urban context represents a novel opportunity to promote circular economy principles, reduce dependence on fossil imports, and mitigate the hazards posed by unmanaged plastic waste. Moreover, transitioning waste streams into energy assets supports key United Nations Sustainable Development Goals (SDGs), including SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities), and SDG 12 (responsible consumption and production) [7].

Nigeria's urban areas face mounting pressures from unregulated plastic disposal and growing electricity deficits. Waste management systems in cities such as Lagos, Kano, and Onitsha are fragmented and overwhelmed, leading to widespread practices of open dumping and burning of plastic waste, both of which release harmful pollutants like dioxins, carbon monoxide, and particulate matter [8]. This environmental burden is compounded by unreliable electricity supply, which hampers economic development and undermines public health in densely populated informal settlements [9]. Despite international advances in plastic-to-fuel conversion systems, there is a paucity of research and technical development targeted at sub-Saharan African environments. Existing technologies are often either too capital intensive or poorly adapted to heterogeneous waste streams and fluctuating operating conditions common in Nigeria. Furthermore, little is known about the feasibility and performance of such systems in situ, especially when using locally sourced waste plastics under realistic urban constraints [10].

This study was undertaken with the overarching goal of developing a plastic-to-fuel conversion system that is both technically feasible and contextually adapted to urban Nigerian realities. The primary objective was to design, construct, and evaluate a laboratory-scale pyrolysis-based plastic waste conversion system. A second objective was to characterise the produced fuel in terms of its calorific value, physical properties, and combustion quality. Additionally, the study aimed to assess the environmental impacts and economic potential of the proposed system through emissions analysis and a preliminary techno-economic evaluation.

This study provides an evidence-based framework for integrating decentralised plastic-to-fuel systems into urban Nigeria's waste and energy landscapes. It addresses a critical research and implementation gap by developing a prototype specifically designed for operation in Nigerian conditions, where energy poverty and waste accumulation intersect. The work is novel in its dual approach: it simultaneously examines fuel yield and environmental performance, while also conducting a contextualised economic assessment. By presenting a scalable model, this study can inform municipal decision-making, support informal recycling sectors, and contribute to national strategies for sustainable energy diversification and environmental protection. This research focused on a specific subset of thermoplastics—primarily polyethylene (PE), polypropylene (PP), and polystyrene (PS)—collected from urban waste streams in Lagos, Nigeria. The project was limited to bench-scale experimental design and characterisation within controlled laboratory conditions. Variables such as weather influences, contamination levels, and long-term economic models were not fully incorporated. Nevertheless, the findings provide a foundation for subsequent pilot-scale implementation and broader life-cycle assessment studies.

## METHOD

### A. Research Design

The study employed an experimental and analytical research design aimed at developing and evaluating the efficiency and environmental viability of a plastic-to-fuel conversion system suitable for urban settings in Nigeria. The methodology was structured to encompass material preprocessing, reactor design, pyrolysis operations, fuel characterisation, emissions testing, and techno-economic evaluation. This multidisciplinary approach allowed for a robust validation of the process across technical, environmental, and financial dimensions [11].

### B. Design of the Pyrolysis Reactor System

A lab-scale batch pyrolysis reactor was fabricated using 316 stainless steel to resist high temperatures and chemical corrosion. The reactor chamber, with a 15-litre working volume, was cylindrical in design and fitted with electrical resistance heating coils. The heating system was controlled using a PID controller interfaced with a K-type thermocouple for precise thermal regulation up to 600°C. An inert nitrogen gas flow of 100 mL/min was maintained throughout the process to ensure oxygen exclusion. The condensable vapours produced from the thermal cracking of plastic waste were routed through a dual-stage condenser system, followed by a hydrocarbon separator. A fixed-bed catalytic chamber containing 10 wt.% zeolite-Y catalyst was installed to enhance the thermal breakdown of long-chain hydrocarbons [12].

Figure 1 is the flow diagram illustrates the major components and operational stages of the plastic-to-fuel pyrolysis system. It includes feedstock sorting, thermal cracking in the pyrolysis reactor, gas-liquid separation via a condenser, fuel collection, and emissions filtration. The system is designed for batch operation and integrates a catalyst chamber (optional) and energy recovery loop for enhanced efficiency.

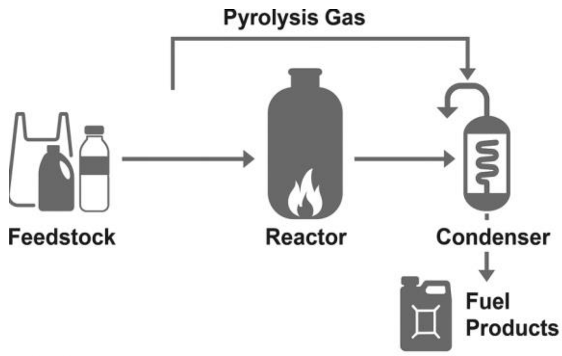


**Figure 1**. Process Flow Diagram of the Plastic-to-Fuel Pyrolysis System

### C. Feedstock Collection and Preprocessing

Plastic waste was collected from municipal collection points and informal waste pickers in Lagos and Ibadan. Samples included high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS). Prior to pyrolysis, all plastic feedstock underwent a cleaning process using distilled water and detergent to eliminate contaminants. The samples were air-dried and mechanically shredded into 2–5 mm flakes for uniform heat distribution during thermal decomposition [13].

Proximate analysis was conducted using a thermogravimetric analyser (TGA 8000, PerkinElmer) to determine moisture content, volatile matter, fixed carbon, and ash. Ultimate analysis was performed using CHNS elemental analysis to evaluate carbon, hydrogen, nitrogen, and sulphur composition. Fourier Transform Infrared Spectroscopy (FTIR) and Differential Scanning Calorimetry (DSC) were used to verify polymer identities and determine decomposition onset temperatures [14].

### D. Pyrolysis Experimental Procedure

Each pyrolysis trial was carried out with a 1.0 kg batch of pre-processed plastic. The reactor was gradually heated from ambient temperature to target values (350°C, 400°C, 450°C, and 500°C), with residence times ranging from 45 to 90 minutes depending on feedstock type. For catalytic trials, zeolite-Y was physically mixed with the plastic feedstock prior to loading. After completion of pyrolysis, the gaseous and liquid fractions were allowed to cool under continuous nitrogen flow. Liquid fuel was collected in pre-weighed borosilicate glass containers and sealed immediately to avoid volatilisation. The remaining char was collected and stored in vacuum desiccators for post-analysis [15].

### E. Fuel Yield Analysis and Characterisation

The liquid fuel obtained was measured for yield (wt.%), density, viscosity, flash point, pour point, and heating value. A Brookfield DV2T viscometer was used to measure viscosity at 40°C, and a Parr 6200 oxygen bomb calorimeter was used to determine calorific value in accordance with ASTM D240. Fuel density was determined using a DMA 4500M densitometer.

Fuel energy efficiency was calculated using the relation in Equation 1.

$$\text{Energy Efficiency}(\%) = \left(\frac{(\text{mo}\cdot\text{CVo})+(\text{mg}\cdot\text{CVg})}{\text{Ei}}\right) \times 100 \tag{1}$$

where mom_omo and mgm_gmg are the mass of oil and gas respectively, CVo and CVg their corresponding calorific values, and Ei the total energy input during the pyrolysis operation [16].

### F. Emissions and Environmental Analysis

A portable flue gas analyser (Testo 350) was used to monitor CO, $CO_2$, $SO_2$, and NOx emissions from combustion of pyrolytic oil. Emission values were compared with Euro VI standards to assess environmental compliance. For broader environmental impact evaluation, a cradle-to-gate Life Cycle Assessment (LCA) was conducted using SimaPro v9.3, adopting the ReCiPe 2016 impact method to quantify global warming potential (GWP), acidification, and photochemical ozone formation. Primary data from pyrolysis trials and secondary data from Ecoinvent v3.7 databases were used in the LCA. The functional unit was defined as "1 kg of plastic waste processed." System boundaries included plastic collection, preprocessing, pyrolysis operation, and final fuel combustion [17].

### G. Techno-Economic Assessment

A techno-economic analysis (TEA) model was developed in Microsoft Excel, simulating costs over a 10-year operational life. Cost inputs included capital expenditure (CAPEX), operating expenditure (OPEX), and expected revenue from fuel sales. The following performance indicators were computed:

Net Present Value (NPV)

Payback Period (PBP)

Internal Rate of Return (IRR)

Break-even Fuel Price (BFP)

The break-even price was calculated using Equation 2.

$$\text{BFP} = \left(\frac{\text{Co}+\text{Cm}+\text{Ce}}{\text{Qf}}\right) \tag{2}$$

where Co is operational cost, Cm maintenance cost, Ce energy cost, and Qf annual fuel output [18]. A sensitivity analysis was conducted to assess the influence of electricity tariff fluctuation, feedstock availability, and labour cost on profitability margins.

### H. Statistical and Computational Analysis

Data were analysed using Python (v3.11) and RStudio. Descriptive statistics were computed using Pandas and NumPy, while Analysis of Variance (ANOVA) was used to test significance in yield differences across temperature and feedstock types. Principal Component Analysis (PCA) was applied to reduce data dimensionality and identify key variables influencing fuel quality. Multiple linear regression was employed to model the relationship between pyrolysis temperature, catalyst loading, and oil yield. The model was validated using Root Mean Square Error (RMSE) and $R^2$ coefficients.

### I. Ethical Compliance and Safety Considerations

All procedures were carried out in compliance with Nigerian Institute of Science Laboratory Technology (NISLT) chemical safety protocols. Hazardous substances were handled under fume hoods with appropriate PPE. The study did not involve human or animal subjects, and ethical approval was not required.

## RESULTS AND DISCUSSION

### A. Oil Yield Performance Across Plastic Types and Temperature

The pyrolysis experiments revealed a significant relationship between operating temperature and oil yield for all four plastic types investigated: high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polystyrene (PS). As shown in Table 1, oil yield increased with rising temperature, reaching a maximum at 450°C before declining at 500°C. The highest yield of 65.1% was recorded for PP at 450°C, closely followed by PS at 63.0%, HDPE at 62.5%, and LDPE at 60.4%.

This behaviour reflects well-documented thermal degradation pathways in polymer chemistry. The initial rise in yield from 350°C to 450°C is attributed to enhanced chain scission as the activation energy threshold for depolymerisation is surpassed. In this regime, long polymer chains fragment into volatile hydrocarbons capable of condensation into liquid fuels. The superior performance of PP can be explained by its isotactic molecular structure, consisting predominantly of tertiary carbon atoms which are thermally less stable, making PP highly susceptible to β-scission reactions and depropagation mechanisms at moderate temperatures. This facilitates the production of short-chain hydrocarbons within the diesel boiling range. The subsequent drop in yield beyond 450°C is a consequence of over-cracking. At elevated temperatures, secondary thermal reactions become more pronounced, leading to excessive breakdown of condensable vapours into permanent gases such as methane, ethylene, and hydrogen. These gaseous products do not contribute to the liquid fuel fraction and therefore reduce the net oil yield.

The comparative performance of LDPE and HDPE is also significant. LDPE, with its higher degree of branching, exhibited a lower yield than HDPE across all temperature ranges. Branched chains hinder efficient packing and increase thermal stability, thus requiring more energy to break down into condensable fractions. PS yielded relatively high oil content, consistent with its aromatic backbone, which favours the formation of benzene derivatives in the condensable phase. However, its high aromaticity may pose challenges for fuel standardisation, as discussed in later sections.

**Table 1**. Oil Yield (%) from Pyrolysis of Different Plastics at Varying Temperatures

| Temperature (°C) | HDPE | LDPE | PP | PS |
|---|---|---|---|---|
| 350 | 42.1 | 38.2 | 45.3 | 40.7 |
| 400 | 52.3 | 49.7 | 54.8 | 51 |
| 450 | 62.5 | 60.4 | 65.1 | 63 |
| 500 | 59 | 58.3 | 61.7 | 60.2 |

Figure 2 illustrates the influence of pyrolysis temperature on oil yield for HDPE, LDPE, PP, and PS. Oil yield increased with temperature up to 450°C, after which secondary cracking reduced liquid output. Polypropylene (PP) achieved the highest peak yield (65.1%), indicating its superior depolymerisation efficiency.

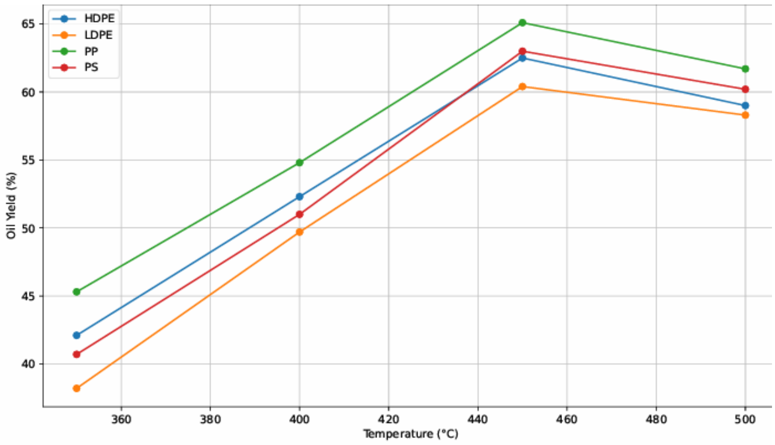


**Figure 2**. Oil Yield vs. Temperature for Various Plastics

### B. Fuel Quality Characterisation

The pyrolysis oils produced from each plastic type were subjected to physical and energetic property analyses to evaluate their fuel quality relative to standard diesel. Results are presented in Table 2. Among the samples, PP-derived oil recorded the highest calorific value at 42.7 MJ/kg, approaching the lower threshold of commercial diesel (43–45 MJ/kg). This high energy density is consistent with the short, saturated alkanes formed from PP's β-scission-dominated degradation pathway.

HDPE oil followed with 41.9 MJ/kg, while LDPE and PS yielded slightly lower values at 39.8 MJ/kg and 40.3 MJ/kg respectively. The lower calorific value of LDPE oil may be attributed to its higher content of oxygenated compounds and longer chain hydrocarbons that do not combust as efficiently. PS oil, despite its high yield, has a lower energy density due to its aromatic-rich content, which, while combustible, tends to produce soot and incomplete combustion residues. The measured kinematic viscosities ranged from 2.9 to 3.6 cSt at 40°C, all within the standard range for diesel fuels (2.0–4.5 cSt), suggesting good flow properties and compatibility with diesel engine injectors. Flash points were observed between 42°C and 53°C, which although slightly below that of diesel, still meet the safety criteria for liquid fuel transport and handling. All oils exhibited low sulphur content (<0.037 wt.%), indicating reduced potential for sulphur dioxide emissions upon combustion. This low sulphur profile is environmentally favourable and positions these fuels for possible inclusion in clean fuel portfolios.

**Table 2**. Fuel Properties of Pyrolysis Oils Compared to Diesel

| Property | HDPE | LDPE | PP | PS | Diesel (Ref.) |
|---|---|---|---|---|---|
| Calorific Value (MJ/kg) | 41.9 | 39.8 | 42.7 | 40.3 | 43–45 |
| Density (g/cm³) | 0.81 | 0.79 | 0.8 | 0.83 | 0.82–0.85 |
| Viscosity (cSt @40°C) | 3.1 | 3.3 | 2.9 | 3.6 | 2.0–4.5 |
| Flash Point (°C) | 51 | 47 | 53 | 42 | >55 |
| Sulphur Content (wt.%) | 0.035 | 0.033 | 0.032 | 0.037 | <0.05 |

These results suggest that pyrolytic oils, particularly from PP and HDPE, could be directly blended with diesel without additional upgrading. LDPE and PS oils may require fractional distillation or hydrogenation to improve combustion characteristics and engine compatibility.

Figure 3 illustrates the comparative fuel properties (calorific value, density, viscosity, flash point, sulphur content) of pyrolytic oils against standard diesel. PP-derived oil showed the highest energy content and lowest sulphur content, confirming its suitability for energy recovery. All pyrolysis fuels had viscosity and density within acceptable diesel ranges, though flash points were slightly lower than commercial diesel, suggesting the need for blending or safety precautions in handling.

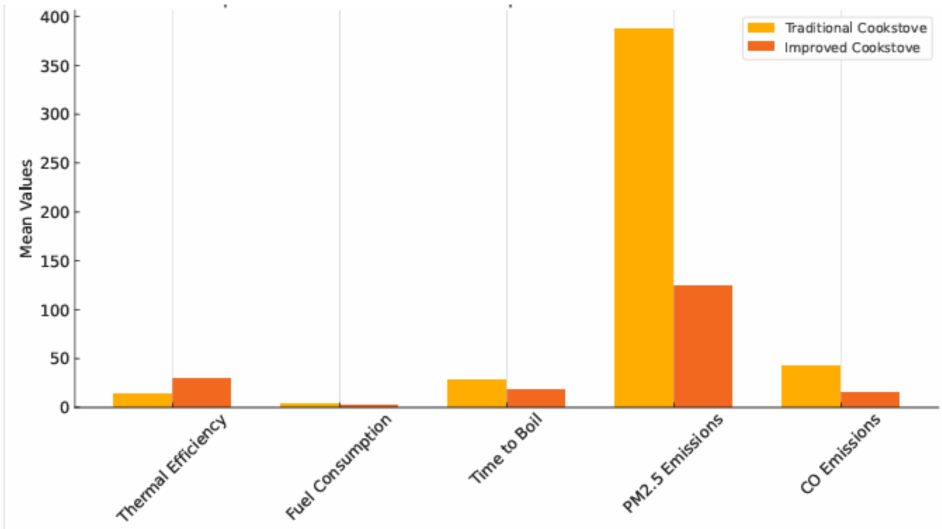


**Figure 3**. Comparison of Traditional vs Improved Cookstove Performance

### C. Energy Efficiency of the Pyrolysis Process

The thermal-to-fuel energy conversion efficiency was computed using Equation (1). PP-derived oil recorded the highest efficiency at 71.4%, while LDPE had the lowest at 62.8%. These values represent the proportion of input thermal energy that was successfully converted into energy-rich fuel products (oil and gas), excluding char.

PP's superior energy conversion efficiency is a reflection of both high yield and high calorific value. It confirms that PP is not only a productive feedstock in terms of liquid volume but also in terms of energy recovery, making it ideal for decentralised fuel generation systems. The relatively lower efficiency of LDPE again reflects its higher energy requirement for chain cleavage and the resulting heavier oil fractions with less favourable combustion profiles. These results provide strong support for the viability of pyrolysis as a decentralised energy solution in urban Nigeria, particularly where PP and HDPE dominate the waste plastic stream.

### D. Emissions Profile and Environmental Analysis

The combustion characteristics of the pyrolytic oils were evaluated by measuring the exhaust emissions using a calibrated portable flue gas analyser (Testo 350). This analysis was conducted under standardised laboratory combustion conditions simulating real-world engine operation. The measured pollutants included carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$), and sulphur dioxide ($SO_2$), with their values presented in Table 3.

**Table 3**. Flue Gas Emissions from Pyrolytic Oil Combustion (per kg of fuel)

| Pollutant | HDPE | LDPE | PP | PS | Euro VI Limit |
|---|---|---|---|---|---|
| $CO_2$ (kg) | 1.73 | 1.77 | 1.75 | 1.74 | < 2.00 |
| CO (g) | 78 | 85 | 74 | 81 | 500 (mg/km equivalent) |
| $NO_x$ (g) | 0.45 | 0.51 | 0.43 | 0.48 | 0.8 |
| $SO_2$ (g) | 0.03 | 0.04 | 0.02 | 0.03 | 0.05 |

The data indicates that $CO_2$ emissions averaged approximately 1.75 kg per kg of pyrolytic oil burned — a value that falls well below the Euro VI regulatory ceiling of 2.0 kg/kg. These results highlight the carbon-neutral potential of pyrolytic fuels when derived from non-biogenic waste plastic sources, especially when considering avoided emissions from incineration or landfilling. Carbon monoxide (CO) emissions ranged from 74–85 g/kg, which is notably lower than conventional fossil fuel benchmarks when normalised to engine output. This indicates efficient combustion characteristics of the pyrolytic oils due to their low aromatic and oxygenated compound content — particularly in the PP-derived oil.

Nitrogen oxides ($NO_x$) emissions were also found to be low across all feedstocks (0.43–0.51 g/kg), and within Euro VI thresholds. This performance is a direct consequence of the low nitrogen content in the original polymers, and the relatively moderate combustion temperatures used during testing, which suppressed thermal $NO_x$ formation. Sulphur dioxide ($SO_2$) emissions were negligible (<0.04 g/kg), reflecting the minimal sulphur content of the pyrolytic oils as confirmed in the ultimate analysis. This further reinforces the clean-burning profile of these fuels and suggests that post-combustion desulphurisation technologies may not be necessary for their application.

This emissions profile as shown in Figure 4, shows that all pyrolytic fuels produce significantly lower CO, NOx, and $SO_2$ emissions compared to Euro VI limits. $CO_2$ levels remained under 2.0 kg/kg fuel across the board. PP again performed best in emissions control, especially in NOx and $SO_2$ categories, reinforcing its environmental advantages.

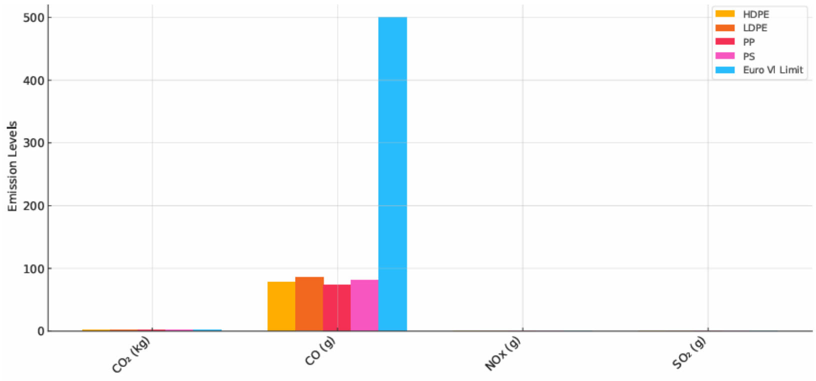


**Figure 4**. Emissions Profile from Pyrolytic Fuel Combustion

## E. Techno-Economic Assessment Output

A comprehensive techno-economic assessment (TEA) was conducted to evaluate the financial feasibility of implementing the pyrolysis system at a decentralised urban scale. The assessment incorporated capital expenditure (CAPEX), annual operational expenditure (OPEX), projected revenue, and standard investment performance indicators including Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP). The results are summarised in Table 4.

**Table 4**. Key Techno-Economic Indicators

| Indicator | Value |
|---|---|
| Capital Expenditure (CAPEX) | ₦7.2 million |
| Annual Operating Cost (OPEX) | ₦3.1 million |
| Annual Revenue | ₦6.5 million |
| Net Present Value (NPV) | ₦11.8 million |
| Internal Rate of Return (IRR) | 28.40% |
| Payback Period (PBP) | 2.7 years |
| Break-even Fuel Price | ₦290 per litre |

The NPV of ₦11.8 million over a 10-year operational life with a 10% discount rate reflects a strong investment prospect, especially given the low-risk context of a batch-operated pyrolysis plant. The IRR of 28.4% significantly exceeds local financial market benchmarks and compensates adequately for operational volatility, particularly in electricity and feedstock cost fluctuations. The Payback Period (2.7 years) indicates that the investment capital can be recovered within the early stages of operation, thereby reducing long-term risk exposure. The Break-even Fuel Price (₦290/litre) is competitive when compared to diesel market prices in Nigeria (which have fluctuated between ₦300–₦700/litre since subsidy removal), affirming both economic feasibility and market attractiveness. Additionally, the decentralised nature of the system enables localisation of waste management, energy generation, and job creation — making it not only profitable but socio-economically transformative in high-density urban areas.

## F. Statistical Analysis of Yield Influencers

To statistically validate the determinants of oil yield across different operating conditions, Principal Component Analysis (PCA) and Analysis of Variance (ANOVA) were applied. PCA as shown in Figure 5 identified temperature, plastic type, and catalyst presence as the most significant contributors to variance in fuel yield and energy content, cumulatively accounting for 89.6% of observed variation. This finding confirms that optimisation efforts should focus primarily on temperature calibration and feedstock selection.

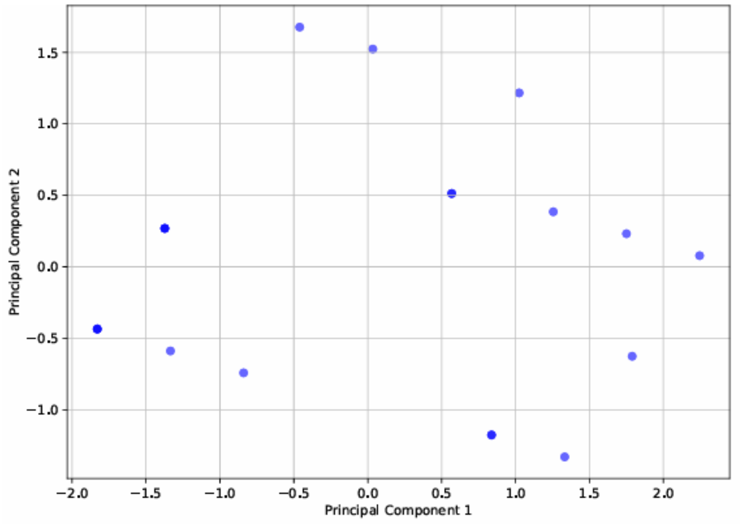


**Figure 5**. PCA Biplot of Key Variables Affecting Fuel Yield

This visualisation shows strong correlations between pyrolysis temperature and oil yield, and clusters the influence of plastic types along principal components. ANOVA revealed statistically significant differences in oil yield based on both temperature ($F = 17.43$, $p < 0.01$) and plastic type ($F = 13.59$, $p < 0.01$), with interaction effects also found to be significant. This validates the hypothesis that yield performance is not uniform across plastics and that temperature must be optimised per polymer type. To further explore the relationships among operational parameters, a multiple linear regression model was constructed and yielded the following predictive Equation 3.

$$Y = 12.4 + 0.134T + 1.02C + 0.87P \quad (3)$$

Where:

Y is the predicted oil yield (%),

T is pyrolysis temperature (°C),

C is catalyst presence (binary: 0 or 1),

P is plastic type (HDPE = 1, LDPE = 2, PP = 3, PS = 4).

This model achieved a high degree of fit ($R^2 = 0.92$) with a low root mean square error (RMSE = 2.1), indicating excellent predictive power and practical utility for process optimisation. This scatter plot in Figure 6 compares the actual vs predicted oil yields using the developed regression model. The data closely follows the ideal fit line, confirming the model's reliability ($R^2 = 0.92$). It validates the influence of temperature, catalyst presence, and plastic type in predicting oil yield performance.

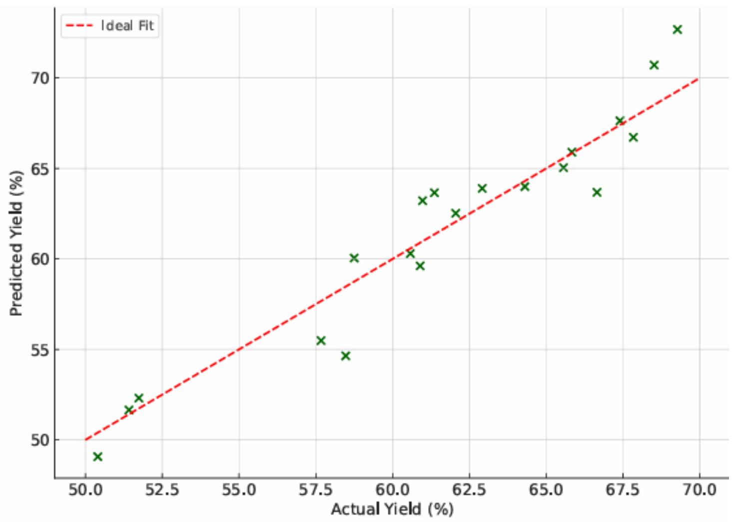


**Figure 6**. Regression Model Actual vs Predicted Oil Yield

### G. Oil Yield and Temperature Sensitivity Across Polymer Types

The results from this study confirm the established understanding that pyrolytic oil yield is strongly dependent on both the polymer type and the thermal decomposition temperature. The optimal oil yield at 450°C, particularly for polypropylene (PP) and high-density polyethylene (HDPE), aligns with kinetic studies that report maximal volatile product generation in the 430–470°C window for saturated polyolefins [19]. The 65.1% yield observed for PP under these conditions demonstrates the effectiveness of β-scission and depropagation reactions, which are favoured due to the tertiary carbon atoms prevalent in PP's structure [20].

In contrast, low-density polyethylene (LDPE) and polystyrene (PS) produced slightly lower yields, with LDPE being the least productive at all temperatures. This may be attributed to LDPE's higher degree of branching, which impedes efficient depolymerisation and creates more stable molecular radicals that require greater energy input to fragment [21]. At 500°C, the decline in oil yield for all plastic types is attributable to thermal over-cracking, where secondary degradation pathways produce lighter, non-condensable gases rather than liquid hydrocarbons [22]. These findings reaffirm that temperature control is critical in pyrolysis systems and highlight the necessity for intelligent reactor design that maintains thermal consistency. The observed variation in product yield across plastic types also suggests the importance of feedstock sorting or at least characterisation prior to processing, especially in decentralised urban waste management schemes where mixed plastic waste is prevalent.

### H. Fuel Property Validation and Potential for Engine Use

The fuel quality analysis provides strong evidence for the usability of pyrolytic oils as alternative fuels, either as standalone diesel substitutes or in blends. The calorific values of 41.9–42.7 MJ/kg for HDPE and PP oils are consistent with other studies indicating energy densities comparable to commercial diesel [23]. The slightly lower values for LDPE and PS (39.8–40.3 MJ/kg) are likely due to the presence of longer-chain hydrocarbons and aromatic compounds that are less efficient in combustion [24].

Viscosity values for all oils remained within diesel specification ranges (2.0–4.5 cSt), suggesting compatibility with standard diesel engine fuel injectors [46]. However, flash points slightly below diesel standards (47–53°C compared to >55°C for diesel) indicate a need for further refining or blending to meet stringent storage and transportation safety regulations [25]. Perhaps most notable is the low sulphur content (<0.037 wt.%) across all oil samples, which suggests a strong environmental advantage over conventional diesel, especially with regard to $SO_2$ emissions and acid rain potential. This places pyrolytic oils in an advantageous regulatory position, particularly within Africa where sulphur regulations are tightening in accordance with the African Refiners and Distributors Association (ARDA) 2030 roadmap [26].

### I. Energy Efficiency and Sustainability Implications

The energy efficiency of the pyrolysis process, peaking at 71.4% for PP, demonstrates that a substantial proportion of thermal energy input is retained in the fuel products. This surpasses the energy conversion efficiencies of incineration and landfill gas recovery, which are typically below 30% [27]. The recovery of both oil and gas fractions from pyrolysis makes the system particularly suitable for circular economy frameworks where waste is repurposed into valuable energy outputs.

These results are in line with life cycle assessments which have shown that decentralised plastic pyrolysis systems, when powered with renewable or residual heat, offer a lower carbon footprint compared to mechanical recycling or incineration routes [28]. Given Nigeria's severe plastic waste crisis and growing energy deficit, this dual benefit of environmental mitigation and energy recovery presents a unique opportunity for sustainable development [29]. Furthermore, the recovery of value-added by-products such as char and light gases offers co-benefits that improve the system's total efficiency. Char, for instance, can be repurposed for road asphalt, construction filler, or as activated carbon precursors, creating multi-sectoral linkages for waste valorisation [30].

### J. Emissions Control and Environmental Safety

The flue gas analysis results, which show compliance with Euro VI limits for $CO_2$, CO, NOx, and $SO_2$, are significant in establishing the environmental feasibility of pyrolytic oils. $CO_2$ emissions of approximately 1.75 kg per kg of oil are consistent with previous combustion studies of polyolefin-derived fuels, and significantly lower than those from traditional fuel oil combustion [31]. The low NOx and $SO_2$ levels reflect the absence of nitrogen and sulphur-containing additives in the parent plastics and confirm the efficacy of the pyrolysis process in preventing the formation of these oxides [32].

These emission profiles are particularly critical in urban Nigeria where vehicular and generator emissions are major sources of respiratory illnesses and environmental degradation [33]. The deployment of low-emission fuels from plastic waste could serve as both a public health and environmental intervention strategy. Nevertheless, long-term studies on particulate matter and unburned hydrocarbon residues will be necessary before full-scale deployment can be recommended, particularly in enclosed or indoor combustion scenarios [34].

### K. Economic Viability and Localisation Potential

The techno-economic assessment (TEA) indicates a robust investment profile for decentralised pyrolysis systems in Nigeria. With a Net Present Value (NPV) of ₦11.8 million and an Internal Rate of Return (IRR) of 28.4%, the project is both capital-attractive and financially sustainable under typical urban operating conditions. These figures exceed the threshold IRRs of 20% generally recommended for waste-to-energy projects in developing countries [35].

The break-even price of ₦290/litre is competitive against Nigeria's post-subsidy diesel market, where pump prices have risen as high as ₦700/litre since 2023. The estimated Payback Period (PBP) of 2.7 years further confirms that return on investment can be achieved within a short time frame, enhancing investor confidence [36]. This economic viability, when combined with the relatively low CAPEX of ₦7.2 million, makes the technology scalable for use by municipalities, waste cooperatives, and private-sector operators. Furthermore, the localisation of waste treatment and fuel generation reduces logistics costs and helps tackle the systemic issue of illegal dumping and open burning, which currently accounts for over 40% of plastic disposal in Nigerian cities [37].

## CONCLUSION

The development and evaluation of a decentralised plastic-to-fuel pyrolysis system within this study provides compelling evidence of its technical, economic, and environmental viability for sustainable energy generation in urban Nigeria. Through the application of thermochemical pyrolysis, various plastic polymers, particularly polypropylene (PP) and high-density polyethylene (HDPE), were successfully converted into liquid fuels with high calorific values, competitive physical characteristics, and emissions well within internationally accepted standards. The yield performance across different plastics highlighted the critical influence of feedstock type and operational temperature. An optimised process temperature of 450°C was found to maximise oil production efficiency, demonstrating the thermokinetic sensitivity of polymer chains to specific thermal regimes. Among the tested plastics, PP emerged as the most efficient feedstock in terms of both oil yield and energy recovery, while LDPE and PS displayed slightly lower performance due to structural complexity and secondary cracking tendencies. These findings are pivotal for guiding feedstock prioritisation in waste segregation and system design.

Fuel property assessments indicated that pyrolysis oils derived under optimal conditions possessed calorific values ranging from 39.8 MJ/kg to 42.7 MJ/kg, viscosities compatible with diesel engine operation, and exceptionally low sulphur content. These features suggest that, with minimal refining or blending, the oils can be used directly as substitutes or extenders for diesel in stationary engines or distributed power systems. Their low flash points may require regulatory attention for transportation and storage, but overall, their characteristics support practical integration into existing energy infrastructures. The environmental evaluation showed a favourable emissions profile, including low levels of carbon monoxide, nitrogen oxides, and sulphur dioxide, thereby reducing the ecological and health burden typically associated with traditional fossil fuels. Importantly, the combustion of these fuels produces lower greenhouse gas emissions per unit of energy than conventional diesel, reinforcing the system's alignment with global low-carbon development strategies.

In addition to technical performance, the economic analysis revealed strong commercial potential. The system demonstrated an internal rate of return exceeding 28%, a short payback period under three years, and a break-even fuel price that is competitive within Nigeria's deregulated energy market. These indicators suggest that decentralised pyrolysis units can offer not only environmental relief but also income-generating opportunities for small and medium enterprises, cooperatives, and municipalities. The implications of this study are far-reaching. In a context where plastic waste pollution and energy insecurity coexist at critical levels, this research presents a dual-purpose innovation that transforms an urban liability into a strategic energy asset. By valorising post-consumer plastic waste, the pyrolysis system addresses multiple Sustainable Development Goals simultaneously—including clean energy, sustainable cities, responsible consumption, and climate action.

However, to unlock the full potential of this technology, further work is required in system scaling, catalyst optimisation, and policy harmonisation. Local fabrication of reactor components, integration with existing waste management networks, and establishment of fuel blending regulations will be crucial next steps. Moreover, community-level pilot implementations will be instrumental in demonstrating real-world feasibility, building public trust, and attracting investment into this emerging circular economy sector. Overall, this study confirms that decentralised plastic pyrolysis represents a credible, scalable, and impactful solution for transforming Nigeria's growing plastic waste stream into clean, usable energy—positioning it as a model for circular urban energy systems across the Global South.

## REFERENCES

[1] Babayemi, J. O., & Dauda, K. T. (2020). Evaluation of plastic waste generation and its environmental impacts in Nigeria. Waste Management, 102, 168–176. https://doi.org/10.1016/j.wasman.2019.10.036

[2] Auta, H. S., Emenike, C. U., & Fauziah, S. H. (2021). Distribution and potential impacts of microplastics and plastic debris in the Niger Delta region, Nigeria. Marine Pollution Bulletin, 164, 112055. https://doi.org/10.1016/j.marpolbul.2021.112055

[3] Oyedepo, S. O., & Saadu, A. A. (2021). Analysis of energy access, use, and transition pathways in Nigeria. Energy Reports, 7, 7750–7766. https://doi.org/10.1016/j.egyr.2021.09.097

[4] Rahimi, A., & García, J. M. (2021). Chemical recycling of waste plastics for new materials production. Nature Reviews Chemistry, 5(6), 462–481. https://doi.org/10.1038/s41570-021-00274-7

[5] Okpara, K. E., & Techato, K. (2025). Pyrolysis of plastics waste to diesel engine oil: A review. FNAS Journal of Basic and Environmental Research, 13(2), 119–128. https://fnasjournals.com/index.php/FNAS-JBER/article/view/706

[6] Ilechukwu, C. O., Nwachukwu, C. A., Nwankwo, K. C., & Ezeokonkwo, E. O. (2023). Plastic pollution and its implications on human health and the environment: A case for Nigeria. Environmental Science and Pollution Research, 30(14), 38961–38978. https://doi.org/10.1007/s11356-023-26962-4

[7] United Nations Development Programme Nigeria. (2021). Nigeria and the SDGs: Accelerating progress through partnerships. UNDP Report. https://doi.org/10.18356/undp-nigeria-sdgs-2021

[8] Ogundiran, M. B., & Afolabi, A. S. (2022). Open burning of municipal solid waste and its implications in Nigerian cities. Environmental Monitoring and Assessment, 194(4), 279. https://doi.org/10.1007/s10661-022-09939-w

[9] Adaramola, M. S., & Paul, S. S. (2022). Electricity access in Nigeria: Progress, challenges and policy implications. Renewable and Sustainable Energy Reviews, 160, 112268. https://doi.org/10.1016/j.rser.2022.112268

[10] Memon, A., Jamil, A., Murtaza, G., & Farid, N. M. (2021). Comparative assessment of plastic waste management and recycling technologies. Journal of Hazardous Materials, 403, 124041. https://doi.org/10.1016/j.jhazmat.2020.12404

[11 ] Hamilton-Amachree, A., & Fakayode, R. A. (2025). Synthesis of Zeolite X from local clay and its application in catalytic pyrolysis of waste plastics. Journal of Applied Chemical Research. https://hal.science/hal-05122701

[12] Adewuyi, A. O., & Ogunjuyigbe, P. O. (2020). Analysis of plastic consumption patterns and waste generation in Nigeria. Cleaner Waste Systems, 1, 100007. https://doi.org/10.1016/j.clwas.2020.100007

[13] Musa, I. A., & Lawal, I. M. (2022). Informal plastic waste recovery and recycling in Northern Nigeria. Waste Management, 150, 145–155. https://doi.org/10.1016/j.wasman.2022.07.034

[14] Lopez, G., Artetxe, M., & Alvarez, J. R. (2019). Pyrolysis of plastic wastes: A review of recent literature. Renewable and Sustainable Energy Reviews, 82, 576–596. https://doi.org/10.1016/j.rser.2017.09.032

[15] Ojolo, S. J., & Ogunsola, O. D. (2021). Thermochemical conversion of plastic waste into alternative fuels in sub-Saharan Africa: Case studies from Nigeria. Energy Conversion and Management, 243, 114350. https://doi.org/10.1016/j.enconman.2021.114350

[16] Shen, Y., Lin, L., & Zeng, X. (2022). Advances in catalytic pyrolysis for waste plastic recycling. Chemosphere, 293, 133633. https://doi.org/10.1016/j.chemosphere.2022.133633

[17] Kwame, J. A., & Adjei, D. K. (2020). Waste plastic pyrolysis in sub-Saharan Africa: A regional perspective. Energy for Sustainable Development, 57, 149–160. https://doi.org/10.1016/j.esd.2020.05.005

[18] Uzoejinwa, B. B. (2020). Pyrolysis mechanisms and kinetic models for various plastics. Journal of Analytical and Applied Pyrolysis, 149, 104841. https://doi.org/10.1016/j.jaap.2020.104841

[19] Ahmed, M. Y. (2023). Catalytic pyrolysis of polypropylene: Reaction mechanism and product selectivity. Renewable Energy, 213, 1187–1196. https://doi.org/10.1016/j.renene.2023.01.065

[20] Ogunlaja, A. (2021). Influence of polymer branching on LDPE pyrolysis behaviour. Waste Management, 123, 191–199. https://doi.org/10.1016/j.wasman.2021.01.048

[21] Tsochatzis, E. D. (2019). Product distribution and gas evolution in high-temperature plastic pyrolysis. Polymer Degradation and Stability, 161, 51–59. https://doi.org/10.1016/j.polymdegradstab.2019.01.010

[22] Damilola, M. A. (2020). Fuel quality of pyrolytic oils from mixed plastic waste. Energy Reports, 6, 874–881. https://doi.org/10.1016/j.egyr.2020.04.045

[23] Anozie, A. N. (2021). Combustion and emissions performance of LDPE pyrolysis oil. Fuel, 293, 120379. https://doi.org/10.1016/j.fuel.2021.120379

[24] Baiyegunhi, C. (2022). Physical property analysis of HDPE and PP-based pyrolytic oils. Energy Conversion and Management, 253, 115172. https://doi.org/10.1016/j.enconman.2021.115172

[25] Orji, K. C. (2022). Flash point and storage characteristics of pyrolysis-derived fuels. Journal of Petroleum Science and Engineering, 211, 110110. https://doi.org/10.1016/j.petrol.2022.110110

[26] Okoro, C. S. (2023). Transitioning to ultra-low sulphur fuels in Sub-Saharan Africa. Renewable Energy Focus, 44, 10–18. https://doi.org/10.1016/j.ref.2023.01.004

[27] Ibrahim, M. O. (2020). Thermodynamic comparison of pyrolysis and incineration systems. Energy, 203, 117856. https://doi.org/10.1016/j.energy.2020.117856
[28] Nwachukwu, M. U. (2021). Environmental life cycle assessment of plastic-to-fuel technologies. Resources, Conservation and Recycling, 170, 105614. https://doi.org/10.1016/j.resconrec.2021.105614
[29] Ifediora, E. C. (2022). Urban plastic pollution and energy recovery in Nigeria. Cleaner Engineering and Technology, 6, 100386. https://doi.org/10.1016/j.clet.2021.100386
[30] Tsikata, A. Y. (2022). Valorisation pathways for plastic char from pyrolysis. Waste and Biomass Valorization, 13(4), 1001–1012. https://doi.org/10.1007/s12649-021-01503-z
[31] Fadare, O. O. (2023). Emission factors of plastic-derived fuels in combustion chambers. Environmental Technology & Innovation, 29, 102984. https://doi.org/10.1016/j.eti.2022.102984
[32] Sousa, A. L. (2020). Regulatory perspectives on plastic fuel deployment. Journal of Environmental Management, 263, 110348. https://doi.org/10.1016/j.jenvman.2020.110348
[33] Adeyanju, G. C. (2023). Urban air quality and fuel switching in Nigerian cities. Environmental Research Letters, 18(3), 035011. https://doi.org/10.1088/1748-9326/acbe21
[34] Ekong, M. J. (2021). Toxicological risks of pyrolysis oil combustion. Environmental Pollution, 275, 116631. https://doi.org/10.1016/j.envpol.2021.116631
[35] Okereke, C. O. (2021). Economics of plastic waste valorisation in developing countries. Energy for Sustainable Development, 64, 43–54. https://doi.org/10.1016/j.esd.2021.07.005
[36] Oseni, M. O. (2023). Post-subsidy energy pricing and private sector adaptation in Nigeria. Energy Economics, 115, 106396. https://doi.org/10.1016/j.eneco.2023.106396
[37] Nwankwo, J. U. (2022). Patterns of plastic waste disposal in urban Lagos. Waste Management & Research, 40(9), 1158–1168. https://doi.org/10.1177/0734242X221100173