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Conversion of Solid Wastes to Fuel Energy Resources through Normal and Catalytic Pyrolysis Process Conditions: A Renewable Resources Strategy

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Abstract

This paper presents findings of a study on solid wastes conversion into fuels through pyrolysis of plastic materials, presenting an alternative renewable approach for waste management. Investigations were conducted on conversion of polypropylene (PP), low-density polyethylene (LDPE) and high-density polyethylene (HDPE) under normal and catalyst mediated process conditions. Plastic wastes were collected from various dumpsites in Nairobi and segregated using plastic resin codes to various classes. Samples were cleaned, dried and shredded to 2 mm and fed into a pyrolysis reactor. The pyrolysis process was conducted at between 220˚C and 420˚C. Pyrolysis gases were condensed in a shell and coil condenser and the incondensable gases were stored in gasbags. Liquid fuels were analysed using Gas chromatograph with a mass spectroscopic detector and Fourier Transform Infrared Spectrometry. The results revealed that the most optimal process conditions were a temperature range of 220˚C - 420˚C at a heating rate of 10˚C per minute. Under these conditions, the oil yields were 53.72% for PP, 62.10% for LDPE, and 64.14% for HDPE. As the heating rate increased from 10˚C/min to 20˚C/min, gas yields increased, rising from 28.05% to 31.12% in PP, 14.96% to 30.62% in LDPE, and 18.51% to 29.49% in HDPE. The introduction of Fe_2O_3 and Al_2O_3 catalyst significantly enhanced gas production during pyrolysis, increasing yields from 18% to 61% and 47% respectively.

Keywords

Pyrolysis, Alternative Fuels, Plastic, Valorization, Polypropylene, High Density Polyethylene, Low Density Polyethylene

1. Introduction

The rapid increases in urbanization, population growth and economic activities have led to increased demand for energy [1]. It has also led to the overuse of fossil fuels, which is estimated to be responsible for 80% of global consumption which is approximately 13.6 million metric tons per day, resulting to release of greenhouse gases and other gases that lead to harmful environmental effects and global warming [2].

Fossil fuel processing also goes with the production of plastics as low-grade products. The global production of plastic has reached staggering levels, resulting in an escalating environmental crisis due to the improper disposal and inefficient recycling of plastic waste [3]. The extensive use of plastics in packaging, consumer goods, and various industrial applications has led to the proliferation of plastic waste, causing pollution of land, water bodies, and marine ecosystems [4]. Plastic waste is the most common type of litter in the ocean, making up 80% of all marine debris [5]. Fourteen million tons of plastic end up in the ocean each year, and plastic is found in drinking water, carbonated beverages, salt, and other digestible [6]. Plastic has been found to cause cancer and damage the body's endocrine system, as well as cause developmental, reproductive, neurological, and immune related disorders in humans. Micro plastics have even been found in human placentas [7]. Currently, awareness of the implications of plastic wastes on the environment is increasing and, hence, micro-scale decisions towards overcoming this challenge are being considered [8].

1.1. Plastic Waste Management

Conventional waste management methods, such as landfilling and incineration, have proven inadequate in mitigating the environmental impact of plastic waste, necessitating the exploration of innovative and sustainable approaches [9]. Plastics are a type of hydrocarbon-based, flexible polymeric material that can be moulded through the application of heat and pressure [10]. This flexibility allows plastics to be fashioned into a wide variety of products for industrial and household use [11]. In today's world, the use of plastic is more widespread than ever before. The increasing generation of wastes has led to significant challenges, as wastes accumulates without an effective method of disposal; thus requiring innovative conversion techniques such as chemical, biochemical, thermochemical and use of microbes in waste processing to energy and other products [12].

The European Union Action Plan for a circular economy introduced a strategy for management of plastics, which aims to curb plastic pollution and its negative impact on the environment [13]. The strategy suggests encouraging industrial processes and innovations that utilize waste plastics as feedstock to create useful chemicals for generation of alternative fuels from various wastes. This will incentivize recycling of waste plastics, reduce the problems caused by them, and create an alternative source of chemicals. This will promote a circular economy.

1.2. Plastic Wastes as Energy Resources

Using waste plastics as an alternative feedstock for alternative fuel production has advantages in that the plastics are produced from fossil fuels and their conversion to hydrogen goes some way to minimize the use of fossil fuels by “recycling” the hydrogen [14]. Pyrolysis is the degradation of organic materials under the effect of heat and in the absence of oxygen. There is rising interest in the thermal conversion of plastics into high-value outputs and pyrolysis-catalysis is considered as a promising technology for plastic utilization [15]. Various research studies have shown that different types of plastics can be converted into high-value products like synthesis gas [16]. Producing alternative fuels from plastics is a promising technology from both economic and environmental perspectives. However, the main challenge is to increase the efficiency of fuels production from pyrolysis of plastic waste. This study investigated the conversion of PP, HDPE, and LDPE into liquid and gaseous alternative fuels under different pyrolysis conditions.

2. Materials and Methods

2.1. Plastic Wastes Collection and Preparation

The plastic waste was sampled from waste dumpsites in Nairobi, Kenya (**Figure 1**). The wastes were segregated using resin codes set by the ASTM (American Society for Testing and Materials) into code 5, for Polypropylene (PP), 4 for high-density polyethylene (HDPE) and 2 for low-density polyethylene (LDPE). Composites of each class were crushed using a blades and Cutters shredder, homogenised, cleaned with detergents and sundried in the open facilitating consistent heat transfer during the thermal degradation process. The shredded waste was then transported to lab for pyrolysis experiments.

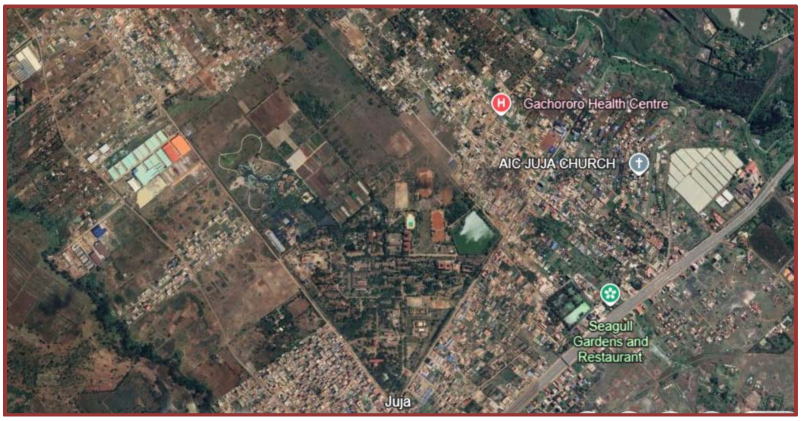


Figure 1. Selected study area for the collection of the plastic waste.

2.2. Processing of Plastic Wastes to Energy Resources

The pelletized plastic samples, each weighing 700 grams, were introduced into the reactor in batch mode. The reactor was preheated to a temperature of 220˚C prior to sample loading. To ensure an oxygen-free environment, nitrogen gas was continuously purged into the reactor at a flow rate of 2 L/min, creating an inert atmosphere conducive to the pyrolysis process. The temperature was increased to 420˚C at a heating rate of 10˚C /minutes.

2.3. The Pyrolysis Reactor Design

The experimental setup utilized a mild steel batch reactor (300 cm height, 30 cm inner diameter, 50 cm outer diameter). As shown in **Figure 2**, the reactor includes the following components:

- **Waste Injection Port:** Allows controlled feeding of plastic feedstock.
- **Catalytic Chamber:** Hosts catalysts (Fe_2O_3 and Al_2O_3) for optimizing cracking reactions.
- **Heating System:** Externally heated helical coil ensuring uniform heat distribution.
- **Gas Cleaning Unit:** Features silica gel and activated carbon for effective gas purification.
- **Cooling System:** An efficient condenser recovers liquid oil from volatile gases.

The reactor, constructed with mild steel, provides excellent corrosion resistance, thermal conductivity, and durability. Insulation minimizes heat loss, enhancing energy efficiency.

The reactor's modular design enables scalability for industrial applications while maintaining cost-effectiveness through locally sourced materials. However, detailed specifications such as the material grades, thickness, and specific insulation properties should be included to ensure reproducibility. Additionally, the design rationale, such as why mild steel was chosen over alternative materials, should be explicitly stated to justify its suitability for high-temperature operations.

Pyrolysis was done aided by a fabricated batch reactor made of solid iron (height 300 cm, inner diameter 30 cm and outer diameter 50 cm) as shown in **Figure 3** [17] [18]. The reactor parts are listed in **Table 1**, along with their specifications

2.4. Dimensions and Operation

A gas cleaning and recovery chamber incorporating a condenser unit, a filtration system to remove impurities, and a non-condensable gas recovery unit. The system also included temperature monitoring and control, using a thermocouple to ensure precise regulation of heating rates and temperatures. The reactor was constructed using mild steel for its high-temperature and corrosion-resistant properties, high thermal conductivity to ensures efficient, uniform heat distribution, enhancing energy efficiency, product quality, and reactor longevity with additional insulation to improve energy efficiency. The reactor was encased in aluminium with a concrete lining inside for thermal insulation and structural durability. A Pyrolysis chamber made of mild steel (height 50 cm, inner diameter 30 cm and outer diameter 40 cm) as shown in **Figure 3** was adopted as described in [18] [19].

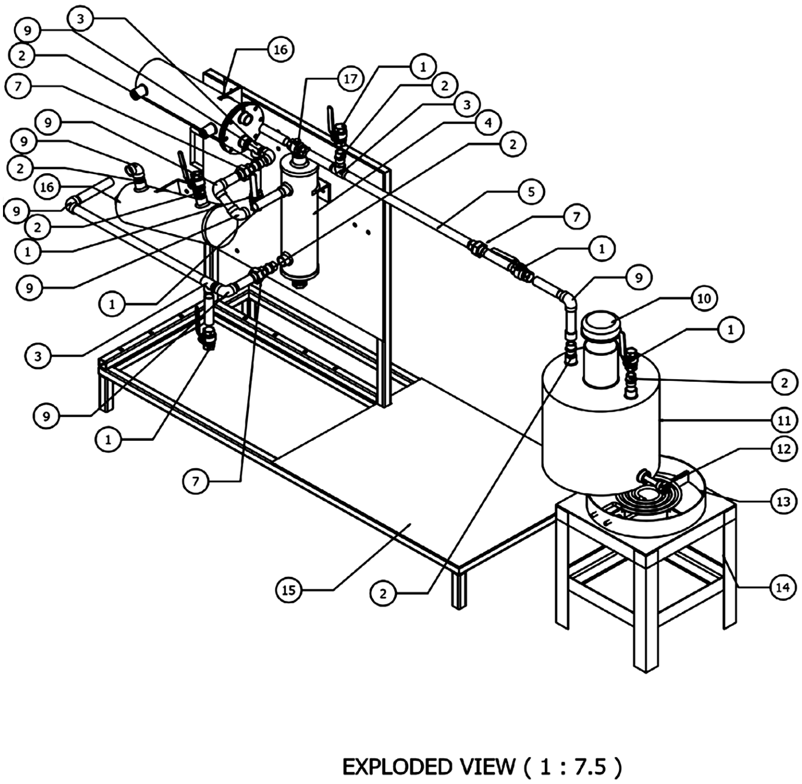


Figure 2. Drawing of the pyrolysis reactor showing its exterior parts.

Table 1. Detailed description of the numbering on **Figure 2**.

Number	Description
1	1/2 inch ball valve with female connection
2	G 1/2 male Hex nipple
3	G 1/2 Female T piece
4	Drier (Silica granules chamber)
5	½ inch galvanised pipe
6	G 1/2 Pipe union
7	G 1/2 Female Elbow
8	G Pyrolysis Chamber Cap
9	Pyrolysis Chamber Reactor
10	3/4 inch Hot well for thermocouple connection
11	Electric Heater Coil
12	Heater Stand
13	Mounting Stand
14	Treatment Channel (Activated Carbon)
15	Condenser

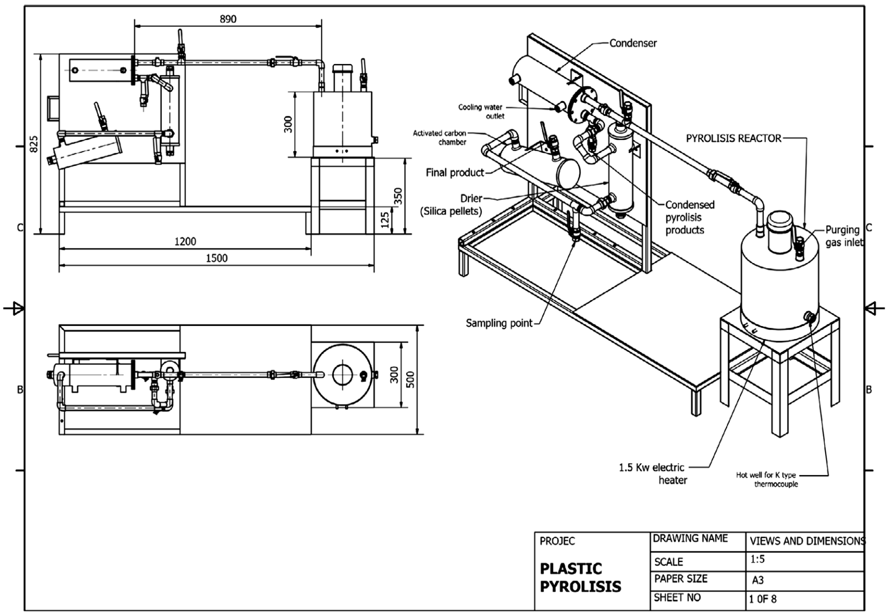


Figure 3. Schematic representation of the pyrolysis reactor with dimensions.

2.5. Pyrolysis Process Control and Conversion of Resultant Gases to Fuels

The pyrolysis process was performed in an oxygen-free environment to avoid oxidation of the feed materials, with temperatures ranging between 220˚C and 450˚C. The reactor was preheated to a 220˚C after which 700 g of plastic waste was added. To ensure an oxygen-free environment, nitrogen gas was continuously purged into the reactor to create an inert atmosphere. As the temperature rose, the plastic was heated and broken down to liquid. With increase in temperature, the liquid plastic's structure long hydrocarbon chains break down into shorter hydrocarbons, converting the liquid to gas [20]. A catalyst chamber integrated into the reactor facilitated cracking reactions.

The resultant volatile gases produced were directed into a cooling system equipped with a condenser and were condensed into liquid pyrolysis oil. Any residual moisture in the gases were removed using a silica gel drying unit, ensuring that the product stream was free of water vapor. The remaining gases were passed through an activated carbon filter and air scrubber. The system's design ensured efficient separation and purification of the pyrolysis products, enhancing both process efficiency and product quality. The waste samples were allowed to pyrolyze until no liquid oil was seen condensing. This pyrolysis time was recorded, and all other gaseous by-products were vented through silica gel drier and activated carbon filter. The oil and gases were then collected and stored as the reactor was allowed to cool to ambient temperature before collecting the ash residues (char) and weighed [21].

2.6. Pyrolysis Process Optimization

2.6.1. Heating Rate

The heating rate affects the thermal decomposition of plastics. Optimization of the pyrolysis process aimed at maximizing the yields of liquid oil and combustible gases at minimal energy consumption. Heating rates of 10, 15 and 20˚C/minute were used to determine the optimal conditions for rapid yet efficient breakdown of the feedstock [22].

2.6.2. Concentration

The feedstock concentration in the reactor influences heat transfer and product distribution. Relative proportions of HDPE, LDPE, and PP were used to assess how each plastic type contributes to oil yield, calorific value, and the formation of by-products, with mixtures analysed to determine the optimal blend for maximizing fuel production [23].

2.6.3. Temperatures

Pyrolysis operates within an optimal temperature range. Lower temperatures favour the production of oils, while higher temperatures shift the output toward gaseous products. The efficiency of the condensation chamber, which converts oil vapours into liquid, was assessed by adjusting its operating temperature and coolant flow rate, aiming to optimize liquid oil recovery while minimizing hydrocarbon loss to the non-condensable gas stream [24].

2.6.4. Catalytic Conversion

Metal oxide catalysts Fe_2O_3 and Al_2O_3 were introduced study effect on pyrolysis reaction. The catalysts were evaluated for their effectiveness in increasing the rate of polymer degradation and improving the quality of the liquid and gases products, thereby potentially increasing the overall yield of pyrolysis oil and combustible gases [25] [26].

2.7. Performance Tests

The total % yield was calculated using the equation (1):

$$\%\ \text{Total Yield} = \left(\left(M_1 - M_{12}\right)\times 100\right)/M_1 \tag{1}$$

where % Total yield is the total yield of liquid and gaseous products, M_1 is the original mass of the plastic sample, M_2 is the mass of the char. The mass of liquid oil (M_3) was obtained by weighing.

$$\text{Oil yield}\left(\%O\right) = \left(M_3 \times 100\right)/M_3 \tag{2}$$

$$\text{Char yield}\left(\%Ch\right) = \left(M_2 \times 100\right)/M_1 \tag{3}$$

Conversion to gas (G) was calculated by the given equation:

$$\text{Gas yield}\left(\%G\right) = 100 - \left(\%O + \%Ch\right) \tag{4}$$

2.8. Characterization of the Pyrolysis Products

Analysis of the functional group vibrations of the liquid and solid hydrocarbon products was carried out using a Fourier transform infrared spectroscopy (FTIR) (Bruker ALPHA) spectrophotometer between 4000 and 400 cm^{-1} wavenumbers.

Other physical properties including bulk density (ρ), calorific value, dynamic viscosity (μ) was measured using a precision weigh balance, digital bomb calorimeter (C200/3/1) and a redwood viscometer respectively. Properties of the extracted fuel properties including flash point (FP) were calculated using standard ASTM methods [27].

3. Results and Discussions

3.1. Physical Properties of Plastic Waste

Characterization of Feedstock

The physical properties of these materials are reported in **Table 2** below.

Table 2. Physical properties of shredded plastic feedstock.

Plastic	Bulk density (kg/m^3)	Calorific value (kJ/kg)
LDPE	0.419 ± 0.017	53135.37 ± 0.16
HDPE	0.413 ± 0.003	49085.78 ± 0.18
PP	0.491 ± 0.007	46300.00 ± 0.11

The calorific values were important to this experiment as they were used to assess for suitability in the pyrolysis process. It was noted that plastics with high calorific values are more desirable for energy recovery processes like pyrolysis. The bulk density which affects the packing of the plastic feedstock in the reactor was determined as it directly impacts heat transfer and overall yield.

These results for calorific values above agree with those reported by [27] earlier of 42,100 kJ/kg, 45,700 kJ/kg and 41,100 kJ/kg for HDPE, LDPE and PP feedstock respectively [12]. Pyrolysis of LDPE yields high amounts of short chain hydrocarbon oils e.g. Paraffin, which has a high calorific value. The study obtained bulk densities for HDPE 0.584 kg/m^3, LDPE 0.552 kg/m^3 and PP 0.574 kg/m^3.

3.2. Pyrolysis Products

Pyrolysis is a thermal decomposition process in the absence of oxygen, where organic materials are heated to break down into smaller molecules, producing three primary products: bio-oil, pyrolysis gas, and char. Bio-oil is a complex liquid mixture of organic compounds that can be used as a biofuel or further processed into chemicals. Pyrolysis gas, a mixture of gases like carbon monoxide, carbon dioxide, combustible gases and methane, can be used for power generation or chemical production. Char is a solid carbon-rich residue, which can serve as a fuel or be used as bio char to improve soil quality. The pyrolysis process involves heating the feedstock to high temperatures above 220˚C to initiate thermal decomposition. The volatiles released are condensed into liquid bio-oil or collected as pyrolysis gas, while the solid char remains in the reactor. The yield and composition of these products depend on various factors, such as temperature, heating rate, and feedstock type. Optimization of pyrolysis involves adjusting these parameters to improve product yield, efficiency, and quality. For example, higher temperatures generally favour gas production, while lower temperatures promote bio-oil formation. The heating rate significantly influence the products, with faster heating typically resulting in more bio-oil and less char.

4. Characterisation of Pyrolysis Products

4.1. Physicochemical Properties

The results of testing the physicochemical properties of the pyrolysis oils are presented in Table 3.

Table 3. The conversion yields and physical properties of the fuels produced from various types of plastics.

Physicochemical properties	Test method	HDPE	PP	LDPE
Density (kg/m³)	ASTM D 2638-10	0.717 ± 0.13	0.704 ± 0.3	0.706 ± 0.54
Calorific value (kJ/kg)	C200/3/1	49085.78	46,300	53135.37
Viscosity @ 28˚C (Cst)	Redwood viscometer	3.76 ± 1.72	2.3 ± 1.72	3.13 ± 1.72
Flash Point ˚C	ASTM, 2018	40	40	39

One of the parameters that determines the quality of fuel is its density. Density of pyrolysis oil was considered in this study as it influences factors including energy content and combustion efficiency as fuels with higher density contain more energy per unit volume enhancing fuel efficiency according to a study conducted by [28]. In a study by [29] the density of waste plastic pyrolysis oil was observed at 0.75 kg/m^3. The fuel derived from HDPE, PP, and LDPE manifested densities of 0.706, 0.704, and 0.717 kg/m^3, respectively, while the lowest density of 0.704 kg/m^3 was obtained for the PP-derived fuel. These values are significant as they are comparable to the density of commercial fuels, such as gasoline and diesel. Thus, the density of pyrolysis oil obtained in the range of 0.7 to 0.8 kg/m^3 corresponded to the density of commercially sold diesel indicating suitability for use as a fuel.

The calorific value of fuel is a measure of its energy content thus a significant determinant in its utilization as an alternative source of energy. The values obtained in this experiment were 49.09 MJ/kg, 46.30 MJ/kg, and 53.14 MJ/kg for HDPE, PP and LDPE respectively. These findings were within the range of conventional petrol and diesel fuel oils as highlighted in the study by [30] who obtained the calorific value for commercial sold petrol and diesel ranging between 35.166 and 42.057 MJ/kg. These oils are seen to consist of hydrocarbons just as conventional fuels demonstrating similar energy content in a unit mass of fuel can be compared to these conventionally sold fuels. The C-C chains in plastics are however longer and therefore, pyrolysis helps crack this high molecular weight fragments to low molecular weight fragments to obtain both gaseous and liquid products. The final oil products are however affected by contamination of the feedstock materials which are waste plastics affecting the quality of oil produced. The results obtained indicate that proper distillation would realize fuels that can be used alongside conventional fuels such as diesel and petrol. The viscosity was analysed to measure the resistance of pyrolysis oil to flow. Viscosity impacts the combustion process as well the engine efficiency as indicated by a research [31]. The study focused on the influence of viscosity on diesel engines performance with high viscosity attributed to poor fuel atomization and increase CO and HC emissions thus affecting combustion efficiency. The viscosity of fuel is influenced by factors such as feedstock type, temperature range, and pyrolysis conditions. Higher viscosity fuels lead to increased fuel consumption, as well as higher engine load and friction. The viscosity values of fuels derived from the pyrolysis of HDPE, PP, and LDPE plastics were 3.76, 2.3, and 1.72 cSt, respectively, which are comparable to those of commercially used high-speed diesel. [32] found a viscosity of 3.8 cSt for HDPE-derived fuels, similar to value of 3.76 cSt obtained. [33] reported 2.5 cSt for PP-derived fuels, which is comparable to observed value of 2.3 cSt and 1.75 cSt for LDPE-based fuels, close to the obtained value of 1.72 cSt.

The flash point of a fuel is the temperature at which it emits enough vapor to ignite when exposed to an open flame or spark. The given flash points for HDPE, PP, and LDPE are 40˚C, 40˚C, and 39˚C, respectively. These relatively low flash points indicate that the pyrolysis fuels derived from these plastics have similar flammability characteristics and are quite volatile, which is typical for fuels produced from plastic waste. Researchers [34] and [33] have reported similar flash point values for fuels derived from the pyrolysis of various plastics. [34] reported a flash point of 40˚C for HDPE-derived fuel, while [33] reported a flash point of 39˚C - 41˚C for pyrolysis fuels obtained from PP and LDPE. These studies support the notion that pyrolysis of plastics, particularly HDPE, PP, and LDPE, results in fuels with comparable volatility, making them suitable for further refinement and use as alternative fuels to conventional gasoline or diesel.

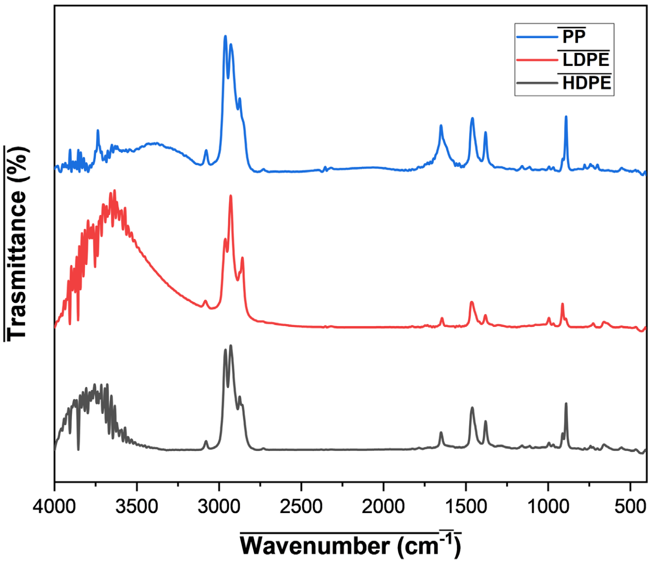
4.2. FTIR Analysis

Chemical Analysis of Fuel by FT-IR

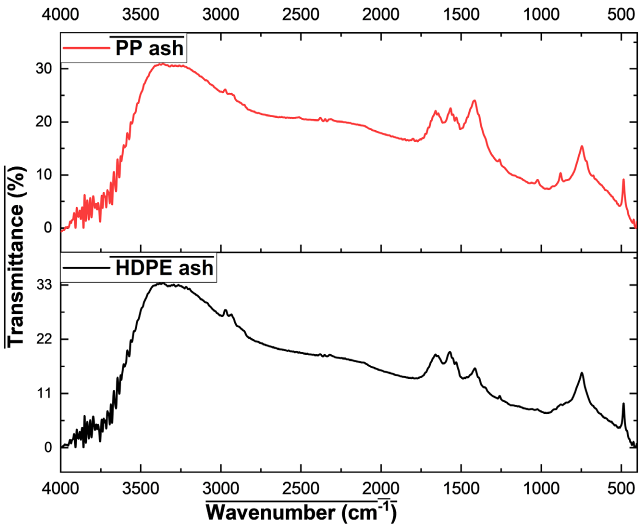
The FT-IR spectra of liquid and solid products derived from the process is represented in **Figure 4(a)** and **Figure 4(b)**.

To evaluate the chemical composition and the application of oils derived from the Pyrolysis process of the three polymers, FTIR analysis was performed. This analysis provides insights into the functional groups present and identifying any impurities that may affect fuel properties.

The FTIR spectra of HDPE, LDPE and PP oils have more similarities than differences since they all are generally made of hydro-carbons with chains of repeating methylene (CH_2–) units. C-H sp^2 vibrations were detected at ~3026 cm^{-1}. The appearance of several peaks between the range 1500 - 1600 cm^{-1} (1461 and 1377 cm) confirmed the presence of C=C functional groups. These two functional groups are an important occurrence since they confirm the forming olefins (olefination) through thermal cracking of the long chains HDPE, LDPE and PP bonds during the pyrolysis process [35]. Stretching vibration of C-H sp^3-hybridised were noticed at ~2950 cm^{-1} including C-H bending vibrations across 1400 - 1500 cm^{-1} [36]. Stretching O-H vibration modes of carboxylic and alkanes functional groups were represented by the peaks at 2961 cm^{-1} and 2908 cm^{-1} repsectively. At 1458 cm^{-1}, the C-C stretching of alkanes' and C-H bonds and aromatic rings of can be seen [28]. C-H Bending vibrations of olefins and alkanes can be seen with the peaks at 1374 cm^{-1}, 1162 cm^{-1}, and 964 cm^{-1} [37]. Also, wavenumbers 1746 cm^{-1} and 1169 cm^{-1} indicate the presence of C=O/CO ester functional groups [38]. Further analysis provided a quantitative comparison of peak intensities for example, the peak at 1746 cm^{-1} was found to have relative intensity ratios of 1.3:1 compared to the peak at 2950 cm^{-1}, suggesting a moderate presence of oxygenated impurities [39]. Minor peaks between 1450 and 1600 cm^{-1} were attributed to aromatic compounds, indicating incomplete cracking. The 3026 cm^{-1} peak intensity, representing olefins, dominated the spectra, confirming efficient cracking of long-chain hydrocarbons [40]. Expanded analysis provided a quantitative comparison of peak intensities. For example, the peak at 1746 cm^{-1} was found to have relative intensity ratios of 1.3:1 compared to the peak at 2950 cm^{-1}, suggesting a moderate presence of oxygenated impurities. Minor peaks between 1450 and 1600 cm^{-1} were attributed to aromatic compounds, indicating incomplete cracking. The 3026 cm^{-1} peak intensity, representing olefins, dominated the spectra, confirming efficient cracking of long-chain hydrocarbons. Potential impurities identified included oxygenated compounds (e.g., carboxylic acids and esters) and trace sulfur derivatives, which may affect fuel stability and performance [41]. These impurities necessitate additional refining for commercial applications. This detailed analysis improves the understanding of the chemical composition of the produced oils.



(a)



(b)

Figure 4. FTIR absorption bonds and functional groups present in pyrolysis oils (a) and ash (b).

4.3. Composition of Non-Condensable Gas Fuels

The pyrolysis process led to the formation of carbon monoxide (CO), nitrogen oxides (NO and NO_2), sulfur dioxide (SO_2), hydrocarbons (C_xH_y), and nitrogen oxides (NOx) as shown in Figure 5. It was observed that hydrocarbons (combustible gases) (C_xH_y) dominate the gas composition with concentrations in the range of 100 thousand PPM, while CO also shows consistently high value of 100 ppm. Nitrogen oxides were also present at this sampling point and remained steady over time. The spectrum also included SO_2 in minimal variations. In comparison to the raw pyrolysis gases, hydrocarbons (CxHy) are dominant after filtration while Carbon monoxide (CO) are reduced indicating the effectiveness of passing the gases through the filtering mechanisms. Nitrogen oxides and Sulfur oxides were considerably reduced displaying negligible concentrations as a result of the filtration process.

4.4. Effect of Pyrolysis Parameters on the Production of Products

The pyrolysis experimental setup (shown in Figure 2 and Figure 3) contains a non-isothermal, electrically heated reactor equipped an oil and gas collection unit. The plastic waste (feedstock) degrades during heating into volatiles which make their way through an in-built condenser where the condensates are cooled down and collected as liquid (oil). The extra non-condensable fumes and gases continue through to the gas collection chamber after a semi-purification process through activated charcoal. The remainder char residue (after burning) in the reactor can be later collected from inside the reactor after cooling for sampling and analysis.

4.5. Effect of Temperature

The effects of pyrolysis temperatures below 220˚C on oil yield are presented in Table 4.

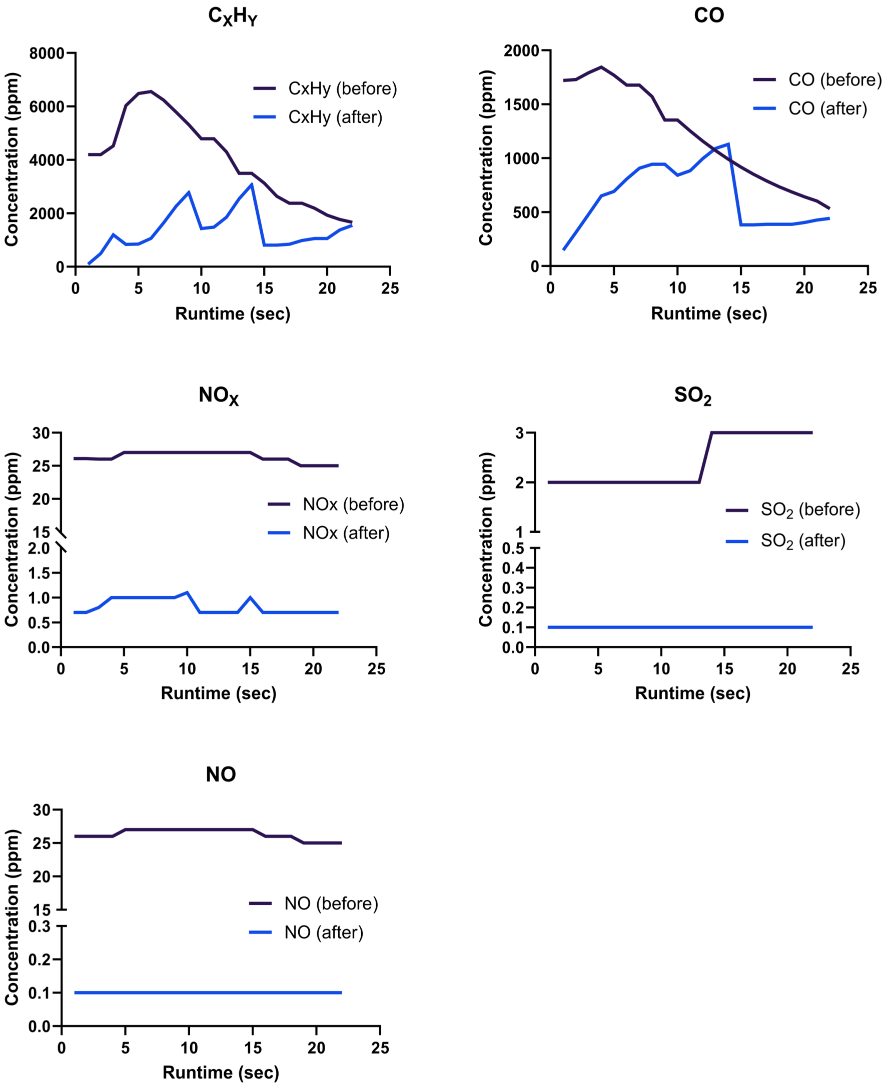


Figure 5. HDPE gas yield before and after upgrading with activated carbon and silica gel.

Table 4. Impact of pyrolysis temperature on product yields at a temperature range of 160˚C - 220˚C.

Impact of pyrolysis temperature range on product yields at a temperature range of 160˚C - 220˚C						
Parameters	PP		LDPE		HDPE	
	Mass (g)	Yield %(w/w)	Mass (g)	Yield %(w/w)	Mass (g)	Yield %(w/w)
Solid Residue	416.86 ± 0.43	66.48 ± 0.18	404.47 ± 0.13	76.75 ± 0.69	417.93 ± 0.22	77.73 ± 0.19
Liquid Oil	179.78 ± 0.34	28.67 ± 0.76	97.62 ± 0.56	18.52 ± 0.47	102.12 ± 0.76	18.99 ± 1.05
Gaseous Product	30.35 ± 0.27	4.84 ± 0.61	24.87 ± 0.81	4.72 ± 0.23	17.55 ± 0.12	3.26 ± 0.37
Total	627.00288		526.975		537.6108	

From **Table 4**, pyrolysis of plastics at temperatures below 220˚C generated high amounts of solid residue, while liquid oil and gas were produced in smaller quantities. The solid residue is generated because of the decomposition of plastics, which are composed of long-chain hydrocarbons. [42] noted that the decomposition of polymer chains is the breakdown of long-chain molecules into smaller fragments or monomers. The bond-breaking process is influenced by the pyrolysis temperature, where higher temperatures facilitate the breaking of C-C bonds, resulting in the formation of gas and liquid fuels while lower pyrolysis temperatures favour the formation of high molecular weight fragments. Similar findings were reported by [43] who worked with low-density polyethylene plastic waste.

These products are produced due to the breaking down of plastics. Plastics, being long carbon chain by-products of the oil refinery process, consist of hydrocarbons like petroleum. During pyrolysis plastics undergo significant chemical changes due to heat. The organic polymer chains decompose into lower molecular weight compounds, including gaseous and liquid fuels [44]. **Figure 5** illustrates the results suggest that HDPE and LDPE are viable waste materials for producing petroleum products such as gas, liquid oils through pyrolysis. The pyrolysis of PP, LDPE, and HDPE at various temperature ranges showed distinct trends in fuel production. HDPE yielded the highest liquid oil at 67.7%, followed by LDPE at 62.1%, and PP at 53.72%, indicating HDPE and LDPE are more efficient in liquid fuel production as presented in **Table 5**. Gas yields increased with temperature, with HDPE producing 31.07% at 400˚C - 420˚C, higher than PP (20.53%) and LDPE (20.3%), which aligns with studies by [32]. Solid residue yields were low, with HDPE producing the least (1.34%), suggesting more complete pyrolysis compared to PP and LDPE. These trends are consistent with findings by [37] [45] and [23].

Table 5. Effect of higher temperature ranges (220˚C - 420˚C) on product distribution, highlighting the shift from solid products to more liquid production as the temperature rises.

Parameters	Temperature Range (˚C)	PP		LDPE		HDPE	
		Mass (g)	Yield % (w/w)	Mass (g)	Yield % (w/w)	Mass (g)	Yield % (w/w)
Liquid Oil	220 - 350	322.31 ± 0.95	53.72 ± 0.42	372.58 ± 0.19	62.1 ± 1.42	406.21 ± 0.12	67.7 ± 1.65
	350 - 400	295.39 ± 0.12	49.23 ± 1.21	367.27 ± 0.26	61.21 ± 1.52	362.34 ± 0.15	60.39 ± 1.17
	400 - 420	289.99 ± 0.25	48.33 ± 0.76	361.96 ± 0.13	60.33 ± 1.24	352.73 ± 0.23	58.79 ± 0.57
Gas	220 - 350	168.3 ± 0.11	28.05 ± 0.91	89.75 ± 0.3	14.96 ± 1.11	111.09 ± 0.1	18.51 ± 1.06
	350 - 400	179.73 ± 0.20	29.95 ± 1.33	105.73 ± 0.19	17.62 ± 0.27	116.13 ± 0.14	19.35 ± 1.62
	400 - 420	186.42 ± 0.05	31.07 ± 0.11	121.82 ± 0.26	20.3 ± 0.43	123.16 ± 0.27	20.53 ± 1.13
Solid Residue	220 - 350	5.2 ± 0.07	0.87 ± 1.02	8.39 ± 0.23	1.4 ± 1.68	8.03 ± 0.16	1.34 ± 1.52
	350 - 400	10.31 ± 0.19	1.72 ± 0.92	11.31 ± 0.14	1.88 ± 1.29	7.83 ± 0.28	1.31 ± 1.15
	400 - 420	5.32 ± 0.23	0.89 ± 0.66	6.2 ± 0.25	1.03 ± 0.47	8.39 ± 0.06	1.4 ± 1.46
Wax	220 - 350	4.86 ± 0.29	0.81 ± 0.28	7.32 ± 0.21	1.22 ± 0.68	7.21 ± 0.19	1.2 ± 0.31
	350 - 400	4.13 ± 0.14	0.69 ± 1.61	4.68 ± 0.07	0.78 ± 0.47	5.68 ± 0.24	0.95 ± 1.00
	400 - 420	3.18 ± 0.10	0.53 ± 0.52	4.06 ± 0.21	0.68 ± 1.06	3.57 ± 0.08	0.6 ± 0.56

4.6. Heating Rate

Table 6 presents results that show the effect of varying heating rates on the product distribution during the pyrolysis of three different polymers in the temperature ranges of 220˚C - 420˚C. The table reports the mass in grams and the yield percentage (w/w) for the various products formed at different heating rates (10, 15, and 20˚C/min).

Table 6. Impact of heating rates to production on product distribution for pyrolysis in the temperature range of 220˚C - 420˚C.

Parameters	Heating Rate ˚C/Min	PP		LDPE		HDPE	
		Mass (g)	Yield % (w/w)	Mass (g)	Yield % (w/w)	Mass (g)	Yield % (w/w)
Liquid Oil	10	322.31 ± 0.16	53.72 ± 1.72	372.58 ± 0.13	62.1 ± 1.14	384.81 ± 0.12	64.14 ± 1.25
	15	311.56 ± 0.25	51.93 ± 0.47	349.16 ± 0.18	58.19 ± 0.87	352.75 ±0.17	58.79 ± 0.92
	20	284.69 ± 0.12	47.45 ± 1.13	331.6 ± 0.26	55.27 ± 1.36	334.58 ± 0.21	55.76 ± 0.64
Gas	10	168.3 ± 0.18	28.05 ± 1.05	89.75 ± 0.23	14.96 ± 1.67	111.09 ± 0.22	18.51 ± 0.68
	15	178.82 ± 0.29	29.8 ± 0.7	126.72 ± 0.19	21.12 ± 0.97	150.58 ± 0.27	25.1 ± 0.5
	20	186.7 ± 0.09	31.12 ± 0.61	183.72 ± 0.25	30.62 ± 0.49	176.96 ± 0.11	29.49 ± 0.18
Char	10	5.2 ± 0.27	0.87 ± 0.66	8.39 ± 0.1	1.4 ± 1.45	8.03 ± 0.16	1.34 ± 0.58
	15	5.15 ± 0.14	0.86 ± 0.74	17.26 ± 0.07	2.88 ± 1.33	3.4 ± 0.28	0.57 ± 1.3
	20	4.89 ± 0.06	0.81 ± 0.33	5.76 ± 0.2	0.96 ± 0.53	3.6 ± 0.09	0.6 ± 1.64
Wax	10	4.86 ± 0.11	0.81 ± 0.53	7.32 ± 0.09	1.22 ± 1.67	7.21 ± 0.05	1.2 ± 1.21
	15	3.87 ± 0.22	0.65 ± 0.98	5.03 ± 0.24	0.84 ± 0.19	6.54 ± 0.23	1.09 ± 0.52
	20	2.64 ± 0.08	0.44 ± 1.62	4.5 ± 0.08	0.75 ± 0.88	3.78 ± 0.1	0.63 ± 1.3

The effect of heating rate is clearly illustrated in **Table 6** where at low heating rates, there is a general decrease in the conversion of products into liquid (oil) phase whereas higher heating rates led to the formation of more gas phase products. At 20˚C/min, liquid oil production drops to 47.45%, 55.27 and 55.76% for PP, LDPE and HDPE respectively. At higher heating rates, for instance, when the heating rate was raised from 10˚C/min to 20˚C/min, gas production increased from 28.05 to 31.12%, 14.96 to 30.62 and 18.51 to 29.49% in PP, LDPE and HDPE respectively. Lower heating (@10˚C/min) broke down the feedstock into shorter hydrocarbon chains (C9-C34) and the extended residence time of volatiles in the reactor further broke down these short hydrocarbons into even shorter hydrocarbons (C1-C16). This led to the overall production of more gas and less liquid (oil) as shown in **Figure 6**.

In comparison, at higher heating rates (i.e. 20˚C/min), the short-chained hydrocarbons formed from the cracking process had little time to broken down further because of a limited residence time of volatiles inside the reactor. This ultimately led to a decrease in the yield of gaseous products (high chain hydrocarbons) and an increase in liquid (oil) yield (see **Table 7**) [46]. Similarly, the yields of wax and solid residue decrease with increasing heating rates. For example, wax production in PP drops from 0.81% at 10˚C/min to 0.44% at 20˚C/min, and in HDPE, from 1.20% to 0.63%. Solid residue also follows this pattern, with yields as low as 0.81% for PP and 0.60% for HDPE at the highest heating rates.

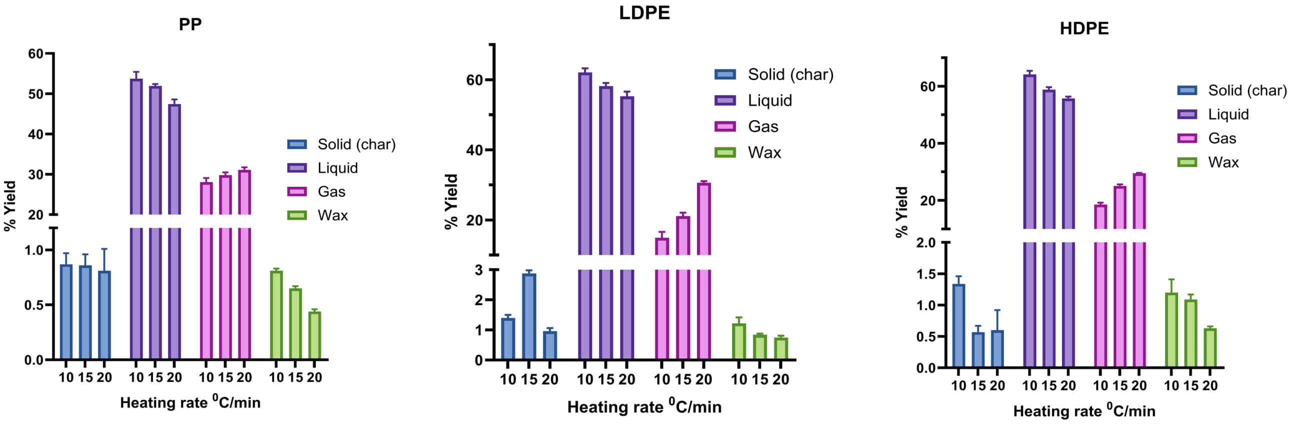


Figure 6. A comparison of products generation at different heating rates of 10, 15 and 20˚C/min at 420˚C

Table 7. Effect of catalyst on product distribution.

Parameters	Catalyst Type	LDPE + Catalyst		LDPE	
		Mass (g)	Yield % (w/w)	Mass (g)	Yield % (w/w)
Liquid Oil	Fe_2O_3	363.98 ± 0.07	60.66 ± 0.25	406.21 ± 0.11	67.7 ± 0.38
	Al_2O_3	229.9 ± 0.2	38.32 ± 0.51		
Gas	Fe_2O_3	370.42 ± 0.08	61.74 ± 1.38	111.08 ± 0.19	18.51 ± 0.12
	Al_2O_3	283.09 ± 0.15	47.18 ± 0.11		
Char	Fe_2O_3	6.52 ± 0.26	1.09 ± 0.43	8.02 ± 0.06	1.34 ± 1.07
	Al_2O_3	10.37 ± 0.18	1.73 ± 0.18		
Wax	Fe_2O_3	6.14 ± 0.24	1.02 ± 0.97	7.21 ± 0.28	1.2 ± 1.5
	Al_2O_3	6.59 ± 0.09	1.1 ± 1.22		

4.7. Effect of Catalyst

The pyrolysis of LDPE was conducted using Fe_2O_3 and Al_2O_3 catalyst, with each catalyst tested separately to assess its impact on product distribution during pyrolysis.

The results indicated that the oil yield with a catalyst was lower among the measured categories. In contrast, the oil yield without a catalyst was higher. The results also indicated that the gas yield with a catalyst was higher among the measured categories. However, the gas yield without catalyst resulted in a lower proportion of fuel gas [47]. Therefore, gas, liquid oil and solid residue are produced during the pyrolysis of plastics, both in the presence and absence of a catalyst as shown in **Figure 7**.

The increase in gas yield is attributed to the catalyst's influence on the pyrolysis reaction. During pyrolysis, LDPE produces straight and long hydrocarbon chains containing carbon atoms. The catalyst promotes further breakdown of these chains, favoring the formation of lighter, gaseous products. Thus, the catalyst promotes production of fuel gas. Similar observations have also been made by other authors [48]. These experimental findings demonstrated that reaction temperatures, heating rates, and catalysts affected the distribution of products from the plastics. As reaction temperatures and heating rates increased, oil yields and reaction times decreased. The use of a catalyst in this experiment led to higher gas yields while reducing both reaction times and heating rates. A study by [49] concluded that the use of catalysts had a higher impact on the production of gaseous hydrocarbons as compared to hydrocarbons due to the higher cracking process. A reduction in the liquid oil yield by 44 wt.% was obtained in this research.

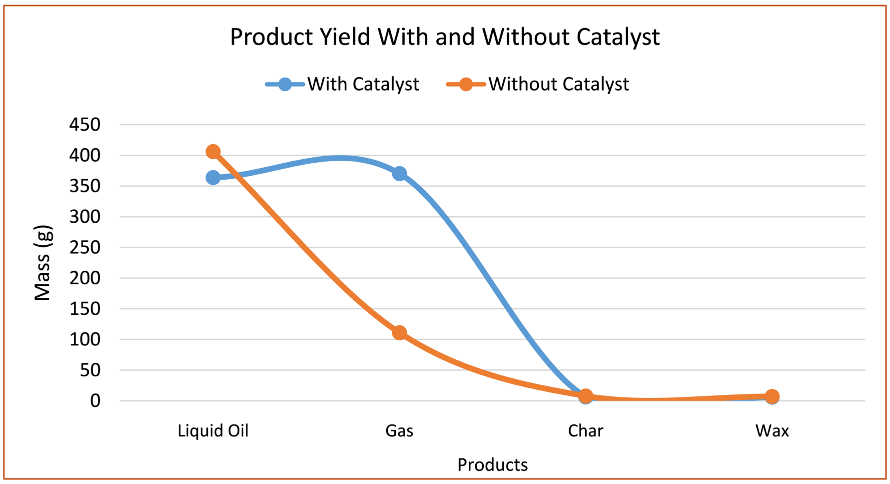


Figure 7. Comparative study of the effect of catalyst on product yield.

5. Conclusions

The study aimed to address two significant challenges in developing countries, such as Kenya: the energy crisis and plastic waste management. The results indicate that pyrolysis of various plastics can generate fuel products that offer potential solutions for energy needs while reducing the accumulation of plastic waste converting these pollutants into valuable energy resources.

This study focused on the performance testing of a plastic valorisation and purification system for production of alternative fuels. The calorific value and density of the feedstock materials for Polypropylene (PP), high-density polyethylene (HDPE), and low-density polyethylene (LDPE) was done to determine their suitability to produce alternative fuels. The reactor design focused on effectiveness and cost as locally soured materials were used while still achieving an energy efficiency of 69%. The pyrolysis process was determined to be effective at temperatures above 220˚C as temperatures below this range resulted in high wax yields and solid char. Temperature played a pivotal role in the product yields with temperatures between 350˚C and 420˚C favouring the production of liquid and gaseous fuels. The addition of a catalyst affected the product distribution with a significant increase in the gaseous fuels and a reduction in the overall reaction time. The introduction of purification system demonstrated the effectiveness of activated carbon and silica gel in the removal of nitrogen oxides (NOx) and sulphur oxides (SOx) thus addressing environmental concerns associated with pyrolysis processes. The plastic feedstock passed through the reactor yielding liquid fuel with HDPE producing 67.7% followed by LDPE at 62.1% and PP at 53.72%. The calorific values reached 49.09 MJ/kg, 53.14 MJ/kg and 46.30 MJ/kg for HDPE LDPE and PP respectively and are comparable to those of traditional fuels and can therefore be utilized as an alternative source of energy. Analysis through FTIR revealed the presence of compounds typically found in gasoline and diesel.

Further studies and investments should focus on the refining of pyrolysis oil, reactor design and utilization in internal combustion engines promoting sustainable energy solutions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Younas, M., Shafique, S., Hafeez, A., Javed, F. and Rehman, F. (2022) An Overview of Hydrogen Production: Current Status, Potential, and Challenges. *Fuel*, **316**, Article 123317. https://doi.org/10.1016/j.fuel.2022.123317

[2] Al-Fatesh, A.S., AL-Garadi, N.Y.A., Osman, A.I., Al-Mubaddel, F.S., Ibrahim, A.A., Khan, W.U., *et al.* (2023) From Plastic Waste Pyrolysis to Fuel: Impact of Process Parameters and Material Selection on Hydrogen Production. *Fuel*, **344**, Article 128107. https://doi.org/10.1016/j.fuel.2023.128107

[3] Matthews, C., Moran, F. and Jaiswal, A.K. (2021) A Review on European Union's Strategy for Plastics in a Circular Economy and Its Impact on Food Safety. *Journal of Cleaner Production*, **283**, Article 125263. https://doi.org/10.1016/j.jclepro.2020.125263

[4] Evode, N., Qamar, S.A., Bilal, M., Barceló, D. and Iqbal, H.M.N. (2021) Plastic Waste and Its Management Strategies for Environmental Sustainability. *Case Studies in Chemical and Environmental Engineering*, **4**, Article 100142. https://doi.org/10.1016/j.cscee.2021.100142

[5] Reza seyyedi, S., Kowsari, E., Ramakrishna, S., Gheibi, M. and Chinnappan, A. (2023) Marine Plastics, Circular Economy, and Artificial Intelligence: A Comprehensive Review of Challenges, Solutions, and Policies. *Journal of Environmental Management*, **345**, Article 118591. https://doi.org/10.1016/j.jenvman.2023.118591

[6] IUCN (2021) Marine Plastic Pollution. International Union for Conservation of Nature and Natural Resources.

[7] Danmo, F.H., Williamson, B.A.D., Småbråten, D.R., Gaukås, N.H., Østli, E.R., Grande, T., *et al.* (2023) Oxygen Absorption in Nanocrystalline h-*R*MnO_3 (*R*=Y, Ho, Dy) and the Effect of Ti Donor Doping. *Chemistry of Materials*, **35**, 5764-5776. https://doi.org/10.1021/acs.chemmater.3c00189

[8] Nayanathara Thathsarani Pilapitiya, P.G.C. and Ratnayake, A.S. (2024) The World of Plastic Waste: A Review. *Cleaner Materials*, **11**, Article 100220. https://doi.org/10.1016/j.clema.2024.100220

[9] Vuppaladadiyam, S.S.V., Vuppaladadiyam, A.K., Sahoo, A., Urgunde, A., Murugavelh, S., Šrámek, V., *et al.* (2024) Waste to Energy: Trending Key Challenges and Current Technologies in Waste Plastic Management. *Science of The Total Environment*, **913**, Article 169436. https://doi.org/10.1016/j.scitotenv.2023.169436

[10] Kumar, M., Bolan, S., Padhye, L.P., Konarova, M., Foong, S.Y., Lam, S.S., *et al.* (2023) Retrieving Back Plastic Wastes for Conversion to Value Added Petrochemicals: Opportunities, Challenges and Outlooks. *Applied Energy*, **345**, Article 121307. https://doi.org/10.1016/j.apenergy.2023.121307

[11] Koç, A. (2022) Thermal Pyrolysis of Waste Disposable Plastic Syringes and Pyrolysis Thermodynamics. *Advances in Chemical Engineering and Science*, **12**, 96-113. https://doi.org/10.4236/aces.2022.122008

[12] Muturi, S.M., Muthui, L.W., Njogu, P.M., Onguso, J.M., Wachira, F.N., Opiyo, S.O., *et al.* (2021) Metagenomics Survey Unravels Diversity of Biogas Microbiomes with Potential to Enhance Productivity in Kenya. *PLOS ONE*, **16**, e0244755. https://doi.org/10.1371/journal.pone.0244755

[13] European Commission (2018) A European Strategy for Plastics. European Commission.

[14] Kartik, S., Balsora, H.K., Sharma, M., Saptoro, A., Jain, R.K., Joshi, J.B., *et al.* (2022) Valorization of Plastic Wastes for Production of Fuels and Value-Added Chemicals through Pyrolysis—A Review. *Thermal Science and Engineering Progress*, **32**, Article 101316. https://doi.org/10.1016/j.tsep.2022.101316

[15] Peng, Y., Wang, Y., Ke, L., Dai, L., Wu, Q., Cobb, K., *et al.* (2022) A Review on Catalytic Pyrolysis of Plastic Wastes to High-Value Products. *Energy Conversion and Management*, **254**, Article 115243. https://doi.org/10.1016/j.enconman.2022.115243

[16] Saebea, D., Ruengrit, P., Arpornwichanop, A. and Patcharavorachot, Y. (2020) Gasification of Plastic Waste for Synthesis Gas Production. *Energy Reports*, **6**, 202-207. https://doi.org/10.1016/j.egyr.2019.08.043

[17] Sudalaimuthu, P. and Sathyamurthy, R. (2023) The Clean Energy Aspect of Plastic Waste—Hydrogen Gas Production, CO2 Reforming, and Plastic Waste Management Coincide with Catalytic Pyrolysis—An Extensive Review. *Environmental Science and Pollution Research*, **30**, 66559-66584. https://doi.org/10.1007/s11356-023-26908-3

[18] Yansaneh, O.Y. and Zein, S.H. (2022) Latest Advances in Waste Plastic Pyrolytic Catalysis. *Processes*, **10**, Article 683. https://doi.org/10.3390/pr10040683

[19] Sudalaimuthu, P., Ali, U. and Sathyamurthy, R. (2024) Optimization of Process Parameters of Catalytic Pyrolysis Using Natural Zeolite and Synthetic Zeolites on Yield of Plastic Oil through Response Surface Methodology. *Scientific Reports*, **14**, Article No. 28442. https://doi.org/10.1038/s41598-024-78180-1

[20] Miandad, R., Rehan, M., Barakat, M.A., Aburiazaiza, A.S., Khan, H., Ismail, I.M.I., *et al.* (2019) Catalytic Pyrolysis of Plastic Waste: Moving toward Pyrolysis Based Biorefineries. *Frontiers in Energy Research*, **7**, Article 27. https://doi.org/10.3389/fenrg.2019.00027

[21] Mburu, J.N., Njogu, P.M. and Muthengia, J.W. (2015) Pyrolysis Process Studies for Post Consumer Polyethene Waste Conversion and Upgrading of the Pyrolysis Oil. *International Journal of Science and Research*, **5**, 101-105.

[22] Mahapatra, P.M., Aech, S., Mandal, P.K. and Panda, A.K. (2024) Pyrolysis of Multilayered Plastic Packets to Hydrocarbon Fuel Feedstock: Thermal Degradation Behaviour, Kinetics and Thermodynamic Analysis, and Semi-Batch Studies. *Journal of the Energy Institute*, **115**, Article 101690. https://doi.org/10.1016/j.joei.2024.101690

[23] Sogancioglu, M., Yel, E. and Ahmetli, G. (2017) Pyrolysis of Waste High Density Polyethylene (HDPE) and Low Density Polyethylene (LDPE) Plastics and Production of Epoxy Composites with Their Pyrolysis Chars. *Journal of Cleaner Production*, **165**, 369-381. https://doi.org/10.1016/j.jclepro.2017.07.157

[24] Ahmad, I., Khan, M.I., Khan, H., Ishaq, M., Tariq, R., Gul, K., *et al.* (2014) Pyrolysis Study of Polypropylene and Polyethylene into Premium Oil Products. *International Journal of Green Energy*, **12**, 663-671. https://doi.org/10.1080/15435075.2014.880146

[25] Hendrawati, Liandi, A.R., Solehah, M., Setyono, M.H., Aziz, I. and Siregar, Y.D.I. (2023) Pyrolysis of PP and HDPE from Plastic Packaging Waste into Liquid Hydrocarbons Using Natural Zeolite Lampung as a Catalyst. *Case Studies in Chemical and Environmental Engineering*, **7**, Article 100290. https://doi.org/10.1016/j.cscee.2022.100290

[26] Cai, N., Xia, S., Li, X., Sun, L., Bartocci, P., Fantozzi, F., *et al.* (2021) Influence of the Ratio of Fe/Al_2O_3 on Waste Polypropylene Pyrolysis for High Value-Added Products. *Journal of Cleaner Production*, **315**, Article 128240. https://doi.org/10.1016/j.jclepro.2021.128240

[27] Ghodke, P.K., Sharma, A.K., Moorthy, K., Chen, W., Patel, A. and Matsakas, L. (2022) Experimental Investigation on Pyrolysis of Domestic Plastic Wastes for Fuel Grade Hydrocarbons. *Processes*, **11**, Article 71. https://doi.org/10.3390/pr11010071

[28] Maithomklang, S., Sukjit, E., Srisertpol, J., Klinkaew, N. and Wathakit, K. (2023) Pyrolysis Oil Derived from Plastic Bottle Caps: Characterization of Combustion and Emissions in a Diesel Engine. *Energies*, **16**, Article 2492. https://doi.org/10.3390/en16052492

[29] Khan, M.Z.H., Sultana, M., Al-Mamun, M.R. and Hasan, M.R. (2016) Pyrolytic Waste Plastic Oil and Its Diesel Blend: Fuel Characterization. *Journal of Environmental and Public Health*, **2016**, Article ID: 7869080. https://doi.org/10.1155/2016/7869080

[30] Arun, A.C., Mahesh, V.M., Sanith, P., Sharon, D., Kanna, R. and Purushotham, T. (2017) Comparison of Calorific Values of Various Fuels from Different Petrol Stations. *International Refereed Journal of Engineering and Science*, **6**, 2319-183.

[31] Pumpuang, A., Klinkaew, N., Wathakit, K., Sukhom, A. and Sukjit, E. (2024) The Influence of Plastic Pyrolysis Oil on Fuel Lubricity and Diesel Engine Performance. *RSC Advances*, **14**, 10070-10087. https://doi.org/10.1039/d3ra08150h

[32] Rahman, M.H., Bhoi, P.R., Saha, A., Patil, V. and Adhikari, S. (2021) Thermo-Catalytic Co-Pyrolysis of Biomass and High-Density Polyethylene for Improving the Yield and Quality of Pyrolysis Liquid. *Energy*, **225**, Article 120231. https://doi.org/10.1016/j.energy.2021.120231

[33] Cai, N., Xia, S., Xiao, H., Chen, Y., Chen, W., Yang, H., *et al.* (2023) Distinguishing the Impact of Temperature on Iron Catalyst during the Catalytic-Pyrolysis of Waste Polypropylene. *Proceedings of the Combustion Institute*, **39**, 835-845. https://doi.org/10.1016/j.proci.2022.06.008

[34] Faisal, F., Rasul, M.G., Jahirul, M.I. and Schaller, D. (2023) Pyrolytic Conversion of

Waste Plastics to Energy Products: A Review on Yields, Properties, and Production Costs. *Science of The Total Environment*, **861**, Article 160721. https://doi.org/10.1016/j.scitotenv.2022.160721

[35] Shoaib, M., Subeshan, B., Khan, W.S. and Asmatulu, E. (2021) Catalytic Pyrolysis of Recycled HDPE, LDPE, and PP. *Progress in Rubber, Plastics and Recycling Technology*, **37**, 264-278. https://doi.org/10.1177/14777606211019414

[36] Hariram, V., Seralathan, S. and Mohammed Raffiq, A. (2017) Formulation and Characterization of Pyrolytic Oil from Waste Tyre and Waste Plastic: A Comparative Study. *Nature Environment & Pollution Technology*, **16**, 1183-1188.

[37] Thahir, R., Irwan, M., Alwathan, A. and Ramli, R. (2021) Effect of Temperature on the Pyrolysis of Plastic Waste Using Zeolite ZSM-5 Using a Refinery Distillation Bubble Cap Plate Column. *Results in Engineering*, **11**, Article 100231. https://doi.org/10.1016/j.rineng.2021.100231

[38] Fulgencio-Medrano, L., García-Fernández, S., Asueta, A., Lopez-Urionabarrenechea, A., Perez-Martinez, B. and Arandes, J. (2022) Oil Production by Pyrolysis of Real Plastic Waste. *Polymers*, **14**, Article 553. https://doi.org/10.3390/polym14030553

[39] Cho, M., Song, Y., Rhu, C. and Go, B. (2023) Pyrolysis Process of Mixed Microplastics Using TG-FTIR and TED-GC-MS. *Polymers*, **15**, Article 241. https://doi.org/10.3390/polym15010241

[40] Pranoto and Mazlan (2023) The Characterization of Pyrolysis Oil from Plastic Waste Using FTIR and GC-MS Techniques. *IOP Conference Series: Earth and Environmental Science*, **1268**, Article 012058. https://doi.org/10.1088/1755-1315/1268/1/012058

[41] Staš, M., Auersvald, M., Kejla, L., Vrtiška, D., Kroufek, J. and Kubička, D. (2020) Quantitative Analysis of Pyrolysis Bio-Oils: A Review. *TrAC Trends in Analytical Chemistry*, **126**, Article 115857. https://doi.org/10.1016/j.trac.2020.115857

[42] Pielichowski, K., Njuguna, J. and Majka, T.M. (2023) Mechanisms of Thermal Degradation of Polymers. In: Pielichowski, K., Njuguna, J. and Majka, T.M., Eds., *Thermal Degradation of Polymeric Materials*, Elsevier, 9-11. https://doi.org/10.1016/b978-0-12-823023-7.00001-0

[43] Wijayanti, W., Musyaroh, M. and Sasongko, M.N. (2022) Low-Density Polyethylene Plastic Waste to Liquid Fuel Using Pyrolysis Method: An Effect of Temperatures on the Oil Yields Physicochemical Properties. *Journal of Sustainable Development of Energy, Water and Environment Systems*, **10**, 1-18. https://doi.org/10.13044/j.sdewes.d9.0402

[44] Arahim, A.A., Widayat, and Hadiyanto, (2020) Liquid Fuel Production from Motorized Vehicle Tires with Pirolysis Process. International Conference on Science and Applied Science, Surakarta, 7 July 2020, Article 020004. https://doi.org/10.1063/5.0030380

[45] Yao, D., Li, H., Dai, Y. and Wang, C. (2021) Impact of Temperature on the Activity of Fe-Ni Catalysts for Pyrolysis and Decomposition Processing of Plastic Waste. *Chemical Engineering Journal*, **408**, Article 127268. https://doi.org/10.1016/j.cej.2020.127268

[46] Singh, R.K., Ruj, B., Sadhukhan, A.K. and Gupta, P. (2019) Impact of Fast and Slow Pyrolysis on the Degradation of Mixed Plastic Waste: Product Yield Analysis and Their Characterization. *Journal of the Energy Institute*, **92**, 1647-1657. https://doi.org/10.1016/j.joei.2019.01.009

[47] Chen, W.-H., Naveen, C., Ghodke, P.K., Sharma, A.K. and Bobde, P. (2023) Co-Pyrolysis of Lignocellulosic Biomass with Other Carbonaceous Materials: A Review on

Advance Technologies, Synergistic Effect, and Future Prospectus. *Fuel*, **345**, Article 128177. https://doi.org/10.1016/j.fuel.2023.128177

[48] Budsaereechai, S., Hunt, A.J. and Ngernyen, Y. (2019) Catalytic Pyrolysis of Plastic Waste for the Production of Liquid Fuels for Engines. *RSC Advances*, **9**, 5844-5857. https://doi.org/10.1039/c8ra10058f

[49] Pal, S., Kumar, A., Sharma, A.K., Ghodke, P.K., Pandey, S. and Patel, A. (2022) Recent Advances in Catalytic Pyrolysis of Municipal Plastic Waste for the Production of Hydrocarbon Fuels. *Processes*, **10**, Article 1497. https://doi.org/10.3390/pr10081497