Characterization of Fuel Produced from Nylon (Polyamide) and Polyethylene Terephthalate (PET) Wastes with Pyrolysis

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Abstract

The escalating accumulation of plastic waste, particularly polyethylene terephthalate (PET) and Polyamide (PA), poses significant environmental challenges due to their non-biodegradable nature and the limitations of conventional disposal methods. Pyrolysis, a thermochemical decomposition process conducted in the absence of oxygen, offers a promising alternative by converting plastic waste into valuable liquid fuels, gases, and char. This technique not only helps to mitigate the environmental burden of plastic pollution but also contributes to the circular economy by recovering energy-rich products from post-consumer polymers. This study explores the potential of pyrolysis as a sustainable thermochemical process to convert PET and PA waste into valuable liquid fuels. The resulting fuels were subjected to comprehensive characterization to assess their physicochemical properties. Comparative analyses between PET and PA-derived fuels were performed to evaluate their respective properties and potential applications. The findings revealed that the PET-PA blended oil yielded slightly higher calorific value (47.55 MJ/kg) compared to pure PA oil (46.75 MJ/kg), indicating a richer energy profile. However, the PA oil showed superior fuel behaviour in terms of volatility and ignition with a lower flash point and higher fire point PET/PA[13.74°C and 263°C] as compared to the PA(15.82 °C and 294 °C). The volatile content of both oils was comparably high (85.5%), but the fixed carbon and ash contents were lower in the PET-PA blend, suggesting cleaner combustion. Additionally, both fuels showed density values (1.12 g/cm³ for PA and 1.10 g/cm³ for PET/PA) above conventional gasoline which is (0.71-0.77g/cm³), indicating higher molecular weight fractions. The sulphur content remained under 1% in both cases. These results demonstrate the feasibility of transforming plastic waste into usable liquid fuel, contributing to both sustainable waste management and alternative energy generation. The findings indicate that pyrolysis offers a viable pathway for mitigating plastic pollution while contributing to sustainable energy production, aligning with global sustainability goals.

Keywords: *Nylon-derived liquid fuel, plastic waste management, polyethylene terephthalate, pyrolysis.*

1.0 Introduction

The increasing accumulation of plastic waste, particularly polyethylene terephthalate (PET) and polyamide (nylon), has emerged as a significant environmental challenge due to its non-biodegradable nature. The global reliance on plastic, especially PET and nylon, has grown significantly due to their versatility and durability [1,2]. These materials are extensively used in various industries including packaging, building, electricity and textiles, contributing substantially to municipal solid waste [3]. Traditional methods of plastic waste disposal, such as landfilling and incineration, pose substantial environmental and health risks [4].

In recent years, research has shifted towards exploring innovative ways to recycle plastics into valuable products. One promising approach is the conversion of PET and PA (nylon) into fuel using pyrolysis [5]. This method (pyrolysis) presents a solution for managing plastic waste but also contributes to addressing the increasing demand for alternative energy sources. The calorific value of plastics is comparable to that of conventional fuels, making pyrolysis an attractive option for energy recovery [6]. Pyrolysis breaks down long-chain polymers into smaller molecules, resulting in products like high-quality oils, high-calorific gases and carbon [7].

This study aims to characterize the fuel produced through the pyrolysis of PET and nylon waste. through thermo-physical and thermo-chemical properties determination, providing a dual solution that aligns with global sustainability goals.

This research focuses on evaluating the pyrolysis process as a sustainable method for converting PET and Polyamide waste (nylon) into liquid fuel. It involves laboratory-scale experiments to optimize process parameters, characterize the physical, chemical and energy properties of the fuel and conduct comparative analysis of fuel yields and qualities between the two plastic types. Production has been growing steadily since the first production in the 1950s.

The main advantages of plastic are that they're cheap, quick to prepare, easy to design and fabricate, durable, non-perishable and recyclable, hence their increasing global usage [7,9].

The kinematic viscosity, density and flash point of the pyrolysis oil indicate values near those of commercial diesel and gasoline [10]. Pyrolysis oil can be used as a good transport fuel when blended with diesel in ratios of 10%, 20%, 30% and 40% resulting in various engine performance characteristics [7].

While existing research establishes the feasibility of pyrolysis for specific plastics, detailed analysis integrating the comparative performance of Nylon and PET under identical conditions is scarce. Also, the thermo-physical and thermo-chemical properties of the produced fuels are often underreported. There is a lack of detailed characterization of the physical properties, chemical properties, and energy properties of fuel derived from PET and Nylon pyrolysis. This information is vital for assessing the sustainability of these fuels for various applications.

2.0 Methodology

The following procedures were adopted for the production and characterization of fuel obtained from polyamide (PA) and Polyethylene terephthalate (PET) waste using pyrolysis.

2.1 Feedstock

Waste polyamide (PA) and Polyethylene terephthalate (PET) plastics were sourced from local scavengers operating in landfills, incineration sites, and public event venues such as parties and clubhouses.

2.2 Reactor Setup

The pyrolysis reactor system comprises a metal drum, a gas hose, a large bowl of water serving as a condenser, and a collecting plastic container for fuel and gas outlet.

The collected plastics were carefully cleaned to remove any residual contaminants, such as dirt, food particles, and labels that can interfere with the pyrolysis reaction and the quality of the resultant fuel. Cleaning was done using water and mild detergents, followed by air drying. The dried feedstock was then cut into pieces to ensure consistent thermal degradation during pyrolysis.

For co-pyrolysis experiments, equal mass (50% each) of PA and PET were mixed to create a homogenous feedstock blend.

2.3 Pyrolysis Procedure

The pyrolysis process was conducted in three distinct stages:
i. Pyrolysis of PET Only
ii. Pyrolysis of PA only
iii. Pyrolysis of PET and PA

At first, PET only was introduced into the preheated reactor which was then sealed to maintain an oxygen-deficient environment at high temperature to facilitate thermal decomposition.

The condensable gas produced was directed through a water-cooled condenser (a large bowl of water) to facilitate the collection of liquid fuel. Non-condensable gases were vented, and the solid residues (char) were collected from the reactor. The vented gases were ignited and observed to be combustible, indicating the presence of flammable components. This procedure was then repeated for PA only, and PET and PA mixture. The rig set-up for the process is as depicted in figure 1.

Figure 1: The pyrolysis rig

The rig was constructed from metal drums connected by steel pipes to be able to withstand the required high temperature. The large one contains the PET, PET and nylon, nylon as the case demands and it was heated underneath to raise the temperature of the contents. The vaporized contents flows through the pipes under pressure to the adjourning drums where it condenses, and from which the pyrolysed fuel is drained.

2.4 Fuel Collection and Storage

The produced fuel was collected from the condenser drum and stored in airtight containers at room temperature to prevent oxidation and degradation before analysis. However, the fuel yield from PET only solidified at room temperature.

2.5 Characterization of Thermophysical Properties of Fuel

Thermo-physical properties help to determine the fuel's efficient storage, safety and handling of the fuel, which includes its moisture content, Density, Specific gravity, viscosity, cloud point, pour point, flash point and fire point.

2.5.1 Moisture Content

The amount of water present in the fuel was determined to be excessive moisture that can lower the fuel's heating value and cause corrosion in combustion systems.

Apparatus: Moisture oven (105°C); Weighing balance; Crucibles or moisture dishes; Desiccator.

Procedures: A crucible was cleaned, dried, and then weighed. Then 50g of fuel was poured into a crucible, and the total weight was recorded. The crucible containing the sample was placed in a hot air oven set at 105°C for 1 hour. After heating, the crucible was removed and allowed to cool in a desiccator. The crucible was reweighed, and the moisture content was calculated as the percentage weight loss.

2.5.2 Density

The mass per unit volume of fuel was determined as a key indication of the fuel quality, and it affects combustion efficiency and engine performance.

Apparatus: Measuring Cylinder (50ml), Digital Balance

Procedures: 50ml of the fuel was measured using the graduated measuring cylinder. The measured fuel was then weighed using a digital weighing balance. The density of the fuel was then calculated by dividing the mass by volume.

2.5.3 Specific Gravity of Fuel

Specific gravity is the ratio of the fuel's density to the density of water at a standard temperature. The specific gravity of a sample is the ratio of the weight in air of a given volume of the sample to the weight in air of an equal volume of 4℃.

$$Specific\ gravity\ = \frac{Density\ of\ pyrolyzed\ fuel}{Density\ of\ water\ @\ 4ºC} \qquad (1)$$

2.5.4 Viscosity (ASTM D445)

Viscosity measures the resistance of the fuel to flow. It affects fuel atomization during injection and overall engine performance.

Apparatus: Viscometer assembly, thermometer, stopwatch.

Procedures: The viscometer was turned on. A selected required spindle type (R2 – larger) was attached. The viscometer was raised to the highest level using a screw on the vertical pole, and the beaker was placed with liquid under the spindle. The viscometer was lowered until the spindle was submerged up to the marked spot on the spindle. The thermometer was also placed in the liquid. Reading was then taken at a constant test temperature of 25°C. The Orifice of the viscometer was opened to allow the flow of 50ml of the fuel.

2.5.5 Cloud Point of Fuel

The cloud point is the temperature at which wax crystals first appear in the fuel. It indicates the lowest temperature at which the fuel can be used without clogging filters.

Apparatus: Test jar, water bath with heater, cork carrying thermometer, cloud point chamber, crushed ice.

Procedures: The Test jar was filled to the level mark, closed tightly by the cork carrying the thermometer, and placed into a bath of crushed ice. The Test jar was removed from the jacket quickly without disturbing the specimen. The inspection for cloud point was done, and the jacket was replaced. The operation was done without exceeding the time duration of three (3) seconds. The cloud point was reported to the nearest 1℃. At this point, a cloud was observed at the bottom of the test jar, which is confirmed by continued cooling

2.5.6 Pour Point of Fuel

The pour point is the lowest temperature at which the fuel remains pourable. It is important for determining usability in cold climates.

Apparatus: Test jar, Water bath with heater, Cork carrying thermometer, Cloud point chamber, Crushed ice

Procedures: 2g of sample fuel was filled to the level mark. The test jar was tightly closed by the cork carrying the test thermometer and placed in a bath of crushed ice. The pour point was reached when the oil surface stayed in the vertical position for 5 seconds without sagging. At this point, the thermometer was inserted to cool for 10 seconds, and the temperature of the oil was taken. The pour point was 3°C higher than the thermometer reading.

2.5.7 Flash Point of Fuel

Flash point is the lowest temperature at which the vapors of the fuel ignite temporarily when exposed to a flame. It is a measure of fuel flammability and safety.

Apparatus: Closed cup flash and fire point apparatus.

Procedures: The fuel was introduced into a cup, and a close-fitting lid was fitted to the top of the cup. Flash points were determined experimentally by heating the liquid in a container (cup) and then introducing a small flame just above the liquid surface. The temperature at which there is a flash/ignition is recorded as the flash point.

2.5.8 Fire Point of Fuel

Fire point is the temperature at which the fuel vapors ignite and continue to burn for at least five seconds. It is slightly higher than the flash point and indicates sustained combustion potential.

Apparatus: Close cup flash and fire point apparatus.

Procedures: The fuel was introduced into a cup, and a close-fitting lid was fitted to the top of the cup. The cup and fuel were heated. Subsequently, apertures were opened in the lid to allow air into the cup and the ignition source to be dipped into the vapors to test for a fire point.

2.6 Characterization of Thermochemical Properties of Fuel

Thermochemical properties of fuel are the chemical reactions that occur when fuel is partially or completely heated or burned. These include calorific value, octane number, Ash content, Carbon content, Volatile content and Sulphur content.

2.6.1 Calorific Value of Fuel (ASTM D240)

The amount of water present in the fuel was determined to be excessive moisture that can lower the fuel's heating value and cause corrosion in combustion systems.

This is the amount of heat energy released when a known quantity of fuel is completely combusted. It indicates the energy content and heating efficiency of the fuel.

Apparatus: Bomb calorimeter; oxygen cylinder; thermometer; water jacket.

Procedures: 50g of fuel was weighed and placed in the combustion crucible. The bomb was filled with oxygen and sealed. The bomb was submerged in a water jacket, and the sample was ignited. The Temperature rise of the water was measured and calculated as the energy content.

2.6.2 Octane Number of Fuel (ASTM D2699)

The octane number is a measure of the fuel's resistance to knocking during combustion. Higher octane ratings imply smoother engine performance.

Apparatus: Gas Chromatograph-Mass Spectrometer (GC-MS)

Procedures: 75g of fuel was injected into the GC-MS system. The hydrocarbon profile was analyzed. The octane number was estimated

2.6.3 Ash Content of Fuel (ASTM D482)

Ash content refers to the inorganic residue left after the fuel was completely combusted. High ash content can lead to deposits in engines and reduce efficiency.

Apparatus: Crucible, muffle furnace, desiccator, digital balance.

Procedures: A 100g mass of fuel was weighed into a crucible. The sample was heated at 600 °C in the muffle furnace until all combustible material burned off. The crucible was then cooled in a desiccator, and the remaining ash was weighed. The ash content was calculated as a percentage of the original sample.

2.6.4 Carbon Content of Fuel (ASTM D5291)

Carbon content shows the percentage of carbon present in the fuel. It helps assess the fuel's combustion characteristics and potential emissions.

Apparatus: CHN Elemental Analyzer

Procedures: A small amount of fuel was placed in the CHN Elemental Analyzer. The sample was subjected to high-temperature oxidation. The CO_2 produced was measured to determine the carbon concentration.

2.6.5 Volatile Content of Fuel (ASTM D3175)

Volatile matter refers to the compounds in the fuel that vaporize when heated. High volatile content generally indicates better ignition properties and ease of combustion.

Apparatus: Muffle furnace (600–700°C) l, silica crucibles with lids, weighing balance.

Procedure: A silica crucible with a fitted lid was cleaned, dried, and weighed. 50g of the fuel sample was placed into the crucible. The crucible was introduced into a preheated muffle furnace at 600°C and covered with its lid. The sample was heated for 10 minutes to allow volatile components to escape. The crucible was removed and cooled in a dry storage container. Finally, the crucible was reweighed, and the volatile matter was determined by the difference in mass before and after heating.

2.6.6 Sulphur Content of Fuel (ASTM D4294)

Sulphur content is critical for assessing the environmental impact of fuel combustion. High sulphur levels can lead to SO_2[Sulphur dioxide] emissions, contributing to acid rain.

Apparatus: Bomb calorimeter with absorption setup, barium chloride solution, distillation flask, filter paper, pH indicator or spectrophotometer.

Procedure: 100 g of the fuel sample was combusted in a bomb calorimeter. The gases released during combustion were passed through distilled water to absorb sulphur dioxide. Barium chloride solution was added to the absorption solution to precipitate sulphate as barium sulphate. The precipitation was filtered, washed, dried, and weighed. The sulphur content in the fuel was calculated based on the mass of barium sulphate formed.

3.0 Results and Discussion

The thermo-physical properties of the fuel produced from the pyrolysis of polyamide (nylon), a blend of polyethylene terephthalate (PET) and polyamide (PA), are as shown on Table 1. Their implications for fuel quality and usability are discussed in comparison to the ASTM D7544-12 standard for pyrolysis liquid fuel (fuel).

3.1 Thermophysical Properties of Fuel

The thermo-physical properties of the fuel produced from the pyrolysis of polyamide (nylon), a blend of polyethylene terephthalate (PET) and polyamide (PA), are as shown on Table 1. Their implications for fuel quality and usability are discussed in comparison to the ASTM D7544-12 standard for pyrolysis liquid fuel (fuel).

Table 1: Thermophysical Properties of the Fuel

Properties	PA [only]	PA & PET	PET [only]	Conventional Gasoline
Moisture Content (%)	13.10±0.4	13.20±0.2		0.02 wt. % [11]
Density @ 30°C (g/ml)	1.12±0.3	1.10±0.1		0.75 g/ml [12]
Specific Gravity	1.123	1.10		0.75 g/ml [12]
Pour Point (°C)	-22	-26		Negligible (very low)
Cloud Point (°C)	-8.47	0.01	0.01	-22 [13]
Flash Point (°C)	15.82	13.74		-44 °C [12]
Fire Point (°C)	294	263		25.0 [13]
Viscosity @ 100°C	3.6±1.60	3.3±1.70		3.0 cSt [14]

3.1.1 Moisture Content

The moisture content of polyamide fuel was 13.10 ± 0.4, while for PET & PA it was 13.10 ± 0.4. Both fuels have identical moisture content (13.10%), well within the ASTM D7544-12 limit of ≤30%, indicating good compliance. Compared to the reference fuel oil range (15–30%), the fuels have lower moisture, which is advantageous for stability, reduced corrosiveness, and higher heating value. Low moisture suggests efficient pyrolysis with minimal water formation or effective water separation post-pyrolysis. This is typical for PET and nylon pyrolysis, as these plastics have low inherent moisture compared to biomass.

3.1.2 Density

Fuel density affects energy content per unit volume, storage capacity, and combustion efficiency. The PET & PA blend had a density of 1.10 ± 0.1 g/ml, whereas PA had a density of 1.12 ± 0.3 g/ml. Densities (1.10–1.12 g/cm³) are typical for fuels, which are denser than petroleum-based fuel oils (0.89 g/cm³) due to oxygenated compounds and complex molecular structures. ASTM D7544-12 requires reporting density but sets no limit, as it varies with fuel composition (typically 1.1–1.3 g/cm³ for biomass-derived fuels).

However, the regular fuel oil has a density of 0.89 g/cm³ thus, the fuel obtained from the pyrolysis process is denser that the regular fuel oil, which is expected for pyrolysis oils from plastics. The findings suggest that the

pyrolyzed fuels have a larger mass per unit volume and may need engine injection settings to be adjusted for optimal performance because they are denser than regular diesel (≈0.89 g/ml). Higher density may affect pumpability and atomization in burners. The value for the pyrolyzed fuels is however, within the expected range for fuels. The slight difference between polyamide (1.12) and PET & PA (1.10) suggests minor compositional variations, possibly due to PET's aromatic content.

3.1.3 Specific Gravity of Fuel

From Table 1, the specific gravity of polyamide was computed as 1.12 ± 0.3, while for the PET & PA blend, it was 1.10 ± 0.3. This specific gravity is slightly higher than the specific gravity for conventional gasoline (0.77). The specific gravity of the fuels was computed as the ratio of the density of the fuel to the density of water at a reference temperature (4°C), the findings suggest that the pyrolyzed fuels have a larger mass per unit volume and may need engine injection settings to be adjusted for optimal performance because they are denser than regular gasoline (0.77 g/ml).

3.1.4 Viscosity

One important factor affecting the fuel's flow and atomization during injection is viscosity. Additionally, it impacts engine component wear characteristics, lubrication capacity, and combustion efficiency. Using ASTM D445, the dynamic viscosity of PA was measured at 100°C and found to be 3.6 ± 1.60 cSt, while the PET & PA blend was found to be 3.3 ± 1.70 cSt, which is significantly lower than the maximum viscosity of fuel according to ASTM D7544-12 Limit (< 12125 mm²/s - Grades G and D).

These viscosity values are within permissible bounds for commercial fuels like kerosene and diesel. Low viscosity indicates good flow and atomization properties, suitable for burner applications. While maintaining enough lubrication to lessen wear on engine parts, lower viscosities show improved flow behaviour, especially at high operating temperatures. The outcome implies that these fuels can burn effectively without additional modification or preheating. The slight difference between polyamide (3.6) and PET & PA (3.3) is negligible, with high uncertainties (±1.60, ±1.70) suggesting measurement variability. Both fuels meet viscosity requirements, making them pumpable and suitable for industrial burners in terms of flow. Low viscosity is advantageous compared to typical fuels (20–100 mm²/s), which are often more viscous.

3.1.5 Cloud Point Analysis

The low-temperature operability of the fuel is shown by the cloud point of the fuel. The cloud point is the temperature at which wax crystals first appear. It is essential for evaluating how well fuel performs in cold climates. While PET and PET & PA both showed a cloud point of 0.01°C, PA's cloud point was -8.47°C.

Cloud points (-8.47°C for polyamide, 0.01°C for PET & PA) indicate the temperature at which solids or wax begin to form, affecting low-temperature performance. The higher cloud point for PET & PA (0.01°C) vs. polyamide (-8.47°C) may reflect PET's aromatic compounds, which can increase cloud point. Both fuels perform well in cold conditions, with Pour points below typical ambient temperatures. The PET & PA blend's near-zero cloud point suggests slightly poorer low-temperature performance, but still within acceptable bounds. PET's aromatic content (e.g., benzoic acid derivatives) may elevate cloud point, while nylon's amide-derived compounds may contribute to lower values.

3.1.6 Pour Point Analysis

The pour points of the fuel indicate the lowest temperature at which the fuel flows, and this is critical for handling and storage. This is essential for evaluating how well fuel performs in cold climates. The PET & PA blend at -26°C and PA at -22°C.

All the samples had noticeably low pour points, indicating that these pyrolyzed fuels retain sufficient flow characteristics even at below-freezing temperatures. The lower pour point for PET & PA (-26°C) vs. polyamide (-22°C) suggests better low-temperature flow, possibly due to PET's influence on molecular structure. Both fuels are suitable for cold climates, with pour points well below typical operating temperatures. The PET & PA blend's lower pour point is advantageous. It is a desirable characteristic for fuels meant for use in moderate or colder climes. The depressed pour and cloud points are probably caused by the presence of long-chain hydrocarbons and their branching, which lessens the likelihood that fuel molecules would form wax crystals. No pour point analysis on PET (only) because the yield solidified at room temperature, an indication that the produced fuel cannot suffix as a liquid fuel at room temperatures.

3.1.7 Flash Point of Fuel

The flash point is the lowest temperature at which fuel vapours briefly burn when an ignition source is present. This is crucial in assessing the volatility of the fuel. As compared to the ASTM D7544-12 minimum of 45°C and the reference value of 60°C for No. 2 fuel oil per ASTM D396, polyamide had a flash point of 15.82°C, and PET

and PA had a flash point was 13.74°C. The flash points of the fuels were lower than the ASTM D7544-12, and low flash points indicate a high content of volatile compounds, increasing fire risk during handling and storage. Both fuels fail to meet ASTM D7544-12 requirements, making them unsuitable for industrial burner applications without upgrading (e.g., distillation to remove volatile fractions). Low flash points pose safety concerns, requiring careful storage below 13–15°C to prevent ignition.

3.1.8 Fire Point of Fuel

The temperature at which continuous combustion takes place is known as the fire point. This fire point is a crucial criterion in evaluating the volatility and safety of fuels. Polyamide had a fire point of 294°C, while PET & PA blend's fire point was 263 °C. These numbers show that the fuels have great thermal stability, even though they are relatively volatile and need to be handled and stored carefully. Fire points (294°C and 263°C) are well above the reference minimum (>50°C), indicating the temperature at which sustained combustion occurs. High fire points are not a concern and indicate robust combustion properties. Hydrocarbons made from high molecular weight polymers have high fire points, which indicate that significant energy input is needed for ongoing combustion. However, the low flash points pose a concern for the proper handling and storage of the fuel. Flash points (15.82°C and 13.74°C) are well below the ASTM D7544-12 minimum (45°C), posing safety risks and making the fuels unsuitable for industrial burners without modification.

3.2 Thermochemical Properties of Fuel

The thermo-properties of fuels include higher heating value (HHV), octane number, volatile content, fixed carbon content, ash content, and Sulphur content were determined, and their values are as presented in Table and are discussed in comparison with ASTM D7544-12 standard for pyrolysis liquid fuel intended for industrial burner applications (Grades G and D).

Table 2: Thermochemical Properties of the Fuel

Properties	PA	PA % PET	**PET**	**Conventional Gasoline**
HHV/Calorific Value (mg/kg)	46.75	47.55	48.37	44.5 MJ/kg [15]
Octane number	90.7	84.4		93.2 [13]
Volatile content (%)	85.53±0.7	85.62±0.8		54-103 kPa [16]
Fixed carbon content (%)	0.55±0.4	0.26±0.8		0.86 [12]
Sulphur content (%)	0.78±0.3	0.80±0.3	0.72±0.2	0.5% max [11]
Ash content (%)	0.82±0.2	0.92±0.1	0.84±0.1	0.03%-0.07% [17]

3.2.1 Calorific Value (Higher Heating Value – HIV)

The amount of energy generated following full combustion of a unit quantity of fuel is known as the calorific value or higher heating value (HHV). PET had the highest HHV at 48.37 MJ/kg, followed by PA (46.75 MJ/kg) and PET & PA (47.55 MJ/kg). Both fuels have exceptionally high HHV (46.75 and 47.55 MJ/kg), far exceeding the ASTM D7544-12 minimum of 15 MJ/kg and typical biomass pyrolysis oil values (15–20 MJ/kg). These figures are also comparable to or marginally greater than those of typical liquid fuels like diesel (42–46 MJ/kg) and gasoline (44–47 MJ/kg), suggesting a low oxygen content and high hydrocarbon content, likely due to PET (aromatic-rich) and nylon (hydrocarbon-like amides) pyrolysis. The breakdown of polymeric chains into energy-rich aliphatic and aromatic hydrocarbons is reflected in the high energy content of the pyrolyzed fuels. The slightly higher HHV for PET & PA (47.55 vs. 46.75 MJ/kg) may reflect PET's contribution of energy-dense aromatics (e.g., benzene derivatives), suggesting that in thermal applications, fuels made from waste PET and polyamide can successfully replace fossil fuels. The high HHV indicates excellent energy content, making these fuels highly suitable for industrial burners in terms of calorific value.

3.2.2 Octane Number

In spark-ignition engines, the octane number is a crucial indicator of combustion quality since it quantifies a fuel's resistance to engine knocking or pre-ignition. Compared to the PET & PA blend, which had an octane number of 84.4, the PA-derived fuel had a higher number of 90.7. The fact that these values are like those of commercial gasoline (octane number: 87–98) suggests that these fuels may be suitable alternatives to gasoline. The reported values (90.7 and 84.4) suggest testing gasoline-like applications, which are unusual for PET/nylon fuels. The high-octane ratings seen are largely due to the pyrolysis products' high amount of aromatic and branching hydrocarbons of PET's aromatics (e.g., benzene derivatives) may contribute to octane, while nylon's linear compounds (e.g., caprolactam derivatives) may enhance it.

3.2.3 Volatile Content (%)

The results shown on Table 4.2 indicate a high percentage of volatile materials, which facilitate easy ignition and prolonged combustion, are indicated by the results. The volatile content for polyamide and PET/PA (85.53% and 85.62% respectively) is higher than the typical range for biomass pyrolysis oils (60–80%), reflecting the plastic-derived nature of the fuels. For liquids, volatility is indirectly assessed via flash point or distillation (ASTM D86). The high volatile content aligns with the low flash points (15.82°C and 13.74°C), indicating significantly low-boiling fractions. High volatility contributes to the low flash point, a safety concern for ASTM D7544-12 compliance.

3.4.4 Fixed Carbon Content (%)

Fixed carbon content (0.55% $\pm$ 0.4 for polyamide and 0.26% $\pm$ 0.5 for PET & PA) is much lower than the typical range for residual char (10–30%), as expected for liquid fuels rather than solid residues, suggesting lesser residue development. The lower fixed carbon in PET & PA (0.26% vs. 0.55%) may indicate cleaner pyrolysis or fewer heavy residues. Lower fixed carbon is favorable, indicating minimal solid residues in the liquid phase, suitable for burner applications.

3.2.5 Ash Content (%)

The ash content of the pyrolysis oil was 0.82 $\pm$ 0.2 (polyamide) and 0.92 $\pm$ 0.1 (PET & PA). These ash contents exceed ASTM D7544-12 limits for both Grade G ($\leq$0.25%) and Grade D ($\leq$0.15%). While low ash concentration predicts fewer contaminants and less combustion chamber fouling, high ash content indicates non-combustible residues, potentially from additives in PET/nylon feedstocks or incomplete pyrolysis. The non-compliance with ASTM D7544-12 limits suggests potential for burner fouling or corrosion. Reduce ash via feedstock purification (e.g., remove fillers) or filtration post-pyrolysis.

3.2.6 Sulphur Content

Low sulphur content is always preferable for cleaner engine operation since sulphur in fuels causes acid rain and engine degradation. The range of sulphur content was 0.72 $\pm$ 0.2% in PET, 0.78 $\pm$ 0.3 in PA and 0.80 $\pm$ 0.3% in PET and PA. The sulphur contents (0.72%, 0.78% and 0.80%) are less than the sulphur content of conventional gasoline (0.5% max) [11]. The sulphur contents of the fuels are marginally lower but are still within acceptable bounds for many conventional fuels.

3.3 General Implications of Results

According to the experimental data, liquid fuels made from the pyrolysis of waste plastics like PET and polyamide have favourable combustion characteristics, a high energy content, and exceptional thermal stability. The results make a compelling case for the valorisation of waste polymers into liquid fuels and are in line with findings from the literature on plastic pyrolysis fuels [18-19].

Polyamide fuels have modest quantities of sulphur and a higher-octane rating. Blends provide fuels with balanced qualities by combining the advantages of both polymers. These fuels have a great deal of potential to replace fossil fuels, particularly when combined with waste-to-energy technology and circular economy methods for managing polymer waste.

The fuels are suitable for industrial burners in terms of viscosity and moisture content, but fail on flash point, requiring upgrading for safety and compliance. However, Low flash points necessitate storage below 13–15°C in sealed, non-sparking environments to prevent ignition. Cloud and pour points indicate good flow in cold conditions, suitable for most climates.

4.0 Conclusion

The study on the physical and chemical properties of fuel produced from the pyrolysis of polyamide (nylon) and a blend of polyethylene terephthalate (PET) and polyamide (PA) gives valuable information of their potential as alternative fuels or chemical feedstocks, evaluated against the conventional fuels. The fuels exhibited promising characteristics, such as the higher heating value (HHV) of 46.75 MJ/kg (PA) and 47.55 MJ/kg (PET & PA), which exceeds that of conventional gasoline. This high energy content, coupled with low viscosity for PA and PET/PA (3.6 and 3.3 mm²/s), suggests a hydrocarbon-rich composition suitable for industrial burner applications, likely due to the lower oxygen content of the fuels.

However, significant challenges prevent compliance with ASTM D7544-12 and practical usability. Ash content (0.82–0.92%, vs. 0.03% - 0.07%) exceeds limits, risking burner fouling and SOx emissions, respectively. Other properties, such as cloud point (-8.47°C and 0.01°C), density (1.12 and 1.10 g/cm³), and specific gravity (1.12 and 1.10 g/cm³), are within expected ranges and suitable for cold-weather performance.

PET contributes aromatics (e.g., benzene derivatives), potentially increasing density and cloud point, while nylon yields nitrogen-containing compounds (e.g., caprolactam), affecting volatility and sulphur content. The high

HHV and volatility indicate low oxygen content (<10 wt%), but high ash and sulphur likely stem from feedstock impurities (e.g., additives, fillers).

Thus, based on the findings of this study, the following conclusions are drawn

i. Both PET-derived and nylon-derived fuels achieved exceptionally high higher heating values (46–47 MJ/kg), comparable to conventional gasoline, indicating their strong potential as alternative fuels.

ii. The fuels exhibited favourable octane numbers, approximately 90 for PA and 84 for the PET-PA blend, making them suitable for use in spark-ignition engines.

iii. High volatile matter content (~85%) demonstrates efficient thermal decomposition and suggests good combustion characteristics.

iv. Fixed carbon content remained below 1%, indicating that the pyrolysis process effectively converted the plastic feedstocks into liquid fuels rather than char.

v. With pour points around –22 to –26 °C and moderate viscosities (3–4 cP), the Nylon [PA] and PET/PA show good cold-flow properties and easy pumpability

Elevated ash (0.82–0.92%) contents exceed conventional fuel limits, indicating a need for pre-treatment or post-treatment to meet regulatory requirements

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