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PYROLYSIS OF PETROLEUM OILY SLUDGE: A SUSTAINABLE APPROACH FOR WASTE VALORISATION AND ENERGY RECOVERY

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ABSTRACT

Petroleum oily sludge (POS) is a hazardous waste generated during crude oil refining, storage, and transportation, containing hydrocarbons, water, sediments, and heavy metals that pose serious environmental risks. This study investigates pyrolysis as a sustainable method for POS treatment, focusing on the effect of residence time on product yield and quality. The sludge obtained from Kaduna Refining and Petrochemical Company Limited, Nigeria, was characterised using proximate and ultimate analyses, total petroleum hydrocarbon (TPH) determination, and SEM–EDS analysis. Results showed high moisture content (70%), high carbon content (85.3%), TPH of 86%, and a high lower heating value of 47.53 MJ/kg, confirming strong suitability for thermal conversion. Pyrolysis experiments were conducted in a fixed-bed batch reactor at 450°C with residence times of 30, 45, 60, 90, and 120 minutes. Pyro-oil yield increased from 0.34 g/g at 30 minutes to a maximum of 0.87 g/g at 90 minutes before decreasing to 0.61 g/g at 120 minutes due to secondary cracking reactions. Solid char yield decreased steadily from 0.70 to 0.48 g/g with increasing residence time. The flue gas contained high methane content (57.4 wt. %), indicating strong energy recovery potential. Solid char showed carbon enrichment (92%) and significant TPH reduction to 5.3%, confirming effective hydrocarbon conversion. Pyro-oil thermal properties showed that 90 minutes provided the best balance of fuel stability and safety. The study confirms pyrolysis as an efficient waste-to-energy strategy for sustainable refinery sludge management.

Keywords: Energy Recovery, Petroleum Oily Sludge, Pyrolysis, Pyro-oil, Solid Char, Waste Valorization

INTRODUCTION

The petroleum industry generates substantial quantities of hazardous waste, among which petroleum oily sludge (POS) is one of the most problematic. This waste is typically produced during crude oil exploration, refining, storage tank cleaning, and wastewater treatment operations (Ali *et al*., 2024). POS contains a complex mixture of hydrocarbons, water, sediments, and heavy metals, making its disposal a major environmental challenge. Traditional disposal methods such as landfilling, incineration, and chemical treatment have limitations, including secondary pollution, high operational costs, and inefficient resource recovery (Ali *et al*., 2020). Consequently, there is increasing interest in sustainable technologies that not only mitigate environmental risks but also convert waste into valuable products.

Pyrolysis, a thermochemical decomposition process carried out in the absence of oxygen, has emerged as a promising technique for the treatment of oily sludge. It enables the conversion of waste into useful products such as liquid oil, combustible gases, and solid char (Pelagalli *et al*., 2024). The efficiency of pyrolysis depends on several parameters; including temperature, heating rate, and residence time (Halalsheh *et al*., 2024). This study focuses on the pyrolysis of petroleum oily sludge with particular emphasis on the effect of residence time on product yield and composition. The objective is to evaluate the potential of pyrolysis as a waste valorisation technique while providing insights into process optimisation.

MATERIALS AND METHODS

Materials

Petroleum oily sludge used in this study was obtained from Kaduna Refining and Petrochemical Company Limited, a petroleum refinery facility located in Kaduna, Northern Nigeria. The sludge sample collected was air-dried, homogenised, and stored in airtight containers before analysis and experimentation.

Characterisation of Feedstock

The physicochemical properties of the sludge were determined using standard analytical methods. Proximate analysis was conducted to determine moisture content, volatile matter, ash content, and fixed carbon. The proximate characteristics were determined using standard methods as described by Ali *et al*. (2017). Moisture content was determined via ASTM D3173, ash content was determined via ASTM D3174, volatile matter was determined via ASTM D3175-11, while the fixed carbon was determined by difference. Lower heating value (LHV) was determined using a bomb calorimeter according to the standard method ASTM D5685-10A. Ultimate analysis was done to determine the elemental composition, CHNS/O, of the sludge. Carbon, hydrogen and nitrogen concentrations were determined using the standard method ASTM D5291, while the sulphur and oxygen concentrations were determined using the standard method ASTM D5373. SEM–EDS analysis was done to examine surface morphology and elemental distribution in the sludge sample. Total Petroleum Hydrocarbon (TPH) analysis was conducted to quantify the hydrocarbon content of the sludge.

Pyrolysis Experiment

The reactor employed in this study was designed and fabricated in the Department of Chemical Engineering, Kaduna Polytechnic, Kaduna, Nigeria. It consists of two main units: the pyrolyser and the condenser, as illustrated in Figure 1.

Figure 1: Pyrolyser Setup for Petroleum Oily Sludge

The design parameters and specifications of the pyrolyser, as reported by Lamido *et al*. (2023), are presented in Table 1. The pyrolyser is a fixed-bed batch reactor designed to operate at a temperature of 450 °C and capable of withstanding a working pressure of 363.806 kPa. It has an internal diameter of 0.210 m, a height of 0.421 m, and a total volume capacity of 0.0079 m^3. This configuration provides suitable conditions for the thermal decomposition of the feedstock during the pyrolysis process. The condenser, also shown in Figure 1, functions to cool and condense the volatile gases produced during pyrolysis into liquid pyro-oil. A shell-and-tube condenser was used for this purpose, with a design duty of 12,815.136 kJ per batch and a total heat transfer area of 0.2744 m^2, ensuring efficient recovery of condensable products. The pyrolysis temperature was measured using an infrared thermometer, and the heating rate was maintained constant throughout the experiments. A known mass of sludge sample was placed in the reactor and heated under an inert atmosphere to prevent oxidation. The key operating parameter investigated was residence time, varied at 30, 45, 60, 90 and 120 minutes.

Table 1: Pyrolyser Design Specification

Parameter	Specification
Operation	Batch
Design volume (m^3)	0.0079
Height to diameter ratio	2
Pyrolyser diameter (m)	0.210
Pyrolyser height (m)	0.421
Shell thickness (mm)	5
Design pressure (kPa)	400.187
Design temperature (°C)	522.315
Material of construction	Mild steel

Product Collection and Analysis

The pyrolysis products were classified into three fractions: liquid, non-condensable gasses, and solid residue. The liquid fraction was condensed through a cooling system and collected as pyro-oil, while the non-condensable gases (flue gas) were collected in a gas bag and subsequently analysed using an offline gas analyser. The solid residue remained in the pyrolyser as char after the completion of the process. The masses of the pyro-oil and solid char were measured directly using a weighing balance. In addition, the pyro-oil was subjected to chromatographic analysis to determine the hydrocarbon composition.

RESULTS AND DISCUSSION

Characteristics of Petroleum Oily Sludge

The characteristics of petroleum oily sludge (POS) are influenced by the nature of the parent crude oil, refining operations, sludge generation sources, and the type of processing equipment involved (Hasan *et al*., 2024). The sludge used in this study appeared as a semi-black, highly viscous, and thick paste. Its proximate characteristics, presented in Table 2, indicate a high moisture content (70%), low ash content (6%), and low volatile matter (10%). The sludge also exhibited a high lower heating value (LHV) of 47.53 MJ/kg, suggesting a high concentration of hydrocarbon-rich components and a predominance of aromatic structures over oxygenated functional groups. These properties indicate strong potential for thermal conversion through pyrolysis. The observed characteristics are consistent with those reported for Malaysian petroleum oily sludge analysed by Ali *et al*., confirming the suitability of the sludge for energy recovery applications.

Table 2: Proximate Characteristics

Characteristics	Current work	Ali *et al*., 2019
Moisture content (%)	70.0	78.91
Ash content (%)	6.0	5.06
Volatile matter (%)	10.0	5.52
Fixed carbon (%)	14.0	10.51
Density (g/ml)	0.904	1.08

Characteristics	Current work	Ali *et al.*, 2019
Lower heating value (MJ/kg)	47.5268	23.60

The ultimate (elemental) composition of the petroleum oily sludge obtained in the current work (Table 3) differs significantly from that reported by Ali *et al*. (2019), indicating variations in sludge origin, processing history, and storage conditions. The current sludge sample shows much higher carbon content (85.3%) compared to 51.4% reported by Ali *et al*. (2019), suggesting a greater concentration of hydrocarbon materials and a higher potential for energy recovery during pyrolysis. Similarly, the total petroleum hydrocarbon (TPH) value of 86% further confirms the richness of the present sludge in combustible organic matter. In contrast, the oxygen content in the current work (6.32%) is significantly lower than the 35.8% reported by Ali *et al*. (2019), indicating that the present sludge is less oxidised and contains fewer oxygenated compounds. Lower oxygen content is generally favourable for thermal conversion processes because it improves calorific value and reduces energy loss during pyrolysis (Lewandowski *et al*., 2020).

Table 3: Ultimate Characteristics and TPH

Characteristics	Current Work	Ali *et al*., 2019
Carbon (C)	85.3	51.4
Hydrogen (H)	5.44	7.3
Nitrogen (N)	1.96	3.3
Sulphur (S)	0.98	2.2
Oxygen (O)	6.32	35.8
TPH	86	-
TOC	-	54.48

Hydrogen content is slightly lower in the current study (5.44%) compared to 7.3%, while nitrogen and sulphur contents are also lower at 1.96% and 0.98%, respectively, compared to 3.3% and 2.2%. Lower nitrogen and sulphur contents are advantageous because they reduce the likelihood of harmful NOx and SOx emissions during thermal treatment, thereby improving the environmental performance of the pyrolysis process (Li *et al*., 2022). Although total organic carbon (TOC) was not determined in the current work, the very high carbon content and TPH value strongly indicate a high organic fraction compared to the TOC value of 54.48 reported by Ali *et al*. (2019). The sludge analysed in the current work appears to be richer in hydrocarbons, less oxidised, and more suitable for pyrolytic conversion than that reported by Ali *et al*. (2019). The organic part of the sludge can be expressed empirically by $C_{18}H_{14}O$. The SEM–EDS analysis (shown in Table 4) revealed that the petroleum oily sludge contains significant amounts of inorganic and metallic constituents, including K, Al, Si, P, S, Ca, Ba, Cr, Mn, Fe, Cu, Ag, Sn, and Zn. The prominent presence of Ca, Fe, Mn, Zn, and S indicates substantial mineral matter, heavy metals, and sulfur-containing compounds typically associated with refinery residues, corrosion products, and catalyst contaminants. Elements such as Al and Si suggest the presence of silicates and clay materials, while Ca, K, and Ba are linked to ash-forming mineral salts. The occurrence of heavy metals such as Cr, Fe, Cu, and Zn is environmentally significant, as these metals may concentrate in the solid char during pyrolysis and require proper disposal. Sulfur presence is also important because it may contribute to SOx emissions during thermal treatment. These findings confirm the heterogeneous nature of petroleum oily sludge and support pyrolysis as a suitable treatment method for energy recovery and waste minimisation, provided that adequate emission control and residue management systems are incorporated.

Table 4: Elemental Composition from SEM-EDS Analysis

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	73.03	40.27
29	Cu	Copper	2.35	6.87
26	Fe	Iron	2.43	6.22
50	Sn	Tin	1.07	5.86
24	Cr	Chromium	2.04	4.88
56	Ba	Barium	0.65	4.09
47	Ag	Silver	0.77	3.79
14	Si	Silicon	2.88	3.72
13	Al	Aluminium	2.95	3.66
20	Ca	Calcium	1.90	3.50
30	Zn	Zinc	1.04	3.13
25	Mn	Manganese	1.02	2.58
16	S	Sulphur	1.52	2.24
12	Mg	Magnesium	1.83	2.04
17	Cl	Chlorine	1.16	1.88
19	K	Potassium	1.05	1.88
22	Ti	Titanium	0.69	1.52
11	Na	Sodium	1.09	1.15
15	P	Phosphorus	0.53	0.75

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
82	Pb	Lead	0.00	0.00
40	Zr	Zirconium	0.00	0.00

Products Analysis

Three products were obtained from the pyrolysis of the POS conducted at varying residence time of 30, 45, 60, 90 and 120 minutes. The products are pyro-oil, flue gas and solid char. Figure 2 illustrates the effect of residence time on the product distribution during the pyrolysis of petroleum oily sludge (POS), specifically showing the variation in pyro-oil yield and solid char yield with increasing residence time. The residence times investigated were 30, 45, 60, 90, and 120 minutes.

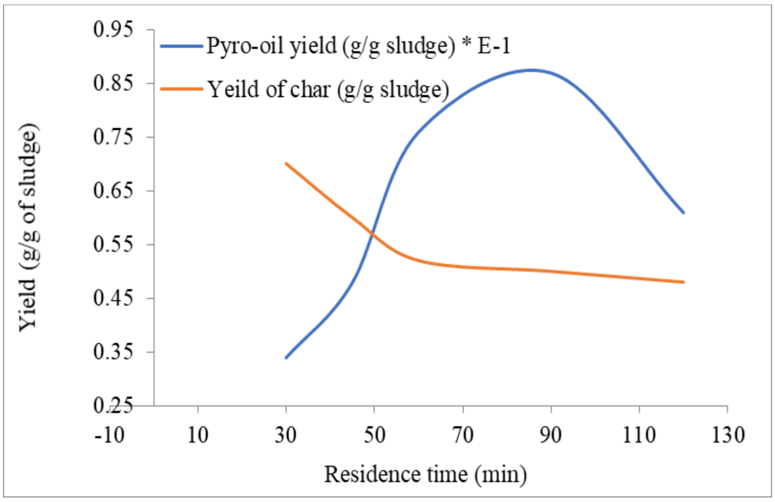

Figure 2: Effect of Residence Time on the Yield of Products

The results show that pyro-oil yield increased progressively from 0.34 g/g of sludge at 30 minutes to 0.48 g/g at 45 minutes, 0.76 g/g at 60 minutes, and reached a maximum value of 0.87 g/g at 90 minutes. However, at 120 minutes, the pyro-oil yield decreased to 0.61 g/g of sludge. This trend indicates that moderate residence time favours the thermal decomposition of organic components in the sludge into condensable volatile compounds, which are later recovered as pyro-oil. At shorter residence times, the decomposition may be incomplete, resulting in lower oil production. As the residence time increases, more hydrocarbons are cracked and volatilized, leading to higher liquid yield. Beyond the optimum residence time of 90 minutes, the decrease in pyro-oil yield can be attributed to secondary cracking reactions. During prolonged heating, the already-formed condensable vapours undergo further decomposition into lighter, non-condensable gases such as methane, carbon monoxide, and hydrogen-rich gases, thereby reducing the liquid fraction. This observation agrees with the general behaviour of pyrolysis systems, where excessive residence time shifts product distribution from liquid toward gaseous products.

In contrast, the solid char yield showed a continuous decrease with increasing residence time. The solid char yield dropped from 0.70 g/g of sludge at 30 minutes to 0.60 g/g at 45 minutes, 0.52 g/g at 60 minutes, 0.50 g/g at 90 minutes, and finally 0.48 g/g at 120 minutes. This reduction occurs because longer residence times allow more complete thermal degradation of the solid organic matrix, converting more fixed carbon and volatile solids into vapours and gases rather than leaving them as solid residue. The inverse relationship between pyro-oil yield and solid char yield confirms that residence time is a critical operating parameter in optimising POS pyrolysis. The highest pyro-oil recovery at 90 minutes suggests that this is the most suitable residence time for maximising liquid fuel production under the operating conditions of this study. Meanwhile, longer residence times may be preferred when the objective is greater gas production rather than liquid recovery.

Similar observations have been widely reported in sludge pyrolysis studies, where liquid (pyro-oil) yield initially increases with residence time and then declines after an optimum point due to secondary cracking of condensable vapours into permanent gases. For example, Shen and Zhang (2003), in their study on activated sewage sludge pyrolysis in a fluidised-bed reactor, reported that the maximum oil yield of about 30 wt. % was obtained at a short gas residence time of 1.5 s. They observed that increasing gas residence time to 3.5 s favoured the formation of non-condensable gases and reduced oil yield, concluding that this was caused by secondary cracking reactions of the primary condensable vapours. Similarly, a recent review, by Hu and Chen (2025), on sewage sludge pyrolysis noted that prolonged residence time enhances secondary cracking reactions (SCRs), which decompose pyrolysis oil into lighter gaseous products. The review specifically states that short residence times favour liquid formation, whereas longer residence times promote gas production and reduce both bio-oil and biochar yields. This effect becomes more pronounced at elevated temperatures (525–625 °C), where volatile compounds are more susceptible to thermal decomposition.

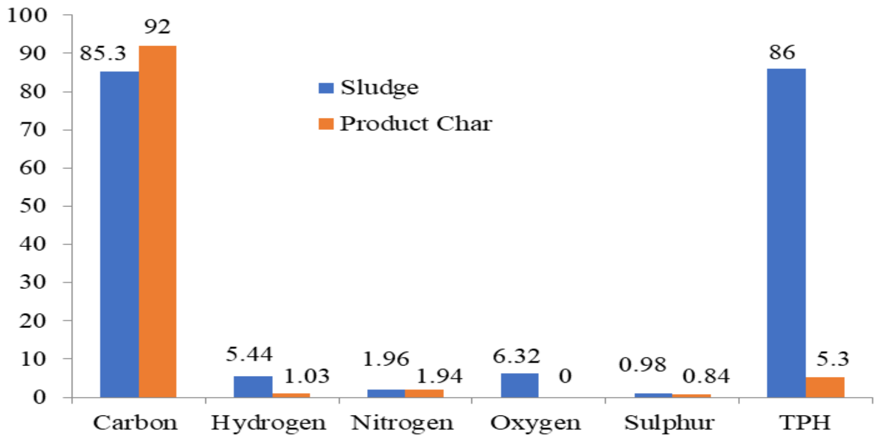

Figure 3: Comparison of the Ultimate Characteristics of the Raw Petroleum Oily Sludge (POS) and the Resulting Solid Char after Pyrolysis

Figure 3 presents a comparison of the ultimate characteristics of the raw petroleum oily sludge (POS) and the resulting solid char after pyrolysis. The parameters compared include carbon, hydrogen, nitrogen, oxygen, sulphur, and total petroleum hydrocarbons (TPH). This comparison provides important insight into the compositional changes that occur during pyrolysis and helps explain the fuel quality and environmental implications of the produced char. The carbon content increased significantly from 85.3% in the raw sludge to 92% in the solid char. This increase indicates strong carbon enrichment during pyrolysis as volatile compounds containing hydrogen and oxygen are released in the form of gases and condensable vapours. The higher carbon concentration suggests that the solid char possesses improved calorific value and greater potential for use as a solid fuel or carbon-rich material for industrial applications. The concentration of fixed carbon after pyrolysis is a common indicator of successful thermal decomposition and enhanced energy density.

Hydrogen content decreased sharply from 5.44% in the sludge to 1.03% in the char. This reduction occurs because hydrogen-containing compounds are largely converted into volatile hydrocarbons, methane, and other gaseous products during thermal cracking. Similarly, oxygen content decreased completely from 6.32% to 0%, indicating substantial deoxygenation during pyrolysis. Lower oxygen content is desirable because it improves fuel quality by increasing heating value and reducing the tendency for oxidation and instability during storage. Nitrogen content showed only a slight decrease from 1.96% to 1.94%, suggesting that nitrogen-containing compounds were relatively stable during pyrolysis and remained largely concentrated in the char fraction. Sulphur content also decreased slightly from 0.98% to 0.84%, indicating partial removal of sulphur during thermal treatment. This is environmentally beneficial because lower sulphur content reduces the potential for sulphur oxide (SOx) emissions if the solid char is later combusted.

A major reduction was also observed in total petroleum hydrocarbons (TPH), which dropped drastically from 86% in the raw sludge to 5.3% in the solid char. This confirms that most of the hydrocarbon-rich organic matter was successfully volatilized and converted into pyro-oil and gaseous products during pyrolysis. The low residual TPH in the solid char suggests that the solid residue is less hazardous and more environmentally stable compared to the untreated sludge.

Table 5 presents the composition of the flue gas generated during the pyrolysis of petroleum oily sludge (POS), showing the concentrations of major gaseous products and emission-related components. The analysed gases include oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), total nitrogen oxides (NOx), sulphur dioxide (SO_2), methane (CH_4), and hydrogen sulphide (H_2S). The composition of these gases provides important information on the efficiency of thermal decomposition, fuel potential of the gas fraction, and possible environmental implications of the process. The most dominant component in the flue gas is methane (CH_4), with a concentration of 57.4 wt. %. This very high methane content indicates that the pyrolysis process generated a combustible gas fraction with strong energy recovery potential. Methane is a major fuel gas with high calorific value, and its abundance suggests that the non-condensable gas produced can be recovered and utilised as a supplementary fuel source for heating or power generation within the pyrolysis system itself. This improves the overall energy efficiency and economic viability of the process.

Oxygen (O_2) was measured at 11.2 wt. %, while carbon dioxide (CO_2) was relatively low at 1.4 wt. %. The moderate oxygen presence may be associated with residual air in the system or minor gas leakage during operation, while the low CO_2 concentration indicates that complete oxidation was limited, which is expected since pyrolysis occurs under oxygen-deficient conditions. This confirms that thermal decomposition rather than combustion was the dominant reaction pathway. Carbon monoxide (CO) was detected at 3.1 ppm, indicating partial cracking and incomplete oxidation of carbon-containing compounds. Although present in low concentration, CO is significant because it contributes to the combustible nature of syngas and can also indicate the extent of secondary decomposition reactions occurring during prolonged heating.

Table 5: Composition of Flue Gas

Component	O_2 (wt. %)	CO (ppm)	CO_2 (wt.%)	NO (wt.%)	NO_2 (wt.%)	NOx (ppm)	SO_2 (ppm)	CH_4 (wt.%)	H_2S (ppm)
Quantity	11.2	3.1	1.4	1.3	0.4	8.0	1.8	57.4	0.11

Nitrogen-containing gases were also detected, with nitric oxide (NO) at 1.3 wt. %, nitrogen dioxide (NO_2) at 0.4 wt. %, and total NOx at 8.0 ppm. These gases originate mainly from nitrogen compounds present in the sludge. Although the concentrations are relatively low, NOx emissions are environmentally important because they contribute to air pollution and acid rain. Their low levels suggest that the relatively low nitrogen content of the sludge helped minimise harmful emissions. Sulphur dioxide (SO_2) was recorded at 1.8 ppm, while hydrogen sulphide (H_2S) was very low at 0.11 ppm. These gases result from the decomposition of sulphur-containing compounds in the sludge. The low concentrations indicate limited sulphur release, which is consistent with the low sulphur content of the feedstock (0.98%) and supports the environmental suitability of the process by reducing the risk of severe SOx-related pollution.

Table 6 presents the thermal properties of the pyro-oil produced from the pyrolysis of petroleum oily sludge at three residence times (45, 90, and 120 minutes). The parameters evaluated are acid value, fire point, and flash point, which are important indicators of fuel quality, storage safety, handling characteristics, and suitability for energy applications. These properties help determine the potential of the pyro-oil as an alternative liquid fuel or as a feedstock for further upgrading.

Table 6: Thermal Properties of Pyro-Oil

Parameter	45 min	90 min	120 min
Acid value (KOH/g)	1.8	9.1	10.4
Fire point	123.6	173.33	123.27
Flash point	129.23	184.90	192.40

The acid value increased significantly with increasing residence time, rising from 1.8 KOH/g at 45 minutes to 9.1 KOH/g at 90 minutes and further to 10.4 KOH/g at 120 minutes. This increase suggests the formation of more acidic oxygenated compounds such as carboxylic acids, phenols, and other polar compounds during prolonged pyrolysis. A low acid value is generally preferred because highly acidic oils can cause corrosion of storage tanks, pipelines, and engine components. Therefore, the lower acid value observed at 45 minutes indicates better fuel stability and less corrosive potential compared to the oils produced at longer residence times. The fire point also varied with residence time. It was 123.6°C at 45 minutes, increased significantly to 173.33°C at 90 minutes, and then decreased slightly to 123.27°C at 120 minutes. A higher fire point indicates that the fuel requires a higher temperature to sustain combustion, which improves safety during handling and storage. The highest fire point at 90 minutes suggests that the pyro-oil produced at this residence time is relatively safer and more thermally stable than those produced at 45 and 120 minutes.

Similarly, the flash point increased from 129.23°C at 45 minutes to 184.90°C at 90 minutes and reached the highest value of 192.40°C at 120 minutes. Flash point refers to the minimum temperature at which the oil produces sufficient vapour to ignite momentarily in the presence of a flame. Higher flash points are desirable because they indicate lower volatility and reduced risk of accidental ignition during transportation and storage. The progressive increase in flash point with residence time suggests that heavier and less volatile compounds became more dominant in the oil as secondary cracking and molecular rearrangement occurred. The combined interpretation of these properties shows that residence time strongly influences the quality of the produced pyro-oil. At shorter residence time (45 minutes), the oil has low acidity and relatively lower flash and fire points, making it less corrosive but more volatile. At 90 minutes, the oil exhibits the highest fire point and moderate acidity, indicating a balance between stability and fuel safety. At 120 minutes, although the flash point is highest, the high acid value reduces its direct fuel suitability without further upgrading.

CONCLUSION

This study demonstrates that pyrolysis is an effective and sustainable approach for the treatment and valorisation of petroleum oily sludge (POS), transforming a hazardous refinery waste into valuable energy products such as pyro-oil, combustible gas, and char. The physicochemical characterisation of the sludge revealed high moisture content, high carbon content (85.3%), significant total petroleum hydrocarbon (86%), and a high lower heating value (47.53 MJ/kg), confirming its strong suitability for thermal conversion. SEM–EDS analysis further showed the presence of inorganic minerals and heavy metals, highlighting the environmental importance of proper treatment and residue management.

Residence time was found to be a critical operating parameter influencing product distribution and fuel quality. Pyro-oil yield increased with increasing residence time and reached a maximum value of 0.87 g/g of sludge at 90 minutes, after which it declined due to secondary cracking reactions that favoured gas formation. Solid char yield decreased steadily with longer residence time, indicating more complete thermal decomposition of the organic matrix. The significant reduction in total petroleum hydrocarbons from 86% in the raw sludge to 5.3% in the solid char confirms the effectiveness of pyrolysis in reducing the hazardous nature of the waste.

The flue gas composition showed a high methane content (57.4 wt. %), indicating strong potential for energy recovery through utilisation of the non-condensable gas fraction as a supplementary fuel source. The relatively low concentrations of CO, SO_2, H_2S, and NOx also suggest improved environmental performance of the process. Thermal property analysis of the pyro-oil showed that residence time significantly affected acid value, flash point, and fire point, with 90 minutes providing the best balance between fuel stability, safety, and energy quality.

The results confirm that petroleum oily sludge can be successfully converted into useful energy products through pyrolysis, reducing environmental pollution while enhancing resource recovery. Among the conditions investigated, a residence time of 90 minutes was identified as the optimum for maximising liquid fuel production and achieving balanced product quality. This study supports pyrolysis as a practical waste-to-energy strategy for sustainable refinery waste management and provides useful data for future scale-up and industrial application.

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