



EXPERIMENTAL ASSESSMENT OF OIL RECOVERY FROM PYROLYSIS EXTRACTION OF WASTE PLASTICS AND TYRES

Seun OYELAMI¹, Wasiu Oyediran ADEDEJI¹, Abideen Temitayo OYEWO^{1*}, Kehinde Adenike OYEWOLE², Busayo Sunday ADEBOYE¹, Abdulhafiz Ademola ADEFAJO¹

¹ Mechanical Engineering Department, Osun State University, Osun State, Nigeria.

² Chemical Engineering Department, Osun State University, Osun State, Nigeria

* Correspondence email: Abideen Temitayo OYEWO (abideen.oyewo@uniosun.edu.ng)

Abstract

Disposing of waste tyres and plastics in landfills and on roads poses significant environmental risks, such as fire, air pollution, blocked drainage, and flooding. Waste tires and plastics from local municipal sources were sorted and exposed to the natural environment for two weeks. The study then carried out thermal pyrolysis of the tyres and plastics in a fixed bed reactor. Three different ratios were tested: 100% tyres (C), 80% tires and 20% plastics (B), and 60% tyres and 40% plastics (A). The resulting pyrolysis oil was condensed into a liquid. The weight percentages of oil, char, and gas were measured, with Sample A producing the highest amounts of oil (25.15 wt.%) and gas (32.52 wt.%) while B produced the highest char (69.20%). Sample A displayed balanced properties suitable for diesel engine use, with a uniform distribution and better connection between the tire and plastic components, suggesting potential for oil production.

Keywords: pyrolysis, waste tyres, proximate analysis, calorific value, pyrolysis reactor.

1.0 Introduction

An effort is being made to find suitable energy sources, particularly those made from waste materials, in order to lessen our reliance on fossil fuels and to establish a circular economy. There is a large-scale production of plastic products, and the production of tyres is necessary for the automotive industry (and rubber in general). Because they are getting worse, issues with the disposal of plastic waste and tyres need to

be taken into account. Research has been done on recycling rubber and plastic waste to produce a useful replacement that can be used as a main source for making fuels and monomers. It is well known that plastics and tyres (generally speaking, rubber) can be recycled (Abdallah et al., 2020; Carmo-Calado et al., 2020; Sharma et al., 2021). Conversely, some of the waste made of plastic and tyres can also be burned in

municipal waste incinerators (Eze et al., 2021).

separated during recycling (Oni et al., 2021; Pandey et al., 2020).

The caloric value of tyres is relatively high (30 MJ kg⁻¹), and their combustion can produce large amounts of energy. Tyres are typically burned off in cement plants as waste. The most environmentally friendly way to use a tyre is to use the material from it, as this avoids wasting scarce raw materials and solves the problem of where to put the tyre. Rubber, fabrics, steel wires, and other additives can be found in tyres. To ensure that the recycled materials are as clean as possible, all of this must be separated during recycling (Qureshi et al., 2020). The tyres are first broken down into "chips," which are then sent to the recycling line, where they turn into granulates. The textile fibres are sucked out as the steel components are separated by powerful magnets. This process is difficult and calls for a respectable level of technique. However, a tonne of material is generated once everything has been separated and can be used in other ways. The textile fibres are used to create sound-insulating products, the steel wires are transported to blast furnaces, and rubber can be used to make paving, insulation boards, shock absorbers, and a variety of surfaces. A lot of energy can be produced from burning tyres because they have a relatively high caloric value (30 MJ kg⁻¹). Tyres are frequently burned to destruction in cement plants. The most environmentally friendly way to use a tyre is to recycle its material, as this avoids wasting finite raw materials and addresses the issue of where to put the tyres. The tyre is made up of additives like steel wires, rubber, and textiles. In order to obtain the cleanest possible materials, all of this must be

Rubber and plastic waste can be processed through pyrolysis to create fuel. The thermochemical breakdown of organic material without the presence of oxygen is referred to as pyrolysis. The material is heated beyond the point at which organic compounds maintain their thermal stability. Semi-coke, liquid pyrolysis oil and pyrolysis gas are the three primary by-products of pyrolysis. The pyrolysis parameters, including temperature, pressure, heating rate, and the amount of time the products spend in the reaction space, can be used to adjust their ratio (Čabalová et al., 2021; Jahirul et al., 2021; Mavukwana & Sempuga, 2022).

The pyrolysis oil made from tyres is thick and smells strongly. It is also dark and viscous, contains BTX and PAH, as well as significant amounts of solid impurities, sulphur and nitrogen, and nitrous oxide (Li et al., 2021). As a result, pyrolysis is constantly being improved to enhance the qualities of the pyrolysis oils from used tyres, which aid in the recycling of used tyres and also provide an alternative for the production of fuel. The yields of the liquid product and its hydrodesulphurization with the aid of various catalysts have both been studied in relation to the pyrolysis of used tyres. The fuel produced by the pyrolysis of used tyres was comparable to diesel fuel for the most crucial parameters when the physical and chemical properties of the pyrolysis oil alone, mixed with diesel, and pure petroleum diesel with EN 590 were compared (Hu et al., 2020; Oyewo et al., 2023). Diesel and diesel combined with 10% tyre oil were compared using a test engine, and experimental

monitoring was done for combustion, engine output, and exhaust emissions. For use in diesel engines, the tyre oil and diesel mixture were suitable (Palos et al., 2021).

To enhance the properties, the oil produced by the pyrolysis of van and passenger car tyres must undergo hydro-treatment under relatively strict conditions. Adding the pyrolysis oil to the motor fuels was not advised, even after rening; instead, it was suggested that it be added to the fuel oils as a potential substitute fuel (Arabiourrutia et al., 2020; Czajczyńska et al., 2020). The characteristics of pyrolysis oil from tyres, including potential complications, as well as their impact on combustion engines and exhaust gas emissions, have been well outlined (Januszewicz et al., 2020). Although the input raw materials may contain chlorinated substances and high levels of nitrogenous substances, which can adversely affect further processing, the properties of pyrolysis oil from plastics are not significantly different from those of the raw materials processed in refineries. The use of pyrolysis oils from plastic as fuel for diesel engines was investigated, much like the use of pyrolysis oil from tyres (Čabalová et al., 2021). These oils' impact on combustion engine performance and emission composition was investigated. In a diesel engine, the addition of pyrolysis oil made from plastics and Nano catalysts improved combustion and decreased CO₂ and hydrocarbon emissions. NOX emissions were reduced, but only slightly (Qureshi et al., 2020).

Disposal of waste tyres and plastics on landfills and roads pose a great threat to the environment such as fire risks (which causes air pollution) and blockage of drainage and water ways (which cause flooding). Additionally, these waste tyres can become

breeding grounds for mosquitoes, which can spread disease to humans and animals. Due to these waste tyres and plastics being non-biodegradable, there is a need to find a better way of disposing or recycling these wastes which would eliminate these risks and also provide a good economic advantage. The aim of the study is to investigate the recovery of oil from pyrolysis extraction of waste plastics and tyres. The specific objectives are: (1) To determine the optimum working circumstances for pyrolysis oil production; (2) To evaluate the quality of pyrolysis oil produced under different operating conditions and (3) To compare the performance of pyrolysis oil with traditional fossil fuels in a diesel engine.

2.0 Methodology

2.1 Materials

10kg of waste tyres and plastics were obtained from various local municipal sources and sorted. Both waste tyres and plastics were exposed to the natural environment for a period of two weeks or less from the time of collection at the dump yard as it is standard practice to do so in an unsanitary manner. The tyres and plastics were blown by air to remove any dust particles and they were shredded or cut into small pieces to increase the surface area and facilitate the pyrolysis process.

2.2 Determination of physical and chemical properties of the samples

The samples were subjected to thermogravimetry using a Tarsus F3 Model NETZSCH Thermo Gravimetric Analyser (TGA) which was used for the thermal decomposition of the samples. Approximately, 10 mg of specimens were cut out from the shavings for the analysis following ISO 11358 (2014) guideline. The samples were heated from room temperature

(RT) to 110°C at 2°C min⁻¹, and then they were kept in isothermal mode at 110°C for 10 min. Samples were then heat to 250°C at 2°C min⁻¹ and kept afterwards at this temperature for 10 min. The last heating stage consisted of heating the samples to 900°C at 10°C min⁻¹. All steps will be kept under constant flow of N₂ equal to 25 ml min⁻¹ in the case of isothermal segments and 50 ml min⁻¹ for dynamic ones (Al-Salem *et al.*, 2021). TGA unit is externally calibrated and maintained annually NETZSCH engineers, using standard reference materials (e.g., Tin, Indium, Zinc, Copper and Silver) traceable to National Institute of Standards and Technology (NIST).

2.3 Pyrolysis reactor

The thermal pyrolysis of the tyre and plastic were carried out in a fixed bed reactor

possessing. 500g of tyre was placed in the fixed bed reactor. After that, the fixed bed reactor was tuned-on and the temperature was set to 500 °C. The pyrolysis process started at 21 °C which is room temperature. A gradual increase in the temperatures begins, until the final desired temperatures are reached. Gas started coming out at 300 °C while the oil started coming at 350 °C. The pyrolyzed oil passed through a condenser which cooled and condensed the vapors, resulting in the liquid pyrolysis oil. This oil was then collected and stored for further analysis. The percentage weight of the Oil, Char and Gas measured. After the completion of the experimental run, the reactor was allowed to cool before removing the char inside the reactor. Figure 1 and Figure 2 show the pyrolysis reactor used and the experimental setup.



Figure 1: Pyrolysis Reactor



Figure 2: Experimental Set-up

2.4 Characterization of pyrolysis oils

The oil samples collected from the pyrolysis of the waste tyre and plastics were analysed for common fuel properties. Table shows the summary of the tests conducted (and methods) on the samples.

2.5 Calorific value

A Gallenkamp Ballistic Bomb Calorimeter apparatus and benzoic acid were used in this study. 0.25gm of each sample depending on bulkiness was weighed into the steel capsule.

A 10cm cotton thread was attached to the thermocouple to touch the capsule. The bomb was closed and charged in with oxygen up to 30 atm. The bomb was fixed up by depression the ignite switch to burn the sample in an excess of oxygen. The maximum temperature rise in the bomb was measured with the thermocouple and galvanometer system. The rise in temperature was compared with that obtained for 0.25gm of Benzoic value of each sample was determined by Equation 1:

$$\text{Calorific Value} = \frac{\text{Galvanometer deflection of sample} \times \text{Calibration constant}}{\text{Weight of sample taken}}, \text{ kcal/g} \quad (1)$$

2.6 Flash point

Automated Pensky – Martens Closed Cup and Mercury in Glass Thermometer (0-10⁰c -400⁰c) were the apparatus used in this study. The sample was filled in the test cup up to the specified level and heated at a slow and constant rate of stirring for proper and uniform heating. The temperature was measured with the help of a thermometer of -10⁰C to 400⁰C. At every 1⁰C temperature rise, the flame was directed into the cup through the opening provided at the top cover. The temperature at which flash was observed is the flash point of the biodiesel.

2.7 Viscosity

A Viscolite 700, Mercury in Glass Thermometer (0 -100⁰C) and 2ml of sample was heated up to the temperature of 40⁰C. It was then poured into a graduated cylinder. A solid stainless-steel sensor of the viscometer (Viscolite 700) was then immersed into the sample. The sample level had to be higher than the line on the sensor and the side of the viscometer sensor must not be touching with the graduated cylinder. The reading of the viscometer result was in mm²/s.

2.8 Gravity

With a specific gravity bottle, 5ml of the biodiesel was weighed on an analytical balance into a previously weighed dried clean specific gravity bottle and new weight of biodiesel plus bottle was weighed on the analytical weighing balance. The specific gravity is calculate using Equation 2:

$$\text{Specific gravity} = \frac{\text{Weight of 5ml of Biodiesel}}{\text{Weight of equal 5ml of distilled water}} \quad (2)$$

2.9 Moisture Content

For this experiment, oven, crucibles, desiccator balance and silica gel and grease (reagents) were used. 2g of the sample was weighed into a previously weighed crucible. The crucible plus sample taken was then transferred into the oven set at 100C to dry to a constant weight for 2 hours. At the end of the 2hours, the crucible plus sample was removed from the oven and transferred to desiccator, cooled for ten minutes and weighed (Equation 3).

$$\% \text{ Moisture} = \frac{W_1 - W_3 \times 100}{W_1 - W_0} \quad (3)$$

Weight of empty crucible is W_0

Weight of crucible plus sample is W_1

Weight of crucible plus oven-dried sample, W_3

2.10 Ash Content

Porcelain crucibles, a desiccator, analytical balances and a furnace are the apparatus employed for this study. A 2.0gm of the sample were weighed into a silver crucible. This was transferred into the muffle furnace set at 550⁰C and left for about 4 hours. About this time, it had turned to white ash. The crucible and its content were cooled to about 100⁰C in air, then room temperature in a desiccator and weighed. This was done in duplicate. The percentage ash was calculated with the aid of Equation 4:

$$\text{Ash content} = \frac{\text{Weight of ash X 100}}{\text{Original weight of sample}} \quad (4)$$

2.11 Cetane

A measurement of 2ml of the biodiesel was introduced into the automated ignition tester at room temperature. The standard combustion procedures of the tester were followed according to the manufacturer's instructions. The ignition key was depressed and combustion was allowed to occur to completion to give the corresponding Cetane No of the biodiesel via the meter reading of the tester.

2.12 Ignition Temperature

This is determined using an automated ignition quality tester fitted with automated temperature sensor that measures the temperature at which the biodiesel will ignite upon application of an ignition source. 2ml of

2.13 Combustible Matter

A measurement of 2g of biodiesel was weighed by means of an analytical balance into an automated combustion chamber fitted with combustion rate sensor in a digital meter calibrated in degree Celsius per seconds. The combustion key was depressed and combustion was allowed to begin until completion of total combustion. The combustible matter was determined gravimetrically by measuring the weight of the combustion chamber after complete of combustion and comparing with the initial weight of the chamber before combustion (Equation 5).

$$\% \text{ Combustible matter} = \frac{\text{weight of combustion chamber} + \text{biodiesel}}{\text{weight of biodiesel taken}} \quad (5)$$

2.16 High Heating Value and Low Heating Value

Equations were developed for the calculation of the Higher Heating Value and Lower Heating Value of biodiesel from their density values. The equation between density and higher heating value for biodiesel is:

$$\text{HHV} = -0.0259 \times \text{density} + 46.77$$

The equation between density and Lower Heating Value for biodiesel is:

$$\text{LHV} = -0.021 \times \text{density} + 43.12.$$

the biodiesel was introduced into the automated ignition tester at room temperature. The temperature sensor key was depressed to measure the temperature at which the biodiesel ignites.

2.14 Combustion Rate

A measurement of 2g of biodiesel was weighed by means of an analytical balance into an automated combustion chamber fitted with combustion rate sensor in a digital meter calibrated in degree Celsius per seconds. The combustion key was depressed and combustion was allowed to begin until completion of total combustion. The combustion rate was measured automatically through the combustion sensor that gives readings on the digital meter for the combustion rate.

3.0 Results and discussion

3.1 Pyrolyzed sample products

Figure 3 presents the weight of the products derived from pyrolyzed samples. As the quantity of plastic increase the percentage char weight reduced with 100/0 tyre/plastic producing the highest char. However, increase in plastic content was proportional to higher gas and oil yield, making 60/40 tyre/plastic superior to other samples. The quality of the product obtained from pyrolysis depends on the type of waste plastic

and various process parameters like residence time, temperature, and catalyst (Čabalová et al., 2021; Jahirul et al., 2021; Mavukwana & Sempuga, 2022). Higher plastic content leads to increased oil production. The average oil yield from waste plastics typically falls within an 82 wt.% range, with pyrolysis generally conducted within 500 °C. Studies suggest that the pyrolytic temperature range for catalytic conversion of plastic wastes

often occurs at lower temperatures and shorter reaction times, resulting in a comparative increase in fuel yield and quality regarding the diesel fuel. Januszewicz et al. (2020) also discovered that a petrol engine running on pyrolysis oil from waste plastic can achieve up to 50% of the Brake Thermal Efficiency (BTE) obtained with standard diesel fuel.

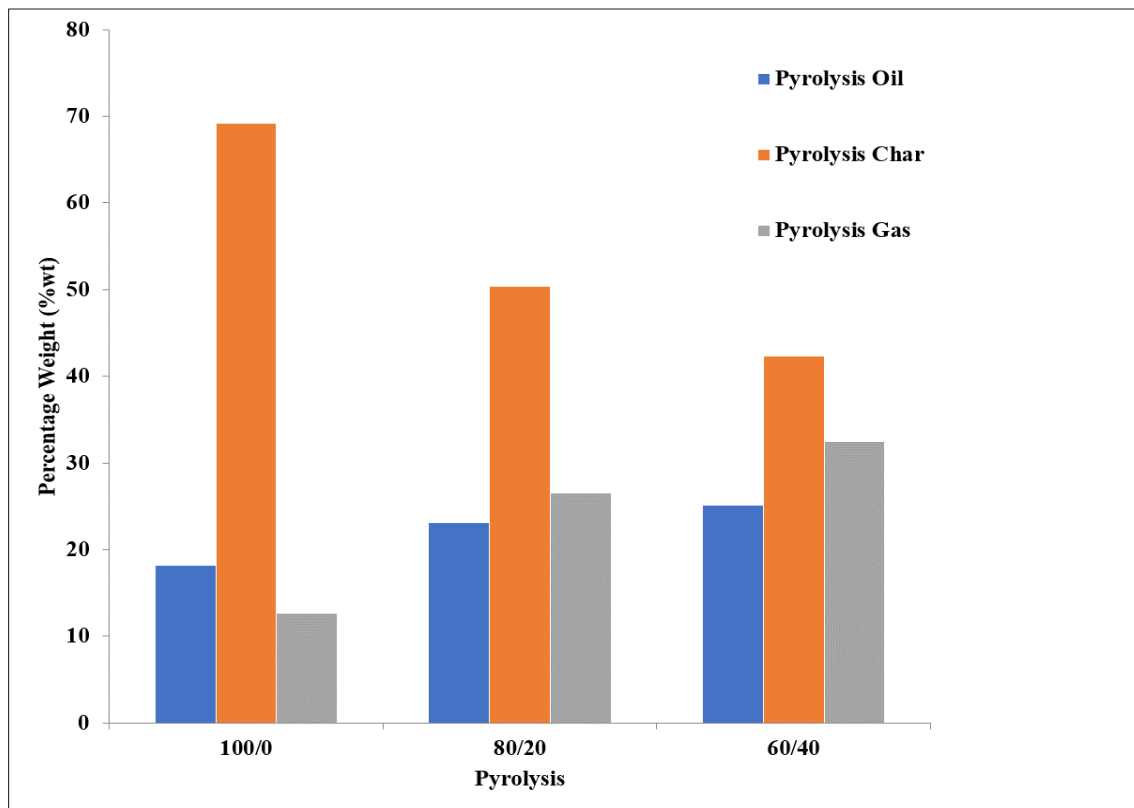


Figure 3: The percentage weight of the pyrolyzed oil, char and gas

3.2 Proximate Analysis

The proximate analysis provides valuable information about the composition of the

Table 1.

3.3 Calorific Value

The calorific value represents the energy content of the pyrolysis oil and is a crucial

waste tyre and plastics. The results of the proximate analysis are shown in

parameter for assessing its potential as a fuel. Also, it signifies the quantity of thermal energy discharged during the process of combustion. As shown in

Table 1 below, Sample 3 displays the most elevated calorific value, hinting at the potential for greater energy release when subjected to burning. Also, by comparing the calorific values, 60/40 is a preferred choice for energy generation due to its higher energy content making it suitable for various energy applications such as combustion or energy recovery processes. The high calorific value suggests that the pyrolysis oil can serve as a valuable alternative or supplementary fuel source.

3.4 Ignition Temperature

The ignition temperature refers to the temperature at which the oil sample can start to burn spontaneously. It provides insights

Table 1, sample 3 has the highest value which means it showcases the swiftest rate of combustion, implying a propensity for faster burning.

3.6 High Heating Value and Low Heating Value

These values represent the heat energy released per unit mass of the oil sample when

Table 1, Sample 1 has the highest high heating value, indicating it has higher energy content when all products of combustion are in a gaseous state. Similar to high heating value, Sample 1 also has the highest low heating value, representing energy content when water vapor isn't condensed.

3.7 Combustible Matter

The combustible matter percentage represents the proportion of the oil sample that can be burned. Higher values indicate a higher concentration of combustible components in the oil. The results show that Sample 3 has the highest combustible matter

into the ease of igniting the oil. Lower ignition temperatures generally indicate higher flammability. By comparing the values of all the samples, sample 3 has the highest ignition temperature, implying it might require slightly higher temperatures to initiate combustion compared to Sample 1 and 2.

3.5 Rate of Combustion

The rate of combustion measures the speed at which the oil sample burns. Faster combustion rates indicate more efficient burning characteristics. Higher combustion rates suggest that the oil can be readily consumed during combustion processes. As shown in

burned completely under different conditions. The high heating value (HHV) considers that the water vapor in the combustion products is condensed, while the low heating value (LHV) assumes that the water remains in a vapor state. Comparing the HHV and LHV can provide insights into the potential heat recovery efficiency. As shown in

percentage, suggesting it contains a higher proportion of materials that can combust.

3.8 Flash Point

The flash point is the lowest temperature at which the oil vapor above the sample can ignite in the presence of an open flame or spark. It is important to determine the flash point because of light hydrocarbon content influence on the diesel volatilization.

3.9 Cetane (n-Hexadecane) Number

The cetane number is a measure of the ignition quality of diesel fuels. Higher cetane numbers indicate better ignition characteristics. As shown in

Table 1, we come to know that sample 3 has the highest cetane number, implying favorable ignition characteristics.

3. 10 Viscosity

Viscosity refers to the oil's resistance to flow and is an important property for determining its suitability for different applications. Sample 2 exhibits the highest viscosity,

Table 1, Sample 2 reports the highest specific gravity, indicating greater density compared to the remaining samples.

3.12 Ash and Moisture Content Percentage

Moisture content and ash percentage indicate the presence of water and inorganic residues, respectively, in the oil sample. Lower values for both parameters are desirable, as they can affect the combustion process and overall oil quality. The main characteristic of the tyre

Table 1. This applies to ignition temperature, Rate of Combustion, High Heating Value, Low Heating Value, Combustible Matter,

Table 1 shows the result of elemental result on Proximate Analysis

Table 1: Proximate Analysis

Sample	Tyre (300g) and plastics (200g)		Tyre (400g) and plastics (100g)		Tyre (500g)	
Parameters	Value 1	Value 2	Value 1	Value 2	Value 1	Value 2
Calorific Value (Mj/kg)	46.89	46.85	45.78	45.76	47.83	47.81
Ignition Temp (k)	912.67	912.69	896.85	896.82	985.26	985.22
Rate of Combustion (⁰ C/s)	359.34	359.31	352.78	352.81	376.58	376.61
High Heating Value	44.3	44.1	43.4	43.7	45.5	45.2

indicating a potential for reduced flow ability compared to the other samples.

3.11 Specific Gravity

Specific gravity represents the density of the oil sample relative to the density of water. It provides information about the oil's buoyancy and can help identify impurities or changes in composition. As shown in

material is showing the detailed proximate analysis conducted on our four samples which were extracted from our tyres. In Calorific temperature there is a small difference between Value 1 and Value 2 of tyre (300g) (200g) combustion result and same as tyre (400g) (100g) and tyre (500g). The rate of combustion differs with a little range within the temperature that means if you test for different samples, you can't get same result for different samples according to our observations in

Flash Point, Cetane No, Viscosity, Specific Gravity, Moisture Content, and Ash Content. The

Low Heating Value	42.5	42.3	41.9	41.6	43.7	41.8
Combustible Matter %	76.59	76.57	75.88	75.92	78.65	78.69
Flash Point (°c)	164.33	164.37	165.52	165.51	159.76	159.78
Cetane No	51.29	51.27	51.13	51.17	52.34	52.37
Viscosity (mm ² /s)	2.68	2.72	2.58	3.62	2.46	2.49
Specific Gravity	0.8625	0.8628	0.8716	0.8714	0.8567	0.8569
Moisture Content %	1.563	1.561	1.584	1.587	1.489	1.492
Ash Content %	0.047	0.049	0.063	0.065	0.036	0.034

3.13 Sem/Edx Analysis

The SEM/EDX analysis result shown in Table 2 provides valuable information about the elemental composition of the recovered oil from the mixture of tires and plastics (Sample A). The significant presence of Oxygen and Carbon suggests the organic nature of the materials, while the presence of Bromine indicates the potential influence of plastic additives. The conditions under which the analysis was performed contribute to accurate interpretation. Further studies could delve into the specific types of plastics, additives, and interactions that contribute to the observed composition in the recovered oil. As shown Table 2, Oxygen and Carbon elements are present in relatively high concentrations, which are expected given their prevalence in organic materials like rubber (tire component) and plastics. The presence of Gold is significant, with a relatively high weight concentration. It's worth noting that Gold is not typically found in tire or plastic materials, suggesting a potential influence from external factors. Sulfur is present in a notable concentration. Sulfur compounds are common in petroleum-based products and could be originating from both the tire and plastic components. Silicon

is present at a low concentration. It could originate from additives, contaminants, or interactions during the pyrolysis process. Oxygen and Carbon are the predominant elements in the sample C as shown in Table 2, with relatively high atomic concentrations of 65.44% and 21.25%, respectively. While Bromine and Rubidium are present in lower atomic concentrations of 8.48% and 4.83%, respectively, but they contribute to higher weight concentrations of 28.32% and 17.26%, respectively. In Table 2, the significant presence of Oxygen and Silicon is expected, as rubber (a major component of tires) contains these elements. Silicon may also originate from additives or materials used in tire manufacturing. Gold presence could be due to various factors, such as contamination, interactions with other materials during the pyrolysis process, or potentially the presence of trace amounts of gold-based materials. Bromine is likely associated with flame retardants used in tire production. Its presence could be relevant for assessing the environmental impact of tire disposal and recycling. Iron is common in many materials, and its presence could be attributed to various sources, including the tire structure and potential contamination.

Table 2: Sem/Edx Analysis

Samples	Tyre (300g) and plastics (200g) (A)		Tyre (400g) and plastics (100g) (B)		Tyre (500g) (C)		Tyre Chips (D)	
Parameters	Atomic Conc.	Weight Conc.	Atomic Conc.	Weight Conc.	Atomic Conc.	Weight Conc.	Atomic Conc.	Weight Conc.
Oxygen (O)	67.39	61.29	46.63	17.10	65.44	43.76	62.14	25.78
Carbon (C)	28.34	19.35	27.12	7.46	21.25	10.67	-	-
Bromine (Br)	4.26	19.36	-	-	8.48	28.32	6.90	14.30
Gold (Au)	-	-	14.88	67.14	-	-	7.73	39.45
Sulfur (S)	-	-	10.73	7.89	-	-	-	-
Silicon (Si)	-	-	0.64	0.41	-	-	18.29	13.32
Rubidium (Rb)	-	-	-	-	4.83	17.26	-	-
Iron (Fe)	-	-	-	-	-	-	4.93	7.15

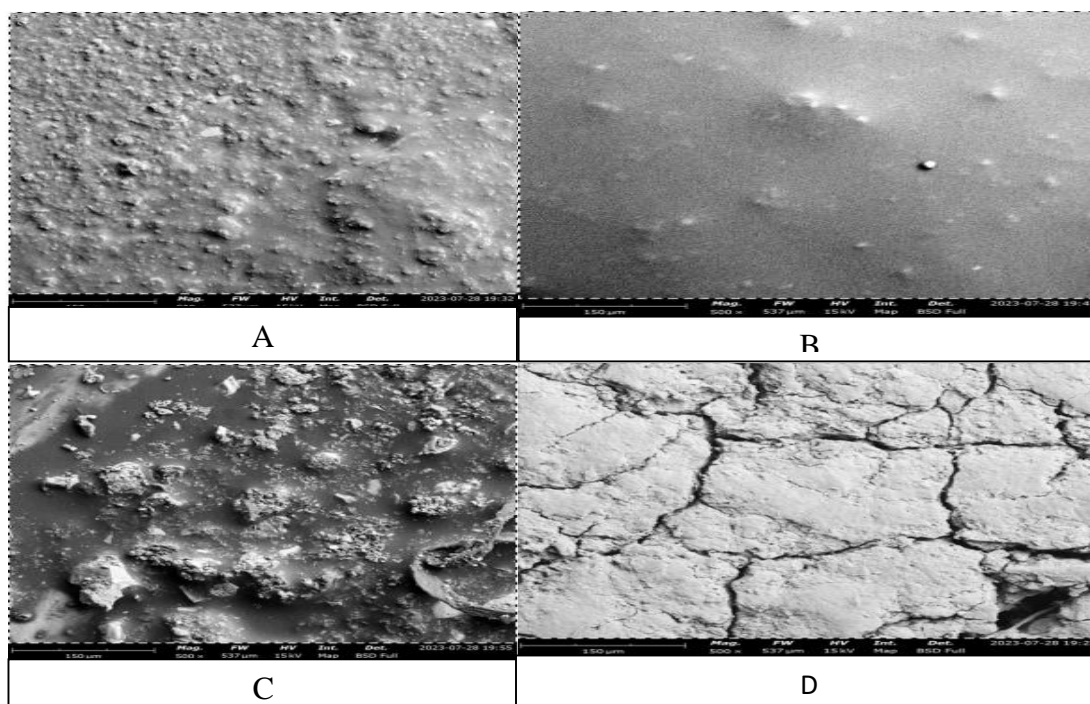


Figure 4: Sem/Edx of the sample

4.0 Conclusion

Based on the provided sample data, the recovery of oil from waste tires and plastics

through pyrolysis shows promising results. The pyrolysis oil obtained from both waste tires and plastics exhibits desirable properties for potential applications. The calorific values of the pyrolysis oil are relatively high, ranging from approximately 45.78 to 47.83 MJ/kg, indicating its potential as a valuable energy source. The oil also demonstrates good combustion characteristics, as evidenced by the ignition temperature and rate of combustion values. The high heating values of the pyrolysis oil range from approximately 43.4 to 45.5 MJ/kg, while the low heating values range from approximately 41.6 to 43.7 MJ/kg. These values indicate the energy content available for various applications, such as combustion or energy recovery processes. The pyrolysis oil exhibits favorable properties for use as a transportation fuel, as indicated by the cetane (n-hexadecane) number, which measures the ignition quality of diesel fuels. The values obtained for the cetane number range from approximately 51.13 to 52.37, suggesting good ignition characteristics. In terms of physical properties, the pyrolysis oil demonstrates suitable viscosity values, ranging from approximately 2.46 to 3.62 mm²/s, which indicate its flow characteristics. The specific gravity values range from approximately 0.8567 to 0.8716, which provides information about the oil's density compared to water. The moisture content and ash content of the pyrolysis oil are relatively low, indicating the effectiveness of the pyrolysis process in removing moisture and inorganic components from the feedstock. Low moisture content is desirable as it reduces the need for additional drying steps, while low ash content indicates lower potential for ash-related issues during combustion or further processing

References

- Abdallah, R., Juaidi, A., Assad, M., Salameh, T., & Manzano-Agugliaro, F. (2020). Energy recovery from waste tires using pyrolysis: Palestine as case of study. *Energies*, *13*(7), 1817.
- Arabiourrutia, M., Lopez, G., Artetxe, M., Alvarez, J., Bilbao, J., & Olazar, M. (2020). Waste tyre valorization by catalytic pyrolysis—A review. *Renewable and Sustainable Energy Reviews*, *129*, 109932.
- Čabalová, I., Ház, A., Krilek, J., Bubeníková, T., Melicherčík, J., & Kuvík, T. (2021). Recycling of wastes plastics and tires from automotive industry. *Polymers*, *13*(13), 2210.
- Carmo-Calado, L., Hermoso-Orzáez, M. J., Mota-Panizio, R., Guilherme-Garcia, B., & Brito, P. (2020). Co-combustion of waste tires and plastic-rubber wastes with biomass technical and environmental analysis. *Sustainability*, *12*(3), 1036.
- Czajczyńska, D., Czajka, K., Krzyżyńska, R., & Jouhara, H. (2020). Waste tyre pyrolysis—Impact of the process and its products on the environment. *Thermal Science and Engineering Progress*, *20*, 100690.
- Eze, W. U., Umunakwe, R., Obasi, H. C., Ugbaja, M. I., Uche, C. C., & Madufor, I. C. (2021). Plastics waste management: A review of pyrolysis technology. *Clean Technol. Recycl*, *1*(1), 50-69.
- Hu, Q., Tang, Z., Yao, D., Yang, H., Shao, J., & Chen, H. (2020). Thermal behavior, kinetics and gas evolution characteristics for the co-pyrolysis of real-world plastic and tyre wastes. *Journal of Cleaner Production*, *260*, 121102.

- Jahirul, M. I., Hossain, F. M., Rasul, M. G., & Chowdhury, A. A. (2021). A review on the thermochemical recycling of waste tyres to oil for automobile engine application. *Energies*, *14*(13), 3837.
- Januszewicz, K., Kazimierski, P., Kosakowski, W., & Lewandowski, W. M. (2020). Waste tyres pyrolysis for obtaining limonene. *Materials*, *13*(6), 1359.
- Li, D., Lei, S., Rajput, G., Zhong, L., Ma, W., & Chen, G. (2021). Study on the co-pyrolysis of waste tires and plastics. *Energy*, *226*, 120381.
- Mavukwana, A.-e., & Sempuga, C. (2022). Recent developments in waste tyre pyrolysis and gasification processes. *Chemical Engineering Communications*, *209*(4), 485-511.
- Oni, B. A., Sanni, S. E., & Olabode, O. S. (2021). Production of fuel-blends from waste tyre and plastic by catalytic and integrated pyrolysis for use in compression ignition (CI) engines. *Fuel*, *297*, 120801.
- Oyewo, A. T., Oluwole, O. O., Ajide, O. O., Omoniyi, T. E., & Hussain, M. (2023). A summary of current advancements in hybrid composites based on aluminium matrix in aerospace applications. *Hybrid Advances*, 100117.
- Palos, R., Gutierrez, A., Vela, F. J., Olazar, M., Arandes, J. M., & Bilbao, J. (2021). Waste refinery: the valorization of waste plastics and end-of-life tires in refinery units. A review. *Energy & Fuels*, *35*(5), 3529-3557.
- Pandey, U., Stormyr, J. A., Hassani, A., Jaiswal, R., Haugen, H. H., & Moldestad, B. M. E. (2020). Pyrolysis of plastic waste to environmentally friendly products. *Energy Production Manage in the 21st century IV: The Quest for Sustain Energy*, *246*, 61-74.
- Qureshi, M. S., Oasmaa, A., Pihkola, H., Deviatkin, I., Tenhunen, A., Mannila, J., Minkkinen, H., Pohjakallio, M., & Laine-Ylijoki, J. (2020). Pyrolysis of plastic waste: Opportunities and challenges. *Journal of Analytical and Applied Pyrolysis*, *152*, 104804.
- Sharma, A., Khatri, D., Goyal, R., Agrawal, A., Mishra, V., & Hansdah, D. (2021). Environmentally friendly fuel obtained from pyrolysis of waste tyres. *Energy Systems and Nanotechnology*, 185-204.

