Characterization of Pyrolytic Oil from Different Blending Ratio of HDPE and PET Plastic Waste Through Gasification Pyrolysis Process

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Abstract: *Pyrolysis is one of the best methods to convert plastic waste into pyrolytic oil. Plastic waste High Density Polyethylene (HDPE) and Polyethylene Terephthalate (PET) have been used as raw materials at different blending ratio for this study. The process is taken place by placing the samples at different blending ratio in the gasification pyrolysis reactor while reaction time is set constant at 90 minutes. As a results, highest yield of pyrolytic oil is obtained from HDPE with the yield of 68%. Calorific value and proximate analysis have been used to analyzed the pyrolytic oil obtained which are 43,430 J/g and 99.8% of volatile matters respectively. It is found that the quality of the pyrolytic oil from HDPE is almost near the commercial diesel. Therefore, pyrolytic oil from HDPE itself without blending is very suitable and can be used as an alternative fuel to substitute the commercial diesel.*

Keywords: Pyrolysis; blending ratio; Plastic waste

1. INTRODUCTION

Nowadays, the world is facing environmental threats due to the pollution produced from vehicles. The increasing human population has caused the use of vehicles to be very significant as transportation for people to move from one place to another. These vehicles require fuel from non-renewable energy that is fossil fuel. Currently, energy sources are produced from coal, natural gas and petroleum oil which are non-renewable fuels [1]. This fuel has a bad effect where it produces substances that pollute the environment and cause a greenhouse effect. The best action needs to be taken to ensure that dependence on non-renewable fuels can be overcome by using renewable energy or materials that can be reused. The main component for the economic growth of a country is the availability of sustainable energy. An important prerequisite in dealing with energy poverty, growing economic growth and increasing job opportunities is access to renewable energy [2]. Therefore, the use of biofuels as a renewable fuel is very coincidental in fulfilling the concept of Sustainable Development Goals (SDG), especially in SDG7 and SDG 13 in ensuring that the world is in a sustainable and safe state [3]. One of the actions that can be used to meet this SDGs is by using pyrolysis process to convert plastic waste into fuel which most of plastic waste can produce more than 80% fuel [4].

Plastic is one of the most important products in human daily life where it contributes to the development of the world and makes human life easier. Various uses of plastic such as in packaging, kitchen appliances, automotive and so on. There are various types of plastic commonly used in our daily lives such as high density polyethylene (HDPE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC) [1,4]. The use of plastic is increasing day by day due to one of the reasons is the increase in the world's population. However, the increase in the use of plastic has caused negative effects such as environmental pollution due to uncontrolled and systematic disposal of plastic [4]. The disposal of plastic in land and sea areas has had an impact mainly in terms of health not only for humans, but also for animals. From the data obtained, it was found that Canadians produce approximately 3.3 million tonnes of plastic waste per year. Of the total plastic waste, 2.8 tonnes or 86% of it ends up on the ground. The rest, which is about 4%, has been burned to produce energy, where it causes pollution problems, and about 1% of it has become garbage and pollutes the environment. Only 9% of it was recycled through mechanical and chemical recycling. [5,6,7]. In 2018 alone, approximately 6 percent or 20.1 million tonnes of plastic waste was exported out of North America [8] and of that amount, 11.2 million tonnes were exported to Malaysia [6]. Most of this plastic waste has been sent to several countries in Southeast Asia such as Vietnam and Indonesia where it is known that these countries have a relatively weak ability to process plastic waste due to facilities that are not complete and can pollute the environment [7,9]. Because of that, researchers have issued several studies in other words to solve this problem to ensure that the environment can be preserved, and the next generation will experience a healthy and sustainable environment.

Some people suggest that some plastics should be banned from use. In the short term, this step may be appropriate. However, it cannot solve the problem of plastic disposal for other sectors. Disposal of plastic waste by using a landfill is a common method used especially by local authorities. However, this method causes more chronic environmental problems with the production of leachate that pollutes the soil and underground water and produces a foul smell. Incineration, which is an energy source from burning plastic waste, can be used, but it will cause a greenhouse effect to the environment. Mechanical recycling is an alternative method that can be used to prevent disposal and reduce virgin materials. However, the separation of plastic according to the color of the resin compound is not efficient and increases the cost. Therefore, the use of chemical technology is the preferred option [4]. Chemical recycling is the process of converting plastic waste into smaller molecules by producing a new resin. However, not many companies are able to manage this process commercially. Chemical recycling of plastic waste is the process of converting plastic waste into shorter molecules, for use in the production of new plastics or fuels. However, currently companies operating these types of facilities generally manage small quantities of post-consumer plastics. While composting is a method that is being explored but very little of this plastic waste is managed where the industry considers compostable and biodegradable plastic as a nuisance to their business [5].

1.1 Properties of pyrolysis process

In 2019, the value of the world plastic to fuel market is US$972.8 million and is expected to increase by 8.2% from 2020 until 2027. The Asia Pacific region alone has dominated the world market which is 35.5% in 2019. The increasing population and urbanization the economy in the region is expected to cause oil consumption to increase every year. Therefore, through this pyrolysis process when compared to depolymerization and gasification, it will produce a global market of 65.3% because this technique will produce a more efficient process when compared to other processes [10]. In term of mass and energy, pyrolysis is more efficient compare to depolymerization and gasification where pyrolysis produces 68% and 87% for each mass and energy efficiency while depolymerization produces 62% and 76% for each mass and energy efficiency. While gasification is less efficient in terms of mass and energy when it only produces 23% and 31% of mass and energy respectively [13]. The pyrolysis process is the best step in producing chemicals, renewable energy, and biofuels even though it contains some side effects such as low biofuel conversion, coke formation and a significant temperature difference to increase the production of gas and chemicals at the same time [11].

Table 1. Pyrolytic oil yield produced from mixed or segregated plastic waste.

Types of plastic waste	Yield of Pyrolytic Oil (wt%)	References
PET and PS	91.8	[13]
PET	28.4	[14]
PE	67.7-76.1	[15]
LDPE	43.9	[16]
3% PVC, 4%PET, 18%PS, 35%PP, 40% PE	72.0	[17]
PS	91.8	[18]
PP	10.91	[20]
PS+10%/20%/30% PET	77.0	[21]
PP	21.7	[22]
50%PE, 50%PET	34.4	[24]

The yield of pyrolytic oil from the non-catalytic pyrolysis process has been shown in Table 1. From the table, PS produces the highest yield of oil which is 91.8% due to the structure of PS containing high phenyl groups. The phenyl group produces a stable benzylic radical and produces a low hydrocarbon chain [18]. The pyrolysis of PS typically leads to the formation of liquid products consisting of aromatic hydrocarbons. These products are more readily formed due to the aromatic structure's tendency to break down into smaller aromatic compounds and radicals, which then recombine to form oils and other volatile compounds [4]. From that table also, PP produces the least yield of pyrolytic oil which is only 10.91% at a temperature of 350℃ [20].

The use of reactors in the pyrolysis process is very important in ensuring that the pyrolysis process can produce the desired product. Table 2 shown the type of reactor and heating medium in pyrolysis process. It was found that most researchers use batch reactors in their pyrolysis process [12,14,20,21,22,23,26]. Some also use semi batch reactor [15,17,18], fluidized bed reactor [16], tubular reactor [24] and packed bed reactor [25]. The use of batch reactors by most researchers may be due to the pyrolysis process being easy to implement in batch reactors where the parameters are easy to change [27]. However, there are researchers who state that the production of products from batch reactors is inefficient and inconsistent because it is necessary to add raw materials frequently and involves high labor costs. Therefore, some suggest fixed bed reactor is the best alternative compared to other reactors due to its simple design and more economical when compared to the operation and maintenance cost of other reactors [28]. The type of heater is also very important in ensuring that the pyrolysis process can be heated according to the desired heating speed. Most researchers use furnaces as their heating medium [12,15,17,22,26]. Some use other heating mediums such as electrical heaters [18,21,23,24,25], stoves [14], fluidizing gas [16] and infrared heaters [20].

Table 2: Type of reactor and heating medium in pyrolysis

Types of plastic waste	Type of reactor	Type of heating medium	Operated Temp (℃)	Ref
PS, PP and PE	Batch	Furnace	560	[12]
PET	Batch	Stoves	412	[14]
Waste Packaging	Semi batch	Furnace	900	[15]
LDPE	Fluidized bed	Fluidizing gas	450	[16]
PE+PP+ PS+PET+PVC	Semi batch	Furnace	600	[17]
HDPE+PP+ PET+PS+LDPE	Semi batch rotary kiln	Electrical	500	[18]
PP	Batch	Infrared heaters	250, 300, 350	[20]
PS. PET	Batch	Electrical	350, 400, 450	[21]
PE	Batch	Furnace	200, 250, 300, 350	[22]

Types of plastic waste	Type of reactor	Type of heating medium	Operated Temp (°C)	Ref
Dump plastic	Batch	Electrical	500, 550, 600	[23]
PET	Tubular	Electrical	600 - 900	[24]
LDPE	Packed Bed	Electrical	300	[25]
PP, LDPE, HDPE and PP+LDPE+ HDPE	Batch	Furnace	400-550	[26]

Table 3 summarized properties of pyrolysis product. It has been observed that high gross calorific value produced low flash point and viscosity of the product. This is due to high amount of volatile material in the product. The best density is in the range of 700-900 g/m^3. Research done by Yohandri et. al. 2020 obtained product that has ideal properties such as heating value of 44.46MJ/kg, density of 774g/m^3, and low flash point of 31.0°C [20]. Meanwhile, B. Sugiartor et. al. 2020 [14] obtained 46.23MJ/kg gross calorific value for municipal plastic waste and it is comparable with commercial fuel gasoline and diesel which were 45.7MJ/kg and 47MJ/kg respectively. Thus, liquid oil produced from plastic waste can be used as an alternative fuel for commercial fuel such as gasoline and diesel.

Table 3: Properties of product of pyrolytic oil

Types of plastic waste	Density (kg/m^3)	Flash Point (°C)	Gross Calorific value (MJ/kg)	Ref.
PS and PET	700-770	11.6	-	[13]
PET	-	10.0	46.23	[14]
PP	800	-	45.56	[19]
PP	774	31.0	44.46	[20]
PP	800	-	5.47	[22]
Dump plastic	-	69.0 (non-catalyst), 65.0 (catalyst)	-	[23]
PP, LDPE, HDPE and PP+LDPE+ HDPE	-	-22.0	44.37	[26]
Commercial Fuel (Gasoline)	750	-	45.7	
Commercial Fuel (Diesel)	830	50	47	

This study will use HDPE plastic waste and PET plastic waste because these two plastic wastes are the most popular used. A total of 67% of plastic waste of this type used the mechanical recycling method in Canada in 2016 [5]. An estimated 60 million tons of HDPE plastic waste is thrown away every year and only one third of it is reused or recycled. This has a negative impact not only on the environment but also on the production of petroleum raw materials to produce more of this type of plastic [29]. According to Recycling International, PET production is close to 20 million tons for the year 2021 alone [30]. Therefore, if these two types of plastic waste can be used in the production of petroleum products again, the disposal of this plastic waste in large quantities every year can be overcome.

A batch reactor will be used in this study where a total of 5 samples will be used in this study, namely HDPE, PET, a mixture of HDPE and PET in a ratio of 2 to 1, 1 to 1 and 1 to 2. The product produced consists of liquid, char and gas. There is a study found that HDPE produces more than 60% liquid after the pyrolysis process [31]. While for PET, there is a study stating that it does not produce liquid, however it produces 50% gas after the pyrolysis process is carried out [32]. However, the result of the mixture according to the ratio between HDPE and PET has not yet been done by any researcher. Therefore, the expectation that may be produced from this study for the mixing between HDPE and PET where the ratio that has a lot of HDPE will produce more liquid when compared to the ratio that has a small ratio of HDPE.

2. MATERIALS AND METHODS

2.1 HDPE and PET samples

The plastic waste which is the raw material for this study are Polyethylene Terephthalate (PET) and High-Density Polyethylene (HDPE) where it is obtained from the trash cans found in the hostel and staff quarters of Institut Kemahiran MARA Bintulu, Sarawak, Malaysia**.**

2.2 Sample Preparation for Characterization and Thermal Analysis

Figure 1 shows the procedure used to prepare the raw materials obtained for analysis in the laboratory. The raw material was dried for one day to remove the moisture. Then the raw material has been cut into small particle using a knife and scissors. The sample will be stored in a container where it will be used for analysis in the laboratory analyses such as different substances, proximate and calorimetric**.** To obtain raw materials to carry out analysis such as Proximate Analysis, Elemental Analysis and so on, the plastic waste that has been obtained has been cut into small pieces until it becomes a powder.

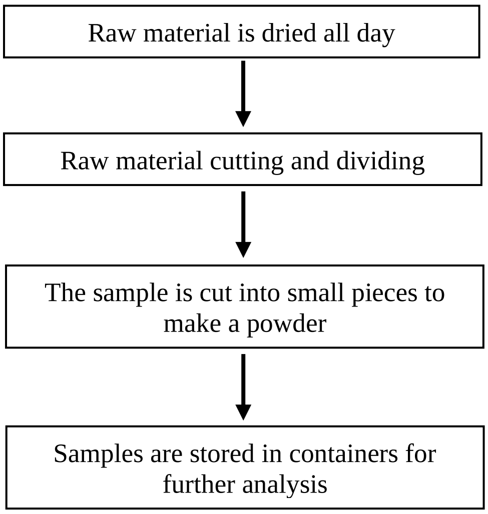

Fig. 1. Flow diagram of procedure used to prepare raw material for analysis.

2.3 Sample Analysis of raw material

2.3.1 Calorific value

Calorimetric analysis is the determination of the gross heating value of a fuel. It measures the heat created by a sample when it is burned under oxidative atmosphere in a closed reactor that is surrounded by water and in controlled conditions. In this study, the calorific value analysis was performed using Bomb Calorimeter model PARR 6400 for a sample before the pyrolysis process. While after pyrolysis, the calorific value analysis was performed using Bomb Calorimeter model IKA C2000 BASIC

2.3.2 Proximate Analysis

Proximate Analysis of plastic waste is a simple way to determine the quantity of substances found in a material. To ensure the quality of the material, several tests such as the determination of moisture content, volatile matter, ash content and fixed carbon need to be done where in this study, the ASTM E870-82 standard has been used [33,34].

Moisture Content (MC) is one of the important properties that exist in plastic waste samples. Moisture content is the number of water molecules found in the plastic waste sample. To obtain the value, 1.5g sample of the plastic waste for each ratio was weighed using a Mettler Toledo Analytical Balance as shown in Figure 2.3.1. The sample was weighed into five types of measurement, namely HDPE, ratio HDPE 2: 1 PET, ratio HDPE 1:1 PET, ratio HDPE 1:2 PET and PET as shown in Figure 2.3.2a and Figure 2.3.2b. The sample is put into a crucible and weighed. Then the sample with the crucible will be put into the Memmert Wisconsin Oven as in Figure 2.4 at a temperature of 110℃ for 16hrs. After that, the crucible containing the sample will be put into a desiccator for about 30 minutes. Then, the crucible will be weighed again and its weight recorded. Moisture Content % is calculated using the formula (1). The same procedure is also done for other samples.

$$\%\ \text{Moisture Content} = \frac{m_1 - m_2}{m_1 - m_0} \times 100 \qquad (1)$$

Where:
m_0 = Empty crucibles weight
m_1 = Crucibles weight with sample
m_2 = Crucible weight with sample after heating (weight of moisture)

Volatile matter (VM) is a substance that will continue to burn when oxygen is present in it. The determination of volatile matter is very important in showing that a substance is flammable. Common substances found in Volatile matter are hydrocarbons, hydrogen, CO, CO_2, CH_4, H_2O and SO_2. It can also prove that if the content is high, the material is easy to process and will produce more liquid [35]. Therefore, to obtain the value of volatile matter, the sample obtained in determining the moisture content was used again in this experiment. The closed crucibles containing the samples were put into the Muffle Furnace Fisher Scientific Model 550-126 as shown in Figure 2.5 and will be heated at a temperature of 900℃ for 10 minutes. Then the crucibles will be put in a desiccator for about 30 minutes. Volatile Matter % is calculated using the formula (2). The same procedure is also done for other samples.

$$\%\ \text{Volatile Content} = \frac{m_2 - m_3}{m_1 - m_0} \times 100 \qquad (2)$$

Where:
m_0 = Empty crucibles weight
m_1 = Crucibles weight with sample
m_2 = Crucible weight with sample after heating (weight of moisture)
m_3 = Crucible weight with sample after heating (weight of volatile matter)

Ash Content (AC) indicates the non-combustible material remaining after the sample has burned completely. If a material produces a high %ash content, it will produce a high char after the pyrolysis process. To obtain the value of ash content, the sample obtained in determining the volatile matter was used again in this experiment. The uncovered crucibles containing the samples were put into the Muffle Furnace Fisher Scientific Model 550-126 and heated at a temperature of 585℃ for 3 hours. Then the crucibles will be put in a desiccator for about 30 minutes. Volatile Matter % is calculated using formula (3). The same procedure is also done for other samples.

$$\%\ \text{Ash Content} = \frac{m_4 - m_0}{m_1 - m_0} \times 100 \qquad (3)$$

Where:
m_0 = Empty crucibles weight
m_1 = Crucibles weight with sample
m_4 = Crucible weight with sample after heating (weight of ash)

Fixed carbon (FC) is the last solid residue left after combustion which is a flammable material after the material is heated and removes the volatile matter of the material. Once MC, VM and AC have been obtained, the FC value can be obtained by using equation (4). All values obtained are in percentage.

$$\%\text{Fixed Carbon} = 100 - (MC + VM + AC) \qquad (4)$$

2.4 Pyrolysis via Pyrolysis Mini Plant

The equipment as per Figure 2 has been used. In this experiment, the study was taken to determine the time required for a change to occur in the yield tank. At the same time, the temperature will be taken when the change occurs. The parameters tested are as in the table below. There are 3 tanks that will be used in this experiment, namely Pyrolysis Reactor, Condenser and Gas Collecting Tank.

Experiment is arranged as follow; 600 g as per propose parameter in Table 4 was used in the experiment and fed into the Pyrolysis Reactor (3), tightly closed, and purged with nitrogen gas (1) at the start of each experiment for 10 min. The water contained in the Compressor (5) will be placed at a temperature of 20 ℃. Gas Collector Tank (6) will be ensured to bubble to indicate that the system is not clogged. After 10 minutes have elapsed, the nitrogen gas will be shut off while the flame from the stove (4) which is sourced from the LPG cylinder (2) will be ignited with an opening of ¼. The temperature on the

Pyrolysis Reactor will be taken every 5 minutes and the temperature on the compressor will be kept at 20°C. The experiment will run for up to one hour and 30 minutes or until the resulting liquid has been fully produced. This experiment was carried out 2 more times to get an average reading of 3 readings.

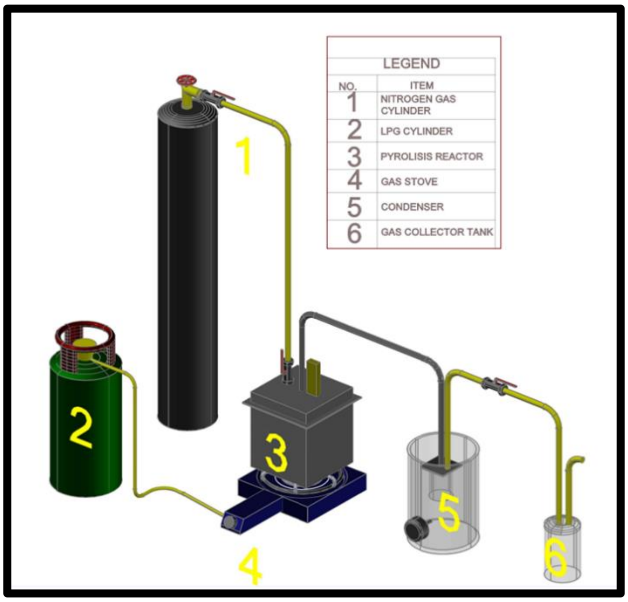

Fig. 2. Pyrolysis Mini Plant.

Table 4: Propose Parameter for Plastic Pyrolysis

Ratio Raw Material	Weight of Raw Material		
	HDPE	PET	Total
HDPE	600g	-	600g
PET	-	600g	600g
1PET:2HDPE	200g	400g	600g
1PET:1HDPE	300g	300g	600g
2PET:1HDPE	400g	200g	600g

3. RESULTS AND DISCUSSION

3.1 Calorific value

Table 5 shows the calorific value of HDPE, PET and the mixture according to the ratio of HDPE to PET which is the ratio of 2:1, 1:1 and 1:2 taken before and after the pyrolysis process. It was found that the calorific value for HDPE is the highest and is close to the calorific value for petrol and diesel which is 43,400 - 46,500J/g for petrol and 42,800 - 45,800J/g for diesel [28]. The calorific value for PET is low due to the presence of oxygen in the hydrocarbon chain. However, after going through the pyrolysis process, the calorific value for all samples increased a lot. The most significant is the calorific value for PET which increased to nearly 44%. HDPE and the mixture according to the 1:1 ratio seem suitable to be used as fuel due to its calorific value close to the calorific value of commercial petrol and diesel. Therefore, the pyrolysis process is very suitable for increasing the calorific value of a material, especially plastic waste.

Table 5: Calorific value of sample before and after the pyrolysis

Ratio Raw Material	Before Pyrolysis (J/g)	After Pyrolysis (J/g)
HDPE	41,868	43,430
HDPE2:1PET	36,006	39,574
HDPE1:1PET	32,238	43,212
HDPE1:2PET	28,888	36,966
PET	22,190	31,938

3.2 Proximate Analysis

Table 6 summarized of proximate analysis result for HDPE, PET and mixing ratio of HDPE2:1PET, HDPE1:1PET and HDPE1:2PET. Found volatile matters for HDPE is higher when compared to plastic mixing ratio and PET. High volatile matters indicate that the material tends to produce a higher liquid after the pyrolysis process [36,37]. Therefore, HDPE will produce more liquid when compared to other ratios. As for ash, it was found that PET produces the highest ash compared to other ratios. A high ash value indicates that the material tends to produce high char [37]. Therefore, PET will produce a high char when compared to other ratios.

Table 6: The proximate analysis result of HDPE, PET and mixing ratio.

Ratio Raw Material	Moisture Content %	Volatile Matters %	Ash %	Fixed Carbon %
HDPE	0.07	99.80	0.13	0.00
HDPE2:1PET	0.13	98.40	1.47	0.00
HDPE1:1PET	0.13	97.60	2.27	0.00
HDPE1:2PET	0.27	97.20	2.53	0.00
PET	0.27	96.40	3.33	0.00

3.3 The pyrolysis process follows the change in temperature

Figures 3, 4, 5, 6 and 7 show the temperature development over time respectively for HDPE, ratio HDPE2:1PET, ratio HDPE1:1PET, HDPE1:2PET and PET plastic waste. Within one hour and 30 minutes, the highest temperature reached to reach a constant value is at a temperature of 320°C, which involves HDPE. While the lowest temperature reached to reach a constant value is at a temperature of 235°C, which involves a ratio of HDPE 1:1PET. Within 25 minutes, each raw material will produce its first liquid product at a temperature between 130°C to 165°C except HDPE1:2PET ratio and PET which did not produce liquid throughout the experiment. This shows that the pyrolysis process takes place at a relatively low temperature which is below 400°C within one hour and 30 minutes.

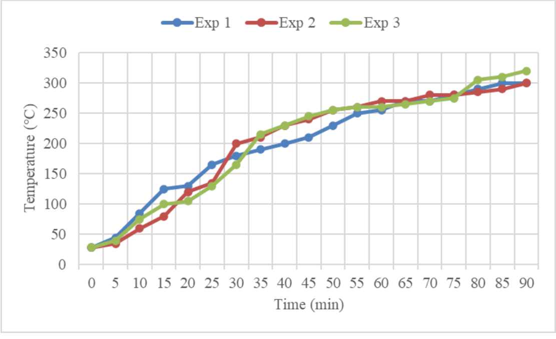

Fig. 3. Temperature development over time for HDPE

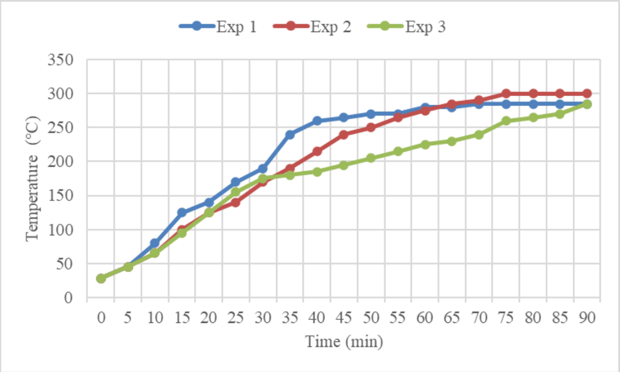

Fig. 4. Temperature development over time for ratio HDPE 2: 1 PET

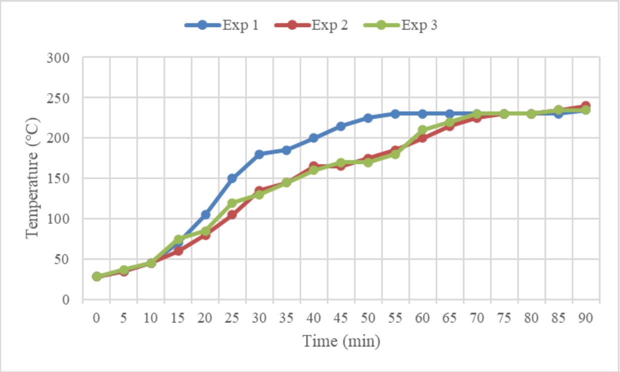

Fig. 5. Temperature development over time for ratio HDPE 1:1: PET

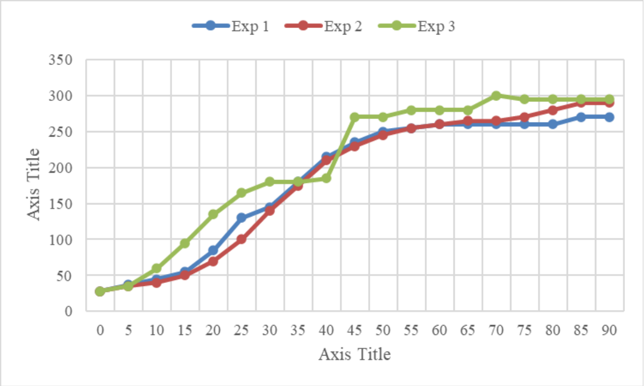

Fig. 6. Temperature development over time for ratio HDPE 1:2 PET

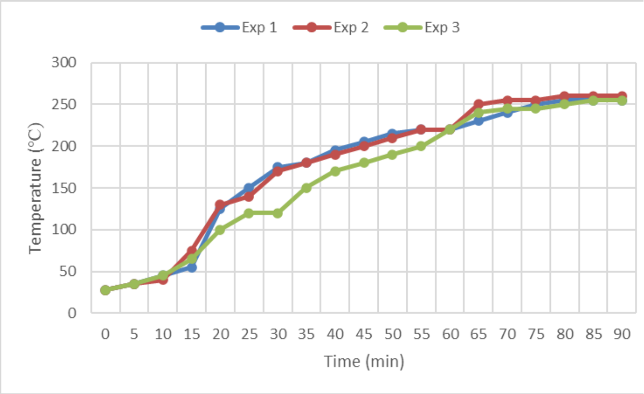

Fig. 7. Temperature development over time for PET

3.4 Percentage Yield

Table 7 shows the percentage yield that results after the pyrolysis process for each raw material. The raw material that produces the highest product oil is HDPE, which on average produces as much as 68%. While PET and HDPE ratio 1:2PET do not produce liquid. The raw material that produces the highest gas content is HDPE1:2PET with an average of 73.11% while the raw material that produces the lowest gas content is HDPE with an average of 5.85%. The highest char production was recorded in the raw material HDPE2:1PET with 41.67% on average while HDPE does not produce char after pyrolysis but produces tar.

Table 7. Percentage Yield of Product after pyrolysis

Ratio raw material	Exp	Product Yield (%)			
		Tar	Char	Oil	Gas
HDPE	1	24.33	-	70.00	5.67
	2	27.83	-	66.67	5.55
	3	26.33	-	67.33	6.33
HDPE2:1PET	1	-	39.17	28.33	32.50
	2	-	42.00	26.67	31.33
	3	-	43.83	25.00	31.17
HDPE1:1PET	1	-	37.83	2.50	59.67
	2	-	36.33	3.33	60.33
	3	-	40.00	5.00	55.00
HDPE1:2PET	1	-	19.00	-	81.00
	2	-	29.00	-	71.00
	3	-	32.67	-	67.33
PET	1	-	34.33	-	65.67
	2	-	34.00	-	66.00
	3	-	42.67	-	57.33

4. CONCLUSION

This study examined the potential of pyrolysis as a method for converting plastic waste, specifically HDPE and PET, into usable fuel. Calorific value analysis revealed that the pyrolysis process significantly increased the energy content of all samples, with HDPE and a 1:1 HDPE:PET mixture producing oils with calorific values comparable to commercial petrol and diesel. This suggests pyrolysis can effectively upgrade the energy potential of plastic waste.

Proximate analysis indicated that HDPE had the highest volatile matter content, predicting its tendency to produce more liquid yield during pyrolysis. Conversely, PET showed the highest ash content, suggesting it would produce more char. These findings align with the actual pyrolysis yields observed.

Temperature profiles during pyrolysis showed that the process occurred at relatively low temperatures (below 400°C) within 90 minutes, with initial liquid production starting around 130-165°C for most samples. This indicates the energy efficiency of the process.

Yield analysis confirmed HDPE as the most promising feedstock, producing up to 70% liquid oil. The blending of HDPE with PET reduced liquid yield but increased gas production, demonstrating how feedstock composition can be manipulated to target desired product ratios.

The study highlighted the variability in product distribution based on plastic type and blending ratios, underscoring the importance of feedstock selection and mixing strategies in pyrolysis operations.

These qualitative findings suggest that pyrolysis, particularly of HDPE-rich plastic waste streams, shows promise as a method for producing alternative fuels from plastic waste. The process offers a pathway to not only manage plastic waste but also recover valuable energy resources, contributing to both waste reduction and renewable energy goals. However, further research into optimizing process conditions and scaling up operations would be beneficial to fully realize the potential of this technology.

5. ACKNOWLEDGEMENT

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