

# Development and Performance Evaluation of a Fixed Batch-type Pyrolysis Reactor for Bio-oil Production from Plastic Wastes

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## ABSTRACT

A fixed bed batch-type bioreactor for pyrolyzing used or discarded plastic wastes was developed and its performance was evaluated. This research explored the option of converting the high-density polyethylene (HDPE) category of plastic wastes into useful bio-oil in the developed pyrolysis fixed-bed batch reactor. The developed 5 kg batch-type pyrolysis system powered by liquefied petroleum gas (LPG) was designed and simulated with SolidWorks computer software to confirm its functionality, fabricated with locally sourced materials, and evaluated with HDPE plastic wastes sorted from dumpsites within the Akure metropolis. The developed reactor evaluation result justified that the pyrolysis reactor has the potential to produce 1.4575 kg of bio-oil per kilogram of liquefied petroleum gas (LPG) consumed. The pyrolytic oil obtained at pyrolysis temperature between 280°C -520°C in this work was thereafter assayed for its composition and fuel properties analyses. The results of the characterization indicated that the pyrolysis of plastic HDPE wastes is a good source of alternative fuel as it shows proximity to the physiochemical characteristics of conventional diesel.

Keywords: Batch-type Pyrolysis System, HDPE Plastic Wastes, Bio-oil, Fuel Properties Analyses.



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## 1 Introduction

Plastic waste generation has continued to increase in Nigeria over the last decade due to the growing population, rapid urbanization, and the increasing demand for sophisticatedly packaged fast-moving consumer goods (FMCG). Plastic has the advantages of easily forming, low cost, non-corrosive, durability, and lightweight, which had made embraced by most industries, including pharmaceutical and cosmetic industries, for packaging their products, which eventually leads to more plastic waste generation[1].

Plastic wastes have outgrown other most man-made materials, as they constitute about 12 % of the total municipal solid waste (MSW) all over the world [2]. Some of these plastic wastes find their way into water bodies through canals causing water pollution, aiding the breeding of mosquitoes, and channel blockage, which eventually leads to flooding.

As pointed out in the study of [3] some of the methods currently in use to control the menaces of plastic waste in the environment are recycling, landfilling, and incineration. The author reported that the landfilling method is not a sustainable option because it requires a large area and it can cause carbon sink which could lead to the leakage of a potential hazard to soil and water bodies, thereby endangering aquatic lives. The use of incinerator generates carbon monoxide, syngas, and other pollutants in the environment, which can affect human and contributes to the greenhouse effects. Reports from the open literature [4], [5], [6], [7], [8] have also pointed out that the oil crisis and environmental concern on the release of greenhouse gas (GHG) emissions from fossil fuel burning coupled with the fact that the magnitude of plastics production also brings with it, a global concern in related problems, including environmental pollution, unsustainable production, and poor recycling mechanisms as pointed out by Zhou *et al.* [9]. Hence there is a need to convert plastic waste into fuel which will reduce our

dependency on fossil fuels and also reduce the hazards caused due to plastic waste. As we know that both Plastics and Petroleum derived fuels are Hydrocarbons that contain the elements of Carbon and Hydrogen. The pyrolysis process becomes an option of waste-to-energy technology to deliver biofuel to replace fossil fuels. According to Sharuddin [10], pyrolysis of plastic wastes has emerged as a promising chemical recycling method; it is capable of decomposing the plastic polymers into lower-molecular-weight products such as fuels and petrochemical feedstocks, to be used for energy or material recovery. More so, controlling the menaces of plastic waste in the environment by applying the Pyrolysis process is advantageous since it will give room for pre-treatment of the waste material in the area of handling unsorted and dirty plastic. The pyrolysis process is also of no toxic emission to the environment, unlike other commonly used disposal methods of waste plastics such as ocean dumping, sanitary landfill incineration, open dumping, and recycling. This method has been widely used to convert several MSW into useful oil by various researchers.

Mogaji *et al.* [7] worked on the production of bio-oil from the pyrolysis of sugarcane bagasse waste using a 3 kg capacity fixed-bed reactor with a maximum temperature of 500 °C. The chemical properties of the liquid produced (bio-oil) were analyzed and compared with the literature values of bio-oil obtained from other wastes. According to the research, the heating value of the bio-oil obtained from the pyrolysis of sugarcane bagasse is 17.33MJ/kg with a negligible amount of nitrogen (0.88 %) and sulfur (0.01 %). The report concluded that bio-oil produced from the pyrolysis of sugarcane waste has a negligible effect on the environment and it is suitable for running such equipment as boilers, reactors, etc. even without any further treatment. Wen *et al* [11] investigated the pyrolysis of corn Stover for bio-oil production using a fluidized bed reactor at a

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temperature between 450 - 525 °C and the produced bio-oil was analyzed to determine its chemical properties (pH, kinetic viscosity, and calorific values) which were put at 3.99, 5.9 and 8.25 MJ/kg respectively. Gaurav *et al.* [12] researched the conversion of Low-density polyethylene (LDPE) plastic waste into bio-fuel by thermal degradation in a batch reactor and the output was fractionated in a distillation furnace. They submitted that LDPE yields 90 % bio-fuel, 6 wt% gases, and 4 wt% ash when subjected to pyrolysis. The high bio-oil yield of 87.97 wt%, 5.81 wt% gases, 6.22 wt% ash content was also established by Olufemi and Olagboye [13] while 89.5 wt% bio-oil, 10 wt% gases 0.5wt% ash by Sharuddin *et al.* [14]. One can conveniently say that LDPE has high vitality matter and good potential for an alternative source of biofuel. Onwudili *et al.* [15] investigated the pyrolysis of polystyrene (PS) in a batch pressurized autoclave reactor at 300–500°C temperature range; the oil yield was 97.0wt%, 2.5wt% gas at an optimum temperature of 425°C. The authors based on their findings concluded that PS can also be used in the production of biofuel.

However, many researches and findings have been made on some of the biodegradable and non-biodegradable waste as alternative sources of bio-fuel using pyrolysis process with no toxic emission to the environment, unlike other commonly used disposal methods of waste plastics such as ocean dumping, sanitary landfill incineration, open dumping, and recycling. Therefore, in order to gain more insight into one of the promising means of converting waste-to-energy technology to deliver bio-fuel to replace fossil fuel consider pyrolysis of HDPE plastic wastes. Research on the development of a 5.0 Kg batch-type bioreactor for pyrolyzing used or discarded plastic waste HDPE type was conducted and its performance was evaluated in this work.

## 2 Materials and Method

The materials entailed those used for developing the system, called fabrication materials, and for evaluating its performance, called feedstock, alongside the attached instrumentations. The fabrication materials whose properties and parameters, used equations and engineering standards as detailed in Table 1 were obtained from Alaaba and Owode-Onirin Markets in Lagos State and King Market in Akure. The feedstock, HDPE, was obtained from dumpsites within Akure Metropolis.

### 2.1 Design Analysis

The following design criteria were taken into consideration in this study:

- i. Thermal decomposition of plastics operation takes about 3hrs between 500-550°C [8], Hence 550°C ( $T_1$ ) is chosen as design temperature
- ii. ambient temperature in Akure is 32°C ( $T_2$ ).
- iii. The height of the reactor is 400 mm
- iv. The operating pressure (p) within the reactor is 150000 N/m<sup>2</sup>,
- v. The factor of safety ( $F_s$ ) is 4;
- vi. The density of HDPE ( $\rho$ ) is 959kg/m<sup>3</sup> [9],
- vii. The efficiency of the welded joints ( $\eta$ ) is 70 %
- viii. The thermal conductivity of Ceramic wool insulator ( $k_{\text{ceramic wool}}$ ) is 0.025W/m<sup>2</sup>K;
- ix. The thermal conductivity of mild steel ( $k_{\text{ms}}$ ) is 43W/m<sup>2</sup>K;
- x. The maximum operating temperature of the reactor ( $T_{\text{max}}$ ).is 800°C

### 2.1.1 Reactor Shape Selection and Size Determination

The shape of the reactor was made cylindrical for design simplicity and ease of fabrication. The reactor, a batch-type, has a top cover for recharging feedstock and offloading residue respectively as it was designed to remain closed during operation. The volume of plastic waste to be charged into it per batch was determined using Eq. (1):

$$\rho = \frac{m}{V} \quad (1)$$

and the size of the reactor that could contain the estimated volume was obtained using Eq. (2):

$$V = h\pi r^2 \quad (2)$$

While considering the void factor to compensate for the void between a piece of feedstock, the actual radius ( $r_d$ ) of the cylindrical reactor was determined using Eq. (3):

$$r_d = 4xr \quad (3)$$

The thickness of the reactor wall was determined by Eq. (4) as given by [16].

$$t = F_s \frac{p \times D}{2 \sigma \eta} \quad (4)$$

where  $\rho$  is the density of HDPE (with the value of 959 kg/m<sup>3</sup>, r, and h are the radius and h height of the cylinder, p is pressure in the reactor (150000N/m<sup>2</sup>). By substituting these values in Eq. (4), the dimensions of the reactor and its thickness are obtained as 504 mm $\emptyset$  and 4 mm respectively.

The flange (diameters d and  $D_o$ , thickness,  $t_f$ , width, B) of the reactor and bolt size (d), including the quantity required (n), were determined using Eq. (5) – (10) as follows:

$$d = 0.75t + 10mm \quad (5)$$

$$n = 0.0275D + 1.6 \quad (6)$$

$$t_f = 1.5t + 3mm \quad (7)$$

$$B = 2.3d \quad (8)$$

$$D_o = D + 2t + 2B \quad (9)$$

$$D_p = D + 2t + 2d + 12 \quad (10)$$

When values are substituted, the diameters (d,  $D_o$ ) are 504 mm and 572 mm, with a width (B) of 30 mm to be fastened 16 pieces of M13 X40 bolts to the top of the reactor at pitch circle diameter ( $D_p$ ) of 550 mm.

### 2.1.2 System Energy Requirement and Properties of Heating Element

The total energy ( $Q_T$ ) and the total power ( $Q_P$ ) required in the system, which connotes the heat energy needed to heat the feedstock through the various phases of depolymerization till complete pyrolysis, can be obtained using Eq. (11) and Eq. (12) as described by [17], [18].

$$Q_T = mc_p(T_m - T_2) + ml_f + mc_p(T_3 - T_2) + mh_p \quad (11)$$

and

$$Q_P = Q_T + (Q_T \times \eta) \quad (12)$$

The length of the wire (L), number of coils ( $N_c$ ) required for each coil of the heating element and their resistance per meter (A) was determined using Eq. (13) – (15), as described by [19].

$$x = \frac{l \times d \times 1000}{\pi \times (D + d)} \quad (13)$$

$$N_c = \frac{\pi \times D_R}{6.1} \times L \quad (14)$$

$$A = \frac{R}{N_c} \quad (15)$$

where:  $D_R$  is the reactor pot diameter, R is the resistance; when values were substituted, the electrical power required for a period of 3.0 hrs is 2.015 kW, and for NiCr 80:20 heating element at 20°C (R) whose temperature resistant factor (F) at 1000 °C is 1.062, the length and resistance per meter and of the heating element are 1.5 m and 0.45Ω/m respectively.

### 2.1.3 Determination of the System Insulation Thickness

Due to the high heat evolved in the reactor with the temperature of 800°C, Ceramic wool was selected ( $T_{max}$ ), the thickness of the insulator ( $t_{ins}$ ) required resistance were determined using Eq. (16)-(17), according to [20].

$$Q = \frac{2 \pi h \{\Delta T\}}{\frac{\ln\left(\frac{r_2}{r_1}\right)}{K_{ms}} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{k_{ceramic}}} \quad (16)$$

$$t_{ins} = F.S (r_3 - r_2) \quad (17)$$

Where:  $r_1$  and  $r_2$  are the pot's internal and external pot radii,  $r_3$  is the external radius of the insulator,

### 2.1.4 Design of Condenser

The plastic vaporization production rate ((PVPR) was determined using Eq. (18);

$$PVPR = \frac{\text{Heat transfer rate}}{\text{latent heat of vapourization}} \quad (18)$$

Based on the principle of energy balance that the heat lost by the plastic vapor oil is equal to the heat gained by the cooling water, and heat dissipated to the condenser to cause phase changing of the vapour (condensate), the production rate of the oil, cooling water demand and geometric properties of the heat exchanger (number of tubes  $N_t$ ) with its overall heat transfer coefficient ( $U_E$ ) were determined using Eq. (19)- (20), according to [21];

$$Q_T = \dot{m}_{oil} c_p \Delta T = \dot{m}_w c_w \Delta = U A \Delta T_m \quad (19)$$

$$N_t = \frac{A}{\pi D_i L} \quad (20)$$

where:  $c_p$  and  $c_w$  are the specific heat capacity of the oil and cooling water,  $\Delta T$  is the logarithm temperature difference (LMTD), A is the heat transfer surface area of the condenser. When values are substituted, the mass flow of water required ( $\dot{m}_w$ ) is 0.066 kg/s (237.6 kg/h), the mass of oil ( $\dot{m}_{oil}$ ) produced is 0.0071kg/s (25.56 kg/h), whilst the computed A and  $N_t$  of the condenser are: 0.394m<sup>2</sup> and 9.57 nos, but 10 nos were adopted.

## 2.2 Validation of the Estimated Design Data Utilized for Developing the Reactor and Condenser

In order to achieve the designed and desired reactor temperature, the heat energy within the system must be preserved; hence, the reactor composite wall was subjected to simulation with SolidWorks computer software. The inner, and outer layers and the insulator that made up the proposed reactor unit wall were assigned, carbon steel, and ceramic wool, Afterward, the designed thermal loads were applied. Fig. 1 presents the results of the thermal analysis. The simulated results revealed that a maximum temperature between 524 and 568°C could be attained; more so, it also indicated that a section of the wall towards the outer surface still maintains the originally assigned temperature of 32°C while a section of the wall from the inner surface maintains the maximum temperature of 568°C. Thus, the findings of the simulation depicted that the reactor is suitable enough to pyrolyze plastic waste at the required burning temperature as the design parameters (temperatures) considered for the reactor lie within the range.

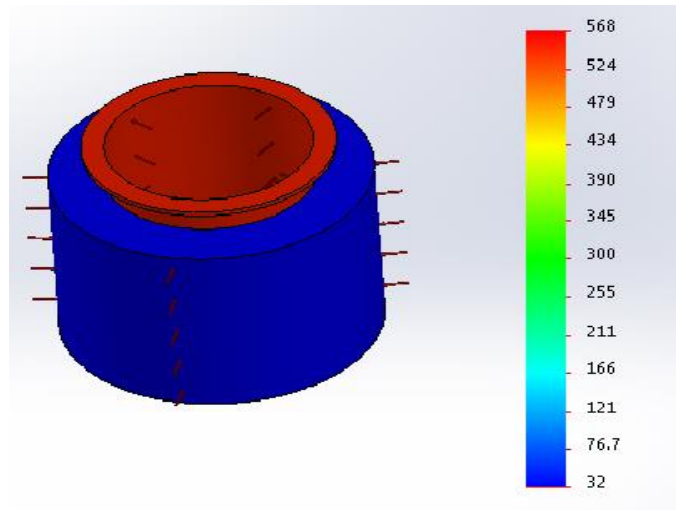


Fig. 1 Simulation Report of the Reactor

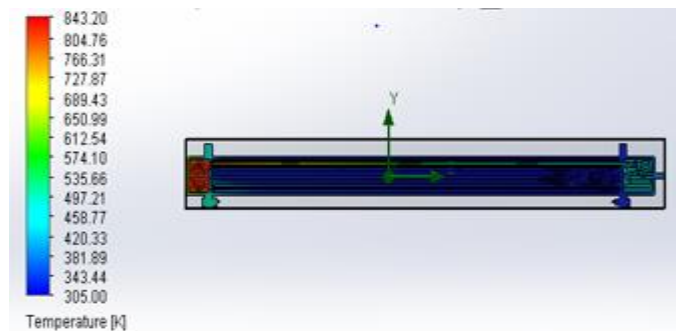


Fig. 2 Condenser Simulation Chart

More so, as the heat energy of the hydrocarbon vapour entry from the cracking unit must be given off, the condenser was subjected to SolidWorks flow simulation by assigning the calculated fluids flow rate, boundary conditions, fluid types, environmental pressure, mesh goals, etc., Fig. 2 presents the simulation output result condenser unit of the system. From the simulation result an average fluid temperature of 332K (~ 59°C) could be attained in the condenser component; a value reasonably closer to the proposed fluid temperature (60°C) selected in the course of designing the condensing unit. Also, it can be seen from Fig. 2 that the proposed entry water to the

condensing unit section of the system still maintains the originally assigned temperature of 305 K ( $\sim 32^\circ\text{C}$ ). Thus, the simulation output indicates that the condenser is capable enough to condense the expected heat-laden-vapour generated that exits from the pyrolysis of the feedstock.

### 2.3 Materials Gathering and Machine Fabrication

The materials comprise the fabrication and machine performance evaluation material (termed feedstock). The fabrication materials, which are mild steel, aluminum, copper, and ceramic wool, and the instrumentations were procured from Arakale Market in Akure, Ondo State, and Alaba Market in Lagos. Fig. 3 presents the isometric view of the developed plastic pyrolyzer and Table 1 shows the specifications of the developed pyrolysis system.

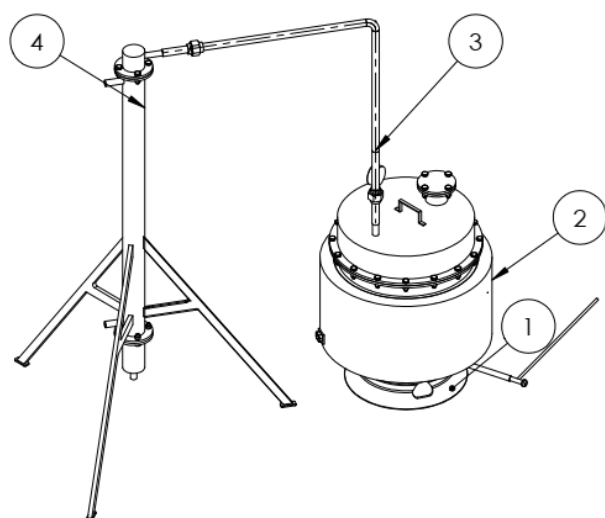


Fig. 3 Isometric View of the Developed Plastic Pyrolyzer

Table 1 Specifications of the developed plastic pyrolyzer

S/N	Name	Description	Quantity
1	Gas Burner	1500 btu/hr. LPG Burner	1
2	Reactor	-	1
3	Pipe	24 mm mild steel pipe	2
4	Condenser	Single-pass shell=tube condenser	1

Waste plastic, the feedstock, was obtained from waste sites located within Akure Metropolis. The feedstock was cleaned to remove impurities. It was then cut into the size of 50 mm by 50 mm with the aid of a hacksaw and Grinding machine (Model: Bosch) to facilitate ease loading into the reactor chamber.

The machine was fabricated and subjected to performance evaluation at the Central Workshop of the Department of Mechanical Engineering of the Federal University of Technology, Akure. Also, all other consumables (such as water,) were obtained from the premises of the University.

### 2.4 Experimental Setup and Performance Test

Performance evaluation of the developed pyrolysis plant (Test rig) was done using samples of the High-Density

Polyethylene (HDPE) type of plastic waste, the selected feedstock, sourced within the Akure metropolis. Prior to the commencement of the evaluation, the Test rig condenser was connected to the water source and filled up. Afterward, a measured quantity (5 kg) of the feedstock (HDPE) measured with a spring dial mechanical weighing scale was charged into the reactor. The reactor lid (cover) was closed and fastened in position with 6 pieces of M12 bolts to prevent air ingress. The reactor burner was then ignited to raise the test rig to the designed pyrolysis temperature ( $550^\circ\text{C}$ ) preset using the attached automatic temperature controller. The pyrolysis process was allowed to continue until no fraction was obtained anymore. The temperature at which the first drop of condensate dropped into the beaker as well as the last drop, including their associated time, was noted with the attached temperature measuring instrument and stopwatch. Also, the temperatures of the cooling water exiting the condenser were recorded at an interval of 30 minutes. At end of the last drop, the Test rig was disengaged from the power source and allowed to cool. Afterward, the reactor lid was again removed, and the remaining fraction, of biochar, left in the reactor was removed (and weighed or its mass recorded). Fig. 4 presents the experimental setup, bottled bio-oil obtained in this study, and the flame test bottle.

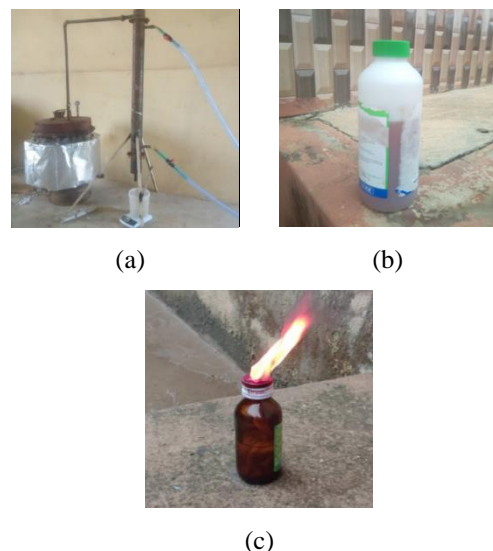


Fig. 4 (a) Experimental setup, (b) Bio-oil, and (c) Flame Test

#### 2.4.1 Transesterification Process Carried Out in this Study

Transesterification was performed with a 500 mL tabletop-mounted biodiesel processor. A unit mass of 300 g of sodium methoxide was measured and mixed with the measured quantity of the extracted oil obtaining a molar ratio of 6:1. The mixture formed was then raised in temperature to  $60^\circ\text{C}$  by heating and stirred at 450 rpm for 2 hours. Afterward, the mixture was poured into a separatory funnel and left for 8 hours to allow the reaction to reach equilibrium and facilitate the biodiesel with glycerol to separate into two distinct layers. The glycerol, at the bottom, was drained off by gravity and the excess methanol in the biodiesel was removed using a reduced pressure (20 mbar,  $30^\circ\text{C}$ ) rotary evaporation. The crude biodiesel was washed with distilled water until a neutral pH value was obtained and, then, dried by passing over magnesium sulfate.

#### 2.4.2 Determination of the Mass of LPG Used

In order to estimate the quantity of fuel, LPG used to achieve the pyrolysis in this study, the mass of the charged LPG gas

cylinder before experimentation was measured with a spring balance and recorded (as  $m_1$  value of 7.0 kg). The final mass of the cylinder at the end of the process was then noted and recorded (as  $m_2$ ). The fuel consumption per batch ( $m_{fc}$ ) was obtained using Eq. (21):

$$m_{fc} = m_1 - m_2 \quad (21)$$

After experimentation, the final mass of the charged LPG gas was found to be 6.2 kg; this shows that 0.8 kg of LPG gas was used for firing the reactor during the pyrolysis process

### 2.5.3. Bio-oil productivity per fuel consumption ( $\phi_p$ )

The Bio-oil productivity per fuel consumption, defined as the ratio of the bio-oil produced ( $m_{bf}$ ) to the mass of fuel consumed ( $m_{fc}$ ) to achieve the pyrolysis process can be determined using Eq. (22):

$$\phi_p = \frac{m_{bf}}{m_{fc}} \quad (22)$$

It was observed that when the bio-oil produced was weighed with a digital mass balance, the mass of bio-oil produced per the feedstock charged used in this work is obtained as 1166 g. Hence, the bio-oil productivity per fuel consumption using Eq. (22) is calculated as 1.4575 kg/kg.

## 3 Results and Discussion

Samples of the bio-oil obtained, grouped as A, B, and C were subjected to physicochemical analyses at Chemical Laboratories of the Federal Institute of Industrial Research Oshodi (FIRO), Lagos State, and the Chemistry Department at Federal University of Technology Akure (FUTA), Ondo State; according to the procedures specified by American Oil Chemists' Society (AOCS, 1990) and American Society for Testing and Materials (ASTM) methods considered for characterization of bio-oil and biodiesel

Table 2 presents details of the characteristics of the bio-oil obtained from the pyrolysis of the HDPE plastic waste, using the developed Test rig in this study.

Table 2 Characteristics of Bio-Oil obtained from HDPE Plastic Wastes

S/N	Property	Sample A	(Unrefined oil) Sample B	(Refined oil) Sample C	Tested Method
1	Acid value	0.444	0.726	0.450	
2	Saponification value	89.047	98.414	88.022	
3	Iodine value	7.016	8.500	6.108	
4	Specific gravity	0.818	0.785	0.778	
5	Kinematic viscosity ( $m^2/s$ )	10.307	0.953	0.820	ASTM D 445
6	Flashpoint ( $^{\circ}C$ )	145.000	39.400	32.785	ASTM D 93
7	Volatile matter (%)	1.539	97.400	99.710	
9	Pour point ( $^{\circ}C$ )	22.000	-32.000	-29.000	ASTM D 97
10	Density ( $kg/m^3$ )	962.000	785.000	778.000	ASTM D1298
11	Heating value ( $kJ/g$ ) 42 – 46	-	39.525	41.231	ASTM D240

With reference to Eq. (21) and Eq. (22) respectively, it was computed that: (i) 0.8 kg of LPG gas was used to fire the test rig while pyrolyzing 5.0 kg HDPE plastic (or 0.16 kg of LPG gas would pyrolyze 1.0 kg of feedstock); (ii) for 5.0 kg HDPE (feedstock) charged for pyrolysis process, 1.166 kg of bio-oil is produced. Similarly, 1.0 kg of feedstock would yield 233.2 g of bio-oil, and (iii) the bio-oil productivity per fuel consumption given as ( $\phi_p$ ) in Eq. (22) is calculated as 1.4575. It should be highlighted that since the  $\phi_p > 1$ , it can be inferred that pyrolysis of considered HDPE plastic wastes is a good alternative source for converting waste to biofuel production

From Table 2, Sample A refers to the denser fluid ratio of pyrolytic oil obtained, it accounts for about 5.4 % of the total condensate collected. Sample B is the remaining portion of the total condensate collected (94.6 %); it is the unrefined bio-oil yield. Sample C is the esterified refined bio-oil yield as aforementioned above. The 94.6 % bio-oil yield depicts the ability of HDPE wastes to yield more bio-oil compared to those reported in the studies of Akinola *et al.* [22], Mogaji *et al* [7], Babajo *et al* [23], and Khuenkaeo *et al* [24]).

It is also found that the heating values of samples shown in Table 2 are almost close to the heating values of the available various fuels, viz: diesel (42 – 46 MJ/kg); crude oil (42 – 47 MJ/kg); LPG (46 – 51 MJ/kg), and natural gas (42 – 55 MJ/kg) and greater than that of solid fuel, like wood (with a value of 17 MJ/kg) and within the range of that of vegetable oil (31 – 48 MJ/kg), this outcome shows that pyrolysis of discarded plastic wastes is a good potential alternative biofuel production source.

The flashpoint of 145  $^{\circ}C$  for sample A indicates that it is not a combustible substance compared to 39.4  $^{\circ}C$  and 32.785  $^{\circ}C$  flashpoint values attained for samples B and C respectively. The achieved flashpoint values for samples B and C (which indicate the lowest temperatures at which its vapour will ignite with a low flame) revealed that they are highly combustible liquid substances as buttressed by the flame test shown in Plate 3. The high value of the flashpoint of sample A, which is higher than that specified for diesel, depicts that it is a safer fuel than diesel; this result aligned with the findings of Bello *et al.*, [25]. This outcome shows that bio-oil from the pyrolysis of discarded plastic is a good potential energy source as it has fuel properties similar to that of petroleum fuels.

## 4 Conclusion

A 5.0 kg batch-type bioreactor for pyrolyzing used or discarded plastic waste has been developed and its performance was evaluated in this study. The evaluation of HDPE waste through Pyrolysis and the creation of a new value for this type of waste was the focus of this study. The pyrolytic oil obtained from the developed system at temperatures between 280 $^{\circ}C$  -520 $^{\circ}C$  was assayed for composition and fuel properties. The performance result revealed that the developed pyrolysis reactor in this study has the potential to produce 1.4575 kg of bio-oil per kilogram of liquified petroleum gas (LPG) consumed. These results justified that the burning of fossil fuel (LPG) to obtain bio-oil from the HPDE plastic waste pyrolyzed in this work is cost-effective and beneficial to achieve alternative biofuel production. The reduced fuel densities of 785 and 778)  $kg/m^3$  for Samples B and C respectively revealed that the alternative biofuel produced in this study would be more environmentally friendly as a considerable reduction in the concentrations of Carbon IV Oxide ( $CO_2$ ), unburnt hydrocarbon (HC) and soot emitted when used in light duty engines. The observed flame

result from obtained pyrolytic oil in this study confirmed that they are combustible liquid substances. It is also found that the heating value 41.231 kJ/g obtained for the esterified Sample C bio-oil in this work is almost a close match with the heating value (42-46) kJ/g of the conventional diesel fuels. Thus, the research yields diesel-like fuel whose properties are similar to that of conventional diesel. However, further post-processing steps are imperative to upgrade the fraction to meet up with regulation standards and specifications.

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### Conflict of Interest

The authors declared that there is no conflict of interest in the article.

### References

- [1] Aziz, M.A., Al-Khulaidi, R.A., Rashid, M.M., Islam, M.R. and Rashid, M.A.N., 2017, March. Design and fabrication of a fixed-bed batch type pyrolysis reactor for pilot scale pyrolytic oil production in Bangladesh. In *IOP Conference Series: Materials Science and Engineering* (Vol. 184, No. 1, p. 012056). IOP Publishing.
- [2] Geyer, R., Jambeck, J.R. and Law, K.L., 2017. Production, use, and fate of all plastics ever made. *Science advances*, 3(7), p.e1700782.
- [3] Chanashetty, V.B. and Patil, B.M., 2015. Fuel from plastic waste. *International Journal on Emerging Technologies*, 6(2), p.121.
- [4] Abnisa, F., Daud, W.W. and Sahu, J.N., 2011. Optimization and characterization studies on bio-oil production from palm shell by pyrolysis using response surface methodology. *Biomass and bioenergy*, 35(8), pp.3604-3616.
- [5] Goyal, H.B., Seal, D. and Saxena, R.C., 2008. Bio-fuels from thermochemical conversion of renewable resources: a review. *Renewable and sustainable energy reviews*, 12(2), pp.504-517.
- [6] Titiladunayo I.F., 2002. Biomass Energy Conversion and the Impact of Bioenergy Utilization on the Environment. *Nigerian Journal of Forestry*, 32, pp.42-49.
- [7] Mogaji, T. S. Akinsade, A., Akintunde, M. A., 2019. Pyrolysis of Sugarcane Bagasse for Bio-Oil Production. *Journal of Engineering and Engineering Technology*, 13(2), pp.150-157.
- [8] Mogaji, T.S., Moses, E.O., Idowu, E.T. and Jen, T.C., 2020. Thermal Degradation Conditions Effects on Selected Biomass Wastes and Characterization of Their Produced Biochar.
- [9] Zhou, N., Dai, L., Lv, Y., Li, H., Deng, W., Guo, F., Chen, P., Lei, H. and Ruan, R., 2021. Catalytic pyrolysis of plastic wastes in a continuous microwave assisted pyrolysis system for fuel production. *Chemical Engineering Journal*, 418, p.129412.
- [10] Sharuddin, S.D.A., Abnisa, F., Daud, W.M.A.W. and Aroua, M.K., 2016. A review on pyrolysis of plastic wastes. *Energy conversion and management*, 115, pp.308-326.
- [11] Wen, Y., Peng, F. and Weiming, Y., 2017. Catalytic fast pyrolysis of corn stover in a fluidized bed heated by hot flue gas: Physicochemical properties of bio-oil and its application. *International Journal of Agricultural and Biological Engineering*, 10(5), pp.226-233.
- [12] Gaurav, M.M., Arunkumar, K.N. and Lingegowda, N.S., 2014. Conversion of LDPE plastic waste into liquid fuel by thermal degradation. *International Journal of Mechanical and Production Engineering*, 2(4), pp.104-107.
- [13] Olufemi, A.S. and Olagboye, S., 2017. Thermal conversion of waste plastics into fuel oil. *Int. j. petrochem. sci. eng*, 2(8), pp.252-257.
- [14] Sharuddin, S.D.A., Abnisa, F., Daud, W.M.A.W. and Aroua, M.K., 2018, March. Pyrolysis of plastic waste for liquid fuel production as prospective energy resource. In *IOP Conference Series: Materials Science and Engineering* (Vol. 334, p. 012001). IOP Publishing.
- [15] Onwudili, J.A., Insura, N. and Williams, P.T., 2009. Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: Effects of temperature and residence time. *Journal of Analytical and Applied Pyrolysis*, 86(2), pp.293-303.
- [16] Khurmi, R.S. and Gupta, J.K. (2015): "A Textbook on Refrigeration and Air Conditioning." Eurasia Publication House (P) Ltd, New Delhi. Page 360-368.
- [17] Khedri, S. and Elyasi, S., 2018. Determination of the heat of pyrolysis of HDPE via isothermal differential scanning calorimetry: A new approach for solid state reactions. *Journal of Thermal Analysis and Calorimetry*, 131, pp.1509-1515.
- [18] Ineos, 2019. Typical Engineering Properties of High-Density Polyethelene, *Ineos olefins and polymers*, USA: www.ineos-op.com accessed 11/12/2019.
- [19] Alloy Wire International, 2019: <https://www.alloywire.com/downloads/> accessed 15/10/2019.
- [20] Rajput K. R., 2011. A Textbook of Heat and Mass Transfer, Revised Edition, Chand and Company Ltd. publication, 7361, Ram Nagar, New Delhi, India, pp.80-95
- [21] Serth, R.W., 2007. Process Heat Transfer Principles and Applications. Department of Chemical and Natural Gas Engineering, Texas A&M University-Kingsville, Kingsville, Texas, USA
- [22] Akinola, A.O., Eiche, J.F., Owolabi, P.O. and Elegbeleye, A.P., 2018. Pyrolytic analysis of cocoa pod for biofuel production. *Nigerian Journal of Technology*, 37(4), pp.1026-1031.
- [23] Babajo, S.A., Enaburekhan, J.S. and Rufa'i, I.A., 2021. Design, fabrication and performance study of co-pyrolysis system for production of liquid fuel from jatropha cake with polystyrene waste. *Journal of Applied Sciences and Environmental Management*, 25(3), pp.407-414.
- [24] Khuenkaeo, N., Phromphithak, S., Onsree, T., Naqvi, S.R. and Tippayawong, N., 2021. Production and characterization of bio-oils from fast pyrolysis of tobacco processing wastes in an ablative reactor under vacuum. *PLoS One*, 16(7), p.e0254485.
- [25] Bello E. I; Ayodeji, O. Z; Ogunbayo, S. and Bello, K., 2019. Characterization and Glycerine Analysis of Mustard (*Brassica juncea*. L) Seed Oil and Biodiesel, *Journal of Advances in Biology and Biotechnology*, 22(2), pp.1 – 8.