Original Research Paper

Design, Fabrication and Operational Evaluation of a Co-Pyrolysis System for Waste-Plastics Derived Fuels: A Study of Edo North

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Abstract: This research work designed, developed, and assessed the performance of a co-pyrolysis system generating waste-plastic extract fuels from mixed Municipal Waste Plastics (MWP) while evaluating High-Density Polyethylene (HDPE), Polypropylene (PP), and Polystyrene (PS) as the main municipal waste plastic sources. The materials selected for the reactor were carefully studied to meet the pyrolysis system's strength, operability, and safety requirements. The equipment was put through its paces in three trials, using 2 kg of mixed municipal waste plastics each. The temperature was optimally constant at 450°C for three hours. The equipment had a functional conversion efficiency (wt %) of 73.17%, a waste reduction efficiency (wt %) of 86.3%, and oil recovery of 0.90L oil/kg MWP, according to the test results. As a result of its re-cracking process, which recycles heavy molecular weight compounds back into the reactor, this reactor was built in such a manner that only compounds in the carbon range of C_1 20 may be created. This process was discovered to have a major impact on the product's distribution. Plastic fuels generated from co-mingled municipal waste plastics had similar characteristics to diesel and based on the characterization and comparative research done in this study.

Keywords: Waste Plastic, Pyrolysis, Fabrication, Operability Study, Efficient Production, Characterization

Introduction

Plastics are manufactured from petrochemical hydrocarbons with stabilizers, oxidants, and flame retardants added as needed. Plastics are, therefore, non-biodegradable and will endure for thousands of years in the environment (Ma *et al*., 2017). The consumption of plastics in Nigeria has grown annually by 7.8% over the past ten years, starting with 578 kilotonnes in 2007 to 1.229 kilotonnes in 2017 and this figure is predicted to be about 1.533 kilotonnes by 2020 (Asoko, 2017). The problem of disposing of generated waste plastics, as well as the environmental consequences, has drawn much attention from the general populace and academia (Jambeck *et al*., 2015). The most recent problem is the presence of solid plastic waste being a significant component of Municipal Waste (MSW), thereby blocking drainages, polluting water, and serving as breeding grounds for predators and disease-causing organisms (Amenaghawon *et al*., 2013). Amongst several options for curbing this menace is turning these waste plastics into feedstock for new products; thus, by combining waste control and material recycling, a continuous economy can be produced (Scheirs and Kaminsky, 2006). The techniques that convert waste from plastics into fuel vary widely dependent on the kind and grades of plastics to be converted and the characteristics of other wastes that may be utilized in the process (Williams and Slaney, 2007). In addition, effective conversion technologies are hinged on the selection of plastics according to the local economy, social, technical, and environmental characteristics. Generally, plastics are classified into two major types: Thermoplastics and thermosets. Low-Density Polyethylene (LDPE), High-Density Polyethylene

(HDPE), Polypropylene (PP), Polycarbonate (PC), Polystyrene (PS), Polyvinyl Chloride (PVC), Polyethylene Terephthalate (PET) and Polymethyl Methacrylate (PMM) are among the thermoplastics (Aisien *et al.*, 2021) while polyester, silicon, Polyurethane (PUR), vinyl ester and melamine resin are examples of thermosets (Kyaw and Hmwe, 2015). In descending order, the global average consumption of plastics is 7% for PET, 10% for PS, 12% for other types of polymers, 13% for PVC, 23 for PP, and 35% for HDPE (Aisien *et al.*, 2021). The most common plastics in waste polymer streams are polyolefins (H and LDPE, PP) and PS (Kyaw and Hmwe, 2015). The production of fuel from these plastic wastes holds a lot of present and future promises due to specific characteristics such as their higher heating value, properties similar to gasoline and diesel, and their environmental abundance (Aisien *et al.*, 2021).

Among the various waste plastic management methods, pyrolysis is gaining popularity because it allows for the conversion of low-energy-density waste plastic materials into high-energy-density fuels and the recovery of high-value compounds (Panda, 2018). Pyrolysis, which is the thermal decomposition of materials in the absence of oxygen or the presence of inert gases alters the chemical composition while being among the most environmentally benign and promising treatments. By churning out a variety of products, the process massively reduces an enormous volume of waste, while lowering the decomposition temperature, cost of capital, and recovering a major part of the energy composition (Patni *et al.*, 2013). Pyrolysis of PE, PP, and PS produces little or no solid unlike PET and PVC which leaves a small amount of solid residue (<10%) (Matsuzawa *et al.*, 2001). Thermal depolymerization, also known as pyrolysis, breaks long-chain polymers using heat at temperatures of about 400-600°C. Instead of the polymer being broken down into its monomers, this process would produce shorter-chain polymers, similar to products from crude oil fractioning thereby maximizing liquid production (Miandad *et al.*, 2019). In a stirred semi-batch reactor at 400°C, Kyong *et al.* (2002) studied the impact of wasted FCC catalyst on the pyrolysis of Low-Density Polyethylene (LDPE), High-density Polyethylene (HDPE), Polystyrene (PS), and Polypropylene (PP). The effectiveness of fresh FCC catalysts on PP plastic was studied by Abbas-Abadi *et al.* (2014). At optimal conditions of 450°C and a 10% catalyst ratio, they got a very high liquid oil yield of 92.3 wt %. They finally concluded that the use of FCC catalyst at an optimal temperature of 450°C in plastic pyrolysis was recommended to increase liquid oil output.

The presence of large molecular weight compounds in the pyrolytic oil implies a massive cost and energy requirement for the separation of its fractions. This means that the useful fuels produced from waste plastics conversions have a low percentage and in turn, decrease the total pyrolysis system conversion rate. Environmental pollution in Edo state (feedstock availability and accessibility) and sorting costs have led to the development of this study project to design, fabricate and access the performance of a pyrolysis system that can handle a wide range of popular municipal waste materials and generate fuels from the pyrolysis system in the C_{11}-C_{20} carbon range. The energy conservation is achieved through the re-cracking reflux of high molecular weight carbons thereby increasing the reactor temperature and encapsulating heat integration. The pyrolytic oil is physically characterized by the performance of the pyrolyzer.

Materials and Methods

Pyrolyzer Design

Reactor Design

The pyrolysis reactor was designed to have a cylindrical cross-section positioned vertically with a core inserted in a squared box to prevent external air interference. The height of the reactor and its thickness were 300, and 8 mm respectively with internal and external diameters of 160 and 250 mm. The internal pressure was 1.2 MPa (10.2 bar), Corrosion Allowance (CA) was 1.5 mm, shell Internal Diameter (I.D) was 180 mm, allowable stress (S) was 70 Mpa, the static head was 0.05 MPa and joint efficiency(I) was 70%. The design pressure allowed between 1.25-3.32 MPa, and the corroded diameter was 187.5 mm with the maximum allowable pressure being. The reactor casing (box) had length, breadth, and height dimensions of 300 mm each. The reactor walls were made of mild steel because of their strength, high melting point, and low cost. The reactor base and box were alternatively made with stainless steel because of their higher thermal conductivity high melting point, lower corrosion vulnerability, and higher tensile strength. The heat source was positioned 300 mm below the cylindrical core inside the reactor box with a burner measuring 4 mm using LPG as fuel. The efficiency of the burner was 51.3%. The reactor was designed to operate at considerable high pressure. Specific spots were located to attach pressure gauge, to connect piping for guiding vapor to the condenser, pressurizing cylinder, Vacuum pump, and a fabricated gas sampling tube. Two flanges, 10 mm thick served as the reactor cover sealing the reactor perfectly when subjected to high temperature and ensuring safety. Figure 1 and 2 shows the orthographic and pictorial views of the reactor, box, and heat supply.

Condenser Design

Figure 3 describes pictorially and orthographically the heat exchangers used in the condensation process. Two condensers were used for the vaporized fractions of the resultants. The first (shell and tube) was designed to have 5 tubes of 1m in length each, using water as coolant and an inlet and outlet temperature of 15 and

60°C respectively while the second (tube-in-tube), arranged in a sequence was designed to have 1 tube of the same length, an inlet temperature of 25°C and outlet of 45°C. The hot pyrolytic oil entering the first exchanger was at a maximum temperature of 500°C and exits at 287°C while the second entered at 287°C and exited at 62.5°C. The overall heat transfer coefficient of the first heat exchanger was designed to be 33 W/m^{2}K, inner pipe (H_i) coefficient was 414.46 W/m^{2}K, outer pipe heat transfer coefficient (H_o) of 4,302.4 W/m^{2}K, and total heating rate (Q) of 37,800 W. The heat transfer area was 3.38 m with 1 m length each of the stainless steel tubes, the first heat exchanger was made of stainless steel (SS-304) 1 mm thick, the outer shell of galvanized pipe had a 1.5 mm thickness, inner stainless steel shell cover 2 mm thick while the second was made of aluminum (2 mm thick) all other parameters remaining unchanged. The overall heat transfer coefficient of the second exchanger was 201.56 W/m^{2}K, heat transfer coefficient based on inner pipe (H_i) -977.5 W/m^{2}K, heat transfer coefficient of the outer pipe (H_o) -3182.4 W/m^{2}K, the total rate of heat transfer (Q) 16,800 W and Area of 0.74 m. Figures 4 and 5 give simulated and schematic views respectively of the pyrolysis system while the entire dimension of the pyrolysis system is given in Table 1.
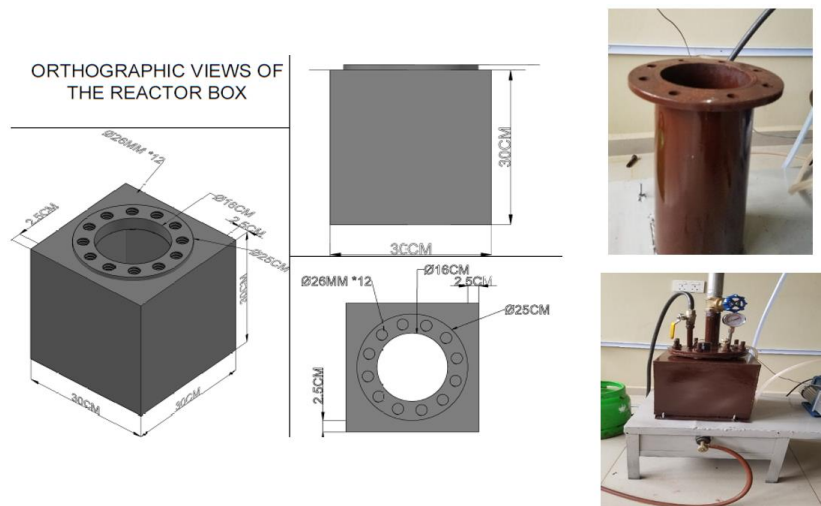

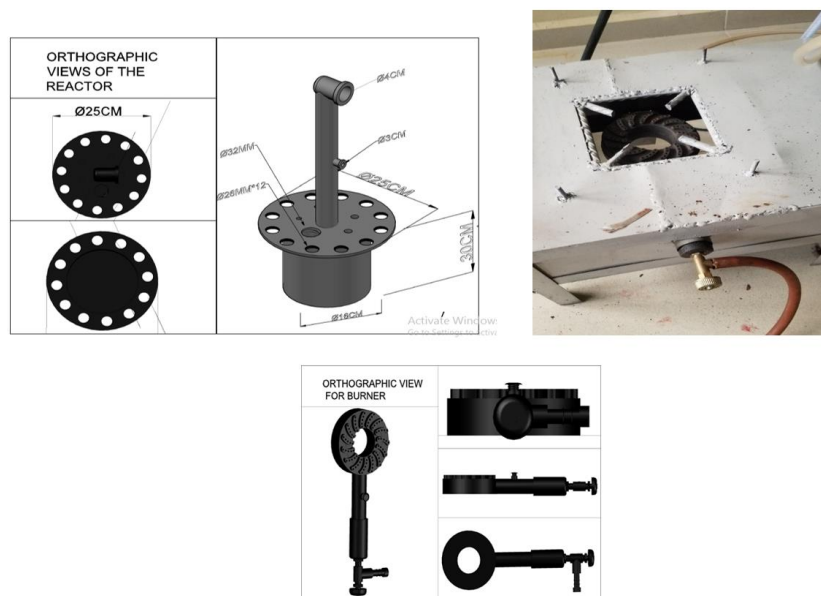**Fig. 1:** Orthographic and pictorial view of the reactor and reactor box

Fig. 2: Orthographic and pictorial view of the heat source

Fig. 3: Orthographic and pictorial view of heat exchangers
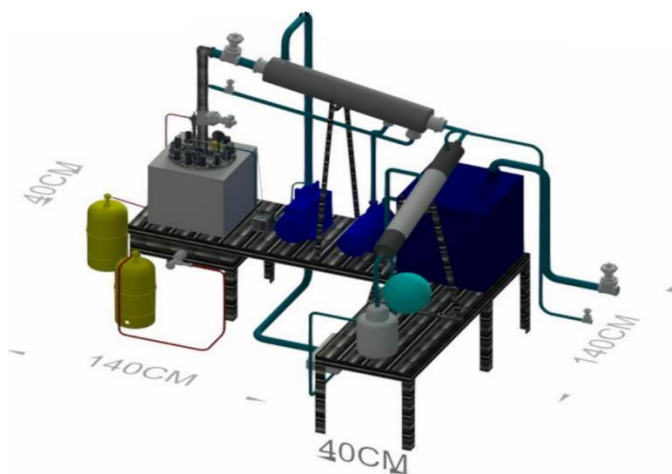

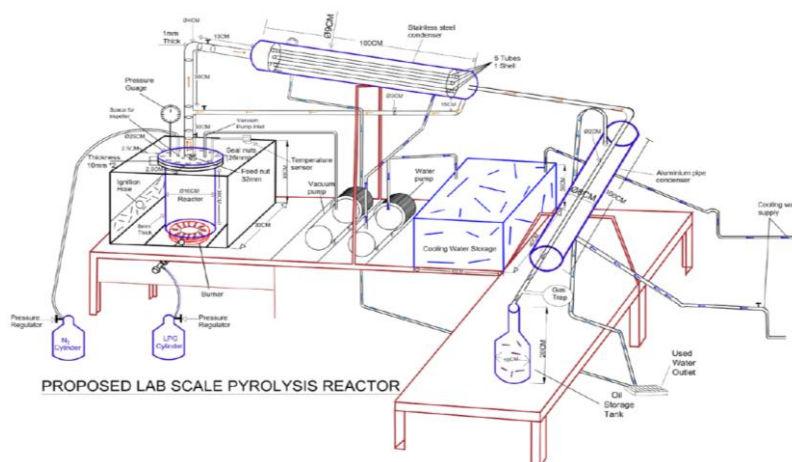**Fig. 4:** 3D Simulated model of pyrolysis plant

Fig. 5: Schematic diagram of the Lab-scale pyrolysis system

Table 1: Summary of pyrolysis plant design dimension

S/N	Parameter	Value	Unit
1	Height of the reactor	300	mm
2	Internal pressure	1.2	Mpa
3	Corrosion Allowance (CA)	1.5	Mm
4	Shell Internal Diameter (I.D)	180	mm
5	The thickness of the reactor	8	mm
6	Inlet/outlet cooling temperature (C1&C2)	15/60 and 25/45	°C
7	Inlet/outlet fluid temperature (C1&C2)	500/270 and 287/62.7	°C
8	Overall heat transfer coefficient (C1&C2)	33 & 201.56	W/m^{2}K
9	Length of condenser pipes	1000	mm
10	Number of tubes	5	_
11	Maximum Allowable pressure	3.21	Mpa
12	Height of the outer box and distance to burner	300 each	mm
13	Total heat transfer rate/Area (C1&C2)	37,800/3.38 & 16,800/0.74	W/mm
14	Height of the burner	4	mm
15	Heating Value of LPG	46,100	Kg/J

Experimental Procedure

The plastic wastes used were collected from different dumpsites in Edo north area of Edo State and downsized into pellets to reduce the void age in the reactor. The waste plastic pallets are weighed according to their plastic-type i.e., PE, PP, and HDPE to make up the comingled feed. The waste plastic pellets are then fed into the reactor through the feeding nut or by removing the top flange and then closing tightly. An attached vacuum pump is used to remove the contained air to avoid burning after which the system is pressurized with inert gas (Nitrogen) about 2 bar. The burners are lit to supply heat to the reactor while the temperature is monitored with the help of a thermocouple at the top of the reactor. The temperature is maintained at an optimal of 450°C as described by Abbas-Abadi *et al*. (2014). The resulting vaporized plastic flows through to the condensers at various temperatures where it is cooled using water. The cracked condensate from the first condenser is refluxed back to the reactor by closing and opening some valves because of its high molecular weight compounds. The final condensate from the second condenser is collected in an air-tight container. The un-condensed gas is trapped using an air trap balloon and sent and analyzed for prospective fuel capabilities in a further modified pyrolysis system. At the end of the reaction, the char is removed and weighed along with the volume of the collected pyrolysis oil. The oil is then purified by washing with water and decanted properly after which further purification is done by a filter paper. The PH is measured and rewashed accordingly to neutralize the oil. This entire process was modified after the first trial and then repeated three consecutive times before the performance was evaluated using the following formulas:

$$Oil\, Conversion\, Ef\, Ficiency\, (CE)\% + = {w^0}/{W_{SM}} \times 100\% \quad (1)$$

$$Oil\, Recovery\, (OR) = {^v}/{W_{SM}} \quad (2)$$

$$Gas\, Yield\, (kg) = Mass\, of\, Feed$$
$$- \left(Mass\, of\, Oil\, Recovered + Mass\, of\, Char \right) \quad (3)$$

where W_0 = Wieght of Oil, W_{sM}
= Wieght of Plastic and V = Volume of Oil.

Characterization of Plastic Oil

Several physicochemical characteristics of the pyrolytic oil were determined according to ASTM standards and compared to standard fuel (diesel) properties. The density was measured using a 25 mL pycnometer at different temperatures and reported in kg/m^3. The calorific value was measured using the bomb calorimeter, and viscosity using the Ferranto portable viscometer. The ash content was measured along with the flashpoint, cloud point, pour point, and pH of the comingled pyrolytic oil.

Results and Discussion

Waste Collection

Figure 6 above shows the distribution of waste in the experimental sample obtained from Edo North. Polypropylene (PP) was the major constituent gotten majorly from buckets, jerry cans, paint rubbers, etc. High-Density Polyethylene (HDPE) had about 37.5% while Polystyrene (PS) was only 12.5% of the entire sample collected.

Pyrolysis Experiment Result

From Table 2 above, three runs of experiments for converting comingled municipal waste plastic of High-Density Polyethylene (HDPE), Polypropylene (PP), and Polystyrene (PS) into comingled pyrolytic oil were conducted. The first, second, and third tests yielded 1.70, 1.85, and 1.80 liters of pyrolytic oil respectively. Similarly, 0.29, 0.26, and 0.27 kg of char were gotten during the first, second, and third tests respectively while 0.26, 0.19, and 0.17 kg of gas were gotten from the three runs consecutively. Equations (1), (2), and (3) were used to respectively calculate

the actual performance of the comingled pyrolytic system using values as explained in Table 2 above forming Table 3.

Conversion Efficiency

From Table 4, it is discovered that an average of 73.17% of the whole waste plastic was converted into pyrolytic oil. This implies that an average of 13.5% of the waste plastic was converted into char while about 10% was converted into gas. In general, over 70% of the municipal waste plastic was converted into oil at each trial of the process with the entire pyrolytic system having an average overall conversion efficiency of 96.67%. Similar efficiency results were achieved by Weldekidan *et al.* (2019) using chicken litter and rice husk as feed.

The heating rate also had a significant effect on the pyrolytic oil production rate. About 185 ml more of oil was collected in the second experiment compared to the first one. This is possible because the heating rate was drastically increased in the second experiment as discovered by Jayswal *et al.* (2017) who discovered a similar occurrence.

Characterization of Comingled Pyrolytic Oil

The comingled pyrolytic oil obtained in this experiment was characterized and compared with those gotten from. The physicochemical properties of comingled oil are shown in Table 4.

Calorific Value and Colour

The comingled oil appeared reddish-orange while having a calorific value of 49.2 MJ/kg which is at least 3.2 MJ/kg higher than that of commercially used diesel (44-46 MJ/kg). Similar results were gotten by Wongkhorsub and Chindaprasert in 2013 when they compared the effects of pyrolytic oil in diesel engines. Calorific value is an important property of diesel fuels because it determines the energy content in the fuel. A higher calorific value indicates that a larger amount of energy is produced utilizing the comingled pyrolytic oil than in the use of diesel. According to Sharuddin *et al.*

(2018), the higher calorific value is a result of the presence of HDPE and PP as major constituents of the comingled plastic which have experimental calorific values of 40 MJ/kg and above. This makes the comingled pyrolytic oil suitable for a new energy resource in terms of energy content. The heating value of the comingled plastic-derived pyrolytic oil was also higher than those derived from tire and furnace oil.

Density and Viscosity

The density, which is defined as the mass of a unit volume of a material at a selected temperature (usually 15°C) (Lois *et al.*, 2003), of the comingled oil was lower than that of commercial diesel while the oils derived from tire and furnace. A similar result was reported by Lee *et al.* (2015). The viscosity however fell within the commercial-grade diesel range for the comingled pyrolytic oil. Viscosity is another very essential parameter to guarantee a good atomization property of a fuel (Lois *et al.*, 2003). Lois *et al.* (2003); referenced that for automotive, 2.0-4.5 is the required range while a maximum of 6 CST at 40°C is the heating maximum according to EN ISO 3104. This invariably means that the pyrolytic oil meets the standard for both heating fuels and automobiles.

Flash Cloud and Pour Point

Flashpoint is a very important property for the storage and handling of fuels (Lois *et al.*, 2003). Diesel fuels are usually stable and do not require special preservation considerations; nevertheless, the flashpoint is a good indicator of diesel fuel contamination with some more volatile chemicals. Lois *et al.* (2003). Hence, a flashpoint as low as 24°C indicates a clean and environmentally friendly energy source as against that of significantly higher diesel (>55°C) than the comingled pyrolytic oil (24°C) making it a very preferable source of heating. The cloud and pour points however fall within the range for the commercial-grade diesel as shown in Table 4 above. A higher pour point (-12°C) than that of diesel (-40 to -33°C) is possibly indicative of a larger amount of paraffin in the feed (Motawie *et al.*, 2015) which contains about 37.5% HDPE.
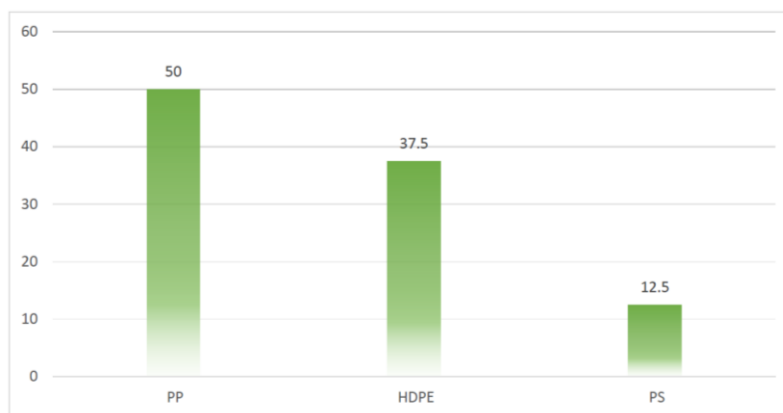

Fig. 6: Percentage distribution of municipal waste plastics sample from Edo North

Table 2: Performance evaluation of comingled pyrolysis system

Parameters	Trials			Total	Average
	1	2	3		
Weight of plastic (Kg)	2.00	2.00	2.00	6.00	2.00
Operation time (hrs)	3.00	3.00	3.00	9.00	3.00
Volume of oil (L)	1.70	1.85	1.80	5.45	1.81
Weight of oil (Kg)	1.40	1.51	1.48	4.39	1.46
Weight of Char (Kg)	0.29	0.26	0.27	0.82	0.27
Weight of gas recovered (kg)	0.26	0.19	0.17	0.62	0.21

Table 3: Performance evaluation of comingled pyrolysis system

Parameters	Trials			Average
	1	2	3	
Oil conversion efficiency (wt %)	70.00	75.50	74.00	73.17
Oil recovery (L/Kg waste plastic)	0.850	0.925	0.900	0.892

Table 4: Physicochemical properties of pyrolytic oil

Property	diesel	Tire derived oil	Furnace oil	Comingled oil
Colour	Bright yellow	_	_	Reddish orange
Density (kg/m^3)	820-860	940-970	880-950	798
Flash point (°C)	>55	≤32	66-93	24
Pour point (°C)	-40 to-30	-3 to-5	18-27	-12
Viscosity (cSt at 40°C)	2-4.5	4.6-4.9	–	3.26
Calorific value (MJ/kg)	44-46	40.8-42.5	43-45	49.2
Cloud point (°C)	>-40	_	_	-37.7
Ash content	<0.01	_	_	<0.004
Sulphur content (ppm)	<500	_	_	nil

In general, the ash content was extremely low which was described by Santaweesuk and Janyalertadun (2017) as evidence of the fluid's lack of metal pollution and high-molecular-weight soot. Agreeing with Wongkhorsub and Chindaprasert (2013) comingled pyrolytic oil can be used as liquid fuels for both industrial furnaces, power plants, boilers, and also diesel engines and can replace diesel fuels. They also found that, although plastic pyrolysis oil provides much-reduced engine performance, the engine may be adjusted to match the combustion state of comingled plastic pyrolysis oil. Furthermore, the volume of plastic trash is tremendous and it is environmentally important to treat it.

Conclusion

In conclusion, this study has proven that:

1. The pyrolysis system designed to utilize comingled feedstock from several types and grades of plastics was successful in producing pyrolytic oil
2. This thermal pyrolysis system produced a maximum of 75.5% pyrolytic oil among the three trials carried out and over 70% average pyrolytic conversion of plastic to oil
3. This pyrolysis setup gives an overall conversion efficiency of above 95% on average

4. The heating rate of the system largely affects the amount of oil extracted from the system as observed in the second trial of the system
5. The comingled pyrolytic oil has excellent fuel characteristics, including a high calorific value. (49.20 MJ/kg), density (798 kg/m^3), viscosity (3.26 cSt), pour point (-12) and flash point (24°C)
6. The comingled pyrolytic oil has close-ranged characteristics and qualities as diesel for heating and/or vehicles

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Author's Contributions

Kevin Otoikhian: Conceptualized the project, designed the pyrolyzer, participated in the experiment, analyzed and Interpretation of results, and reviewed the manuscript Draft.

Ubani Oluwaseun Amune: Analysis and Interpretation of Results, Draft, and Editing of Manuscript.

Kennedy Edogamhe: Participated in the experiment and data collection.

Barnabas Agbodekhe: Conceptualization and design of pyrolyzer, Analysis, and interpretation of the result.

Emmanuel Aluyor: Conceptualization and design of pyrolyzer.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and that no ethical issues are involved.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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Appendix

Pyrolysis System Design Calculations

Reactor Shell Design Calculations

Internal pressure = 1.2 MPa about 10.2 Bar
Corrosion Allowance (CA) = 1.5 mm
Shell Internal Diameter (I.D) = 1
Allowable Stress (S) = 70 MPa
Static Head = 0.05 MPa – 0.5 Bar
Design pressure (P) = internal Pressure + Static Head
1.2 +0.05 = 1.25 MPa
Joint efficiency (E) = 0.7
Corroded Diameter = I.D + 2* C.A 180 + 2* 1.5 = 187.5 mm
Design Radius (r) = $^{187.5}/2$ = 93.75
Required thickness $tr = P*rS*E - 0.6*P$
i.e . $tr =1.25*93.7570*0.7 - 0.6*1.25 = 2.43 \ mm$
Design thickness = $tr + C$.A i.e., 2.43 +1.5 = 3.93 mm
Considering that the pyrolysis reactor will operate at a temperature of over 500°C, for safety reasons, the calculated thickness of the reactor shell has been increased to 8 mm
Thickness = t = tn –C.A = 8 - 1.5 = 6.5

For Maximum Allowable Pressure Calculation

According to MAWP standards defined by the international organization for standardization

$$P = ^{S*E} * t/r + 0.6*t, p = 70*0.7*$$
$$6.5/93.75 + 0.6*6.5 \therefore P = \ 3.26MP\alpha$$

Maximum Allowable pressure = P – Static Head i.e.,
3.26-0.05 = 3.21 MPa

Reactor Design

Heating Value of LPG per kg (QHv) = 46100
Specific heat capacity of pyrolysis oil (Cp) = 2400 J/kg.k
Specific heat capacity of water (Cpw) = 4200 J/kg.k
The average value of heat of fusion of Polyethyene (PE)
Heat requirement for pyrolysis plus vaporization of 2 kg liquid PE = 1047.62 KJ
LPG stove efficiency = 51.3%
Latent heat of vaporization of LDPE = 180.46 J/kg
Assume that time for complete pyrolysis = 2 h
D_o = 8 cm
D_I = 1cm
K_{tube} = 15W / m.k
Viscosity of water μ = 855 *10-6(N.S)m^2 Thermal conductivity of water $K_w = 0.613 W/m.k$)
Temperature claculations:

For Condenser 1 (C1)

Ambient Temperature T_a = 25°C Temperature of Hot oil T_{HI} = 500°C Oil outlet temperature T_{HO} =?
Water inlet temperature T_{WI} = 15°C
Water outlet temperature T_{WO} = 60°C

For Condenser 2 (C2)

Ambient Temperature Ta = 25°C The temperature of Hot oil T_{HI} =?
Oil outlet temperature T_{HO} =?
Water inlet temperature T_{WI} = 25°C
Water outlet temperature T_{Wo} = 45°C
Heat taken by 10kg solid plastic till it starts to melt at 110°C i.e., $Q1 = M * Cp * \Delta T$ = 1785 KJ
Heat requirement to completely melt 10 kg plastic at 110°C, i.e., $Q2 = M * Lf$ = 1213.65 KJ
The heat required by 10kg liquid plastic to reach 450-500 0C i.e., $Q3 = M * Cp * \Delta T$ = 7140 KJ
The heat required for Pyrolysis (Q_4) = mass * Heat requirement for pyrolysis plus vaporization
= 10 kg * 1047.62 KJ/kg = 10476.2 KJ
Total heat required = $Q_1 + Q_2 + Q_{3} + Q_4$ = 20,614.25 KJ
Heat transfer rate required = Total heat requiredtiment taken:

$$i.e. 20614.85 /_2 = 10307.4 KJ / hr$$

Plastic vapor production rate = heat transfer rate latent heat of vaporization:

$$i.e. 10307.4 / 18.46 = 57.12 Kg / hr$$

57.12 kg/hr * 0.000278 = 0.016 i.e., approximately 0.02 kg/secs

Heat Exchanger Design for Condenser 1 (C1) (Holman, 2010 and Kutz, 2006)

$$Q = 0.02*2.4*103(500 - T_{HO})0.2*4.2*103(60-15)$$
$$Q = 24000*48Tho = 378000$$
$$T_{HO} = 13000/48, T_{HO} = 48T_{HO}$$

Heat Exchanger Design for Condenser 2

$$Q = mh*Cph(THI - THO) = mc*Cpw(THI - THO)$$
$$Q = 0.02*2.4*103(287.5 - T_{wo}) = 0.2*4.2*103(45-25)$$
$$Q = 13800*48T_{HO} = 16800$$
$$T_{HO} = \frac{3000}{48} = 6.25°C$$

Logarithmic Mean Temperature Difference for condenser 1:

$$\Delta Tm = {}^{(Th_1 - Tw_O)-(Th_1 - Tw_O)} / In\left(\frac{(Th_1 - Tw_O)}{(Tho - Tw_1)}\right)$$

$$\Delta Tm = {}^{(500-60)-(287.5-15)} / In\left(\frac{500-60}{287.5-15}\right), \Delta Tm = 349°C$$

Logarithmic Mean Temperature Difference for condenser 2:

$$\Delta Tm = {}^{(Th_1 - Tw_O)-(Th_1 - Tw_O)} / In\left(\frac{(Th_1 - Tw_O)}{h}\right)_{(TO - TwI)}$$

$$\Delta Tm = {}^{(287.5-45)-(62.5-25)} / In\left(\frac{287.5-45}{62.5-25}\right), \Delta Tm = 109.8°C$$

Overall Heat Transfer Coefficient Calculation for Condenser 1

$$U = \left[1/\frac{do}{di}*\frac{1}{hi}+\frac{do}{k}*In\frac{do}{di}+\frac{1}{ho}\right]$$

When fouling factor and scale formation are neglected the overall heat transfer coefficient based on the outer surface and inner surface of the tube is given above.
For the heat transfer coefficient based on inner pipe hi
The vapor properties of pyrolysis oil according to (Wongkhorsub and Chindaprasert, 2013) include;
Density ρ = 814.7 kg/m^2
Viscosity υ = 0.00249 Kj/kg
Thermal conductivity of pyrolysis oil K = 0.17 w/m.k
Specific heat capacity of pyrolysis oil vapor Cp = 2.40 *10^3 (Jayswal *et al.*, 2017)

The mass flow rate of the pyrolysis vapor (m) = 0.02 kg/s
Diameter of the inner tube = 0.01m

$$Pr = \upsilon Cp/k, Pr + = 0.00249*2.40*10^3/0.17 = 35.15$$
$$Re = \frac{4m}{\pi d\upsilon}, Re = 4*0.02/_{\pi*0.01*0.00249} = 1022.68$$
$$Nu = 0.023Re^{0.8}*Pr^{0.4}, Nu = 0.023*(1022.68)^{0.8}*35.15^{0.4}, Nu = 24.38$$
$$hi = (k/d), hi = 24.38(^{0.17}/0.01), hi = 414.46 w/m2.K$$

For the heat transfer coefficient based on outer pipe ho:

$$ho = 0.725(^{\rho(\rho-*\rho)}*g*hfg*k_f{}^3/uf*d(T_G - T_O))^{\frac{1}{4}}$$

From the table of the physical characteristics of water,
Density ρ of water @ 15 oC = 999 kg/m2
Viscosity υ of water @ 15 oC = 0.001139 Kj/kg
Thermal conductivity of water k = 0.613 w/m.k
Specific heat capacity of water Cp = 4.186 *103
Gravitational acceleration g = 9.81 m/s^2
Enthalpy difference between gas and fluid h_{fg} = 2255kj/kg

Outer diameter = 0.08

$$ho = 0.725\left(999^2*9.81*2255*10^3*0.613^3/0.001139\right)*0.08*(60-15))\frac{1}{4}, ho$$
$$= 4302.4^w/m2.K$$

Overall heat transfer coefficient for condenser 1;

$$U = \left[1/\frac{do}{di}*\frac{1}{hi}+\frac{do}{k}*In\frac{do}{di}+\frac{1}{ho}\right]$$
$$U = \left[1/\frac{0.08}{0.01}*\frac{1}{414.46}+\frac{0.8}{15}*In\frac{1}{4302.4}\right], U = 33^W/m^{2.k}$$

Evaluating for the Area of condenser 1:

$$Q = UA\Delta Tm, A = \frac{Q}{U}*\Delta Tm$$
$$U = 33^w/m2.K, Q = 37800W, \Delta Tm =$$
$$349°C, A = {}^{37800}/33*349, A = 3.38m$$

Evaluating for the length of the heat exchanger $L = A/\pi * d1 * 2 * nt$
where
A = the area of the heat exchanger Di = the inner diameter of the tube nt = the number of tubes in the shell and tube heat exchanger:

$$L = {}^{3.28}/\pi*0.01*2*5, L = 100cm = 1m$$

Overall heat transfer coefficient calculation for condenser 2:

$$U = \left[1 / \frac{do}{di} * \frac{1}{hi} + \frac{do}{k} * In \frac{do}{di} + \frac{1}{ho} \right]$$

When fouling factor and scale formation are neglected the overall heat transfer coefficient based on the outer surface and inner surface of the tube is given above.

For the heat transfer coefficient based on inner pipe hi
The vapor properties includes
Density ρ = 814.7 kg/m^2
Viscosity υ = 0.00249 kj/kg
Thermal conductivity of pyrolysis oil k = 0.17 w/m.k
Specific heat capacity of pyrolysis oil vapor Cp = 2.40 *10^3
The mass flow rate of the pyrolysis vapor (m) = $0.25 kg/s$
Diameter of the inner tube = 0.02 m:

$Pr = vcCp / k, Pr = 0.00249*2.40*10^3/0.17 = 35.15$
$Re = 4m / \pi d\upsilon, Re + = 4*0.25 /_{\pi*0.02*0.00249} = {}^{6391.76}$
$Re = {}^{4m}/\pi d\upsilon, Re = {}^{4*0.25}/4*0.02*0.00249 = 6391.76$
$Nu = 0.023 Re^{0.8} * Pr^{0.4}, Nu = 0.023 * (6391.76)^{0.8} * 35.15^{0.4},$
$Nu = 115 hi = hi = 115 ({}^{0.17}/0.02), hi = 977.5 {}^{W}/m2.k$

For the heat transfer coefficient based on outer pipe ho:

$$ho = 0.725 ({}^{(\rho(\rho-\rho_*))} * g * hfg * k_f^3 / uf * d(T_G - T_O)^{\frac{1}{4}}$$

From the table of the physical properties of water,
Density ρ of water @ 27°C = 996.59 kg/m2
Viscosity υ of water @ 27°C = 0.00852 Kj/kg
Thermal conductivity of water k = 0.613 w/m.k
Specific heat capacity of water Cp = 4.186 *103
Gravitational acceleration g = 9.81 m/s^2
Enthalpy difference between gas and fluid *Hfg* = 2255 kj/kg
Outer diameter = 0.08:

$$ho = 0.725 (996.59^2 * 9.81 * 2255 * 10^3 * 0.613^3 / 0.00852 * 0.08 * (45-25))^{\frac{1}{4}}$$

$$ho = 3182.4 \frac{W}{m^2}.K$$

Overall heat transfer coefficient for condenser 2:

$$U = \left[1 / \frac{do}{di} * \frac{1}{hi} + \frac{do}{k} * In \frac{do}{di} + \frac{1}{ho} \right]$$

$$U = \left[1 / \frac{0.08}{0.02} * \frac{1}{977.5} + \frac{0.8}{230} * In \frac{0.8}{0.02} + \frac{1}{3182.4} \right], U = 201.56 \, W/m^{2.k}$$

Evaluating for the Area of condenser 2
Q = UAΔTm
$Q/U * \Delta Tm$, U = $204.56^w/m2.K$, Q = 16800W, ΔTm = 109.8°C,
$A =$
$A = 16800/204.56 * 109.8$, A = 0.74m
Evaluating the length of the heat exchanger, $L = {}^A/\pi * d$
Where

A = the area of the heat exchanger ^{d} = the inner diameter of the tube
i.e., $L = {}^{0.74}/\pi * 0.02$, $L = 110cm = 1.1m$