Journal of Energy, Environmental & Chemical Engineering
2023; 8(3): 53-58
http://www.sciencepublishinggroup.com/j/jeece
doi: 10.11648/j.jeece.20230803.11
ISSN: 2637-4331 (Print); ISSN: 2637-434X (Online)

Designing and Fabricating a Prototype Pyrolysis Batch Reactor for Recycling Plastic Waste Materials to Oil

Nankwasa Crispuss*, Ogene Fortunate

Department of Mining, Chemical, and Petroleum Engineering, Kyambogo University, Kampala, Uganda

Email address:

crispussnankwasa@gmail.com (Nankwasa Crispuss)

*Corresponding author

To cite this article:

Nankwasa Crispuss, Ogene Fortunate. Designing and Fabricating a Prototype Pyrolysis Batch Reactor for Recycling Plastic Waste Materials to Oil. *Journal of Energy, Environmental & Chemical Engineering*. Vol. 8, No. 3, 2023, pp. 53-58. doi: 10.11648/j.jeece.20230803.11

Received: July 3, 2023; **Accepted**: August 16, 2023; **Published**: August 28, 2023

Abstract: Plastics like other materials have wide engineering applications. This is because of their lightweight and are resistant to corrosion among others. However, the amount of plastic waste generated every day produces a significant environmental threat. There is therefore a need to convert plastic wastes into useful products using thermochemical techniques. Pyrolysis has been found a reliable method. However, to the best knowledge of the author, few pyrolysis batch reactor designs exist. During the study, attention was focused on designing and fabricating a prototype pyrolysis batch reactor. The reactor was made of mild steel with a capacity of $1.2x10^{-2} m^3$/batch of waste plastic. This was tested for five batches using 1000 g of LDPE plastics per batch. The temperature was maintained at 250, 350, and 450°C and at residence times of 40, 50, and 60 minutes. The test result showed that the highest amount of oil produced was 250 mL while the lowest amount of oil produced was 132 mL at 450°C and 250°C. The lowest char quantity produced was 450 g and the highest was 600 g at 450°C and 250°C respectively. The highest (19.28 %) conversion efficiency was achieved at 450°C whereas the lowest (10.18%) was obtained at 250°C. Similarly, the waste reduction efficiency of waste plastics in oil increased as the external heat temperature was increased with the highest value (55 %) obtained at 450°C and the lowest (40%) waste reduction value obtained at 250°C. The study showed that the pyrolysis reactor was found to be more operational and functional at 450°C and 60 minutes of temperature and residence time respectively.

Keywords: Pyrolysis Reactor, LDPE, Residence Time, Oil, Char

1. Introduction

Plastics are synthetic or semi-synthetic materials that have a wide range of applications including but not limited to construction, packaging, sports safety gear, medical field, electrical, and electronics among others [12]. Based on this wide applicability of plastics, there is no doubt that we can't spend a day without using a material made from plastics. No wonder, the global cumulative plastic production is forecast to grow from 9.2 billion tons as of 2017 to up to 34 billion tons by the year 2050 [14].

Besides this enormous usage and large quantities of plastics produced, plastics are non-biodegradable. In other words, it takes 500 years on average to completely biodegrade a single plastic bag according to the estimation. This has made plastic waste become a major issue, both on land and at sea leading to catastrophic effects on the ecosystem. Not only are landfills and sea an eyesore, but plastics release toxins and greenhouse gasses into the earth and air which are a tremendous threat to the environment.

Admittedly, there is a dire need to urgently 'turn off the tap' regarding virgin plastics production, reduce quantities of uncontrolled or mismanaged plastic wastes disposed of poorly to the oceans, and increase rates of plastic waste recycling, estimated to be below 10%. Plastic waste recycling techniques such as pyrolysis, chemical recycling, plastic combustion in incinerators, and gasification have been employed. Among the recycling techniques, pyrolysis does not generate harmful pollutants, and the by-products can be used as fuel.

However, the pyrolysis process does not generate harmful pollutants, and the by-products are used as alternative fuels because of their high calorific value and can be used directly in vehicles and for heat utilization if combusted [8]. The pyrolysis process has been carried out in different types of reactors in most research studies but the design of these reactors is still lacking. Therefore, during this study, an effort was vested in designing and fabricating a prototype pyrolysis batch reactor that was tested and implemented in carrying out all the experiments because the batch reactor is simple to fabricate and operate for a pilot scale [13].

2. Objectives

2.1. General Objective

To design and fabricate a prototype pyrolysis batch reactor to produce oil from plastic wastes.

2.2. Specific Objectives

1) To determine the effect of temperature on oil yield and char production.
2) To determine the effect of residence time on conversion and waste reduction efficiency.

3. Scope

This study was conducted for nine (9) months using Low-Density Polyethylene (LDPE) as the test material. This is because LDPE is easily available. The materials were collected from down Banda (Kasenyi), cleaned, and taken to Nelcon Plastics, Bweyogerere for shredding. The reactor was fabricated from the Nabisunsa stage welding station, in Kampala. The quantities of oil and char were weighed and measured by the Uganda Industrial Research Institute (UIRI).

4. Literature Review

Aswan et al. [1] re-designed a pyrolysis reactor prototype to carry out the pyrolysis conversion of plastic wastes to liquid fuels. The authors designed a pyrolysis reactor that was 360mm high, 310mm in diameter, and with a capacity of 5 kg. A 200-400°C temperature interval and a range of 40-90 minutes were employed to carry out the tests. It was reported that the 86.40% liquid yield was the best at 350°C and after 90 minutes. The authors continued to carry out ASTM distillation studies on the produced oil and it showed that 67% fraction was in the range of light naphtha, 12% fraction was in the range of heavy naphtha, and 21% fraction in the range of medium naphtha. It was concluded that the physio-chemical study of all the fractions has either the properties of gasoline, kerosene, or diesel oil, and the hydrocarbons were mainly paraffinic and olefinic while some aromatic hydrocarbons were also detected but with no significant concentration.

Similarly, Istoto et al. [2] employed pyrolysis methods using HPDE and LDPE plastic waste as feedstocks to produce liquid fuels. The authors carried out the production method of pyrolysis at temperatures of 450-621°C without a catalyst. The results obtained from the experiments indicated that from 5 kg of HPDE plastic waste, 3.25 liters of naphtha, 0.85 liters of gasoline, 0.325 liters of diesel fuel, and 18.06 grams of residues were obtained. The results further indicated that 5 kg of LDPE yielded 0.5 liters of naphtha, 2.9 liters of gasoline, 0.1 liters of diesel fuel, and 19 grams of residue. The conclusions from the study were that the composition of fuels from polyethylene pyrolysis were naphtha, gasoline, and residues.

Salih et al. [3] designed and fabricated a pyrolysis unit to process 2 kg of waste plastic. The authors obtained a noticeable amount of liquid hydrocarbons alongside gaseous products. The authors concluded that it's possible to produce fuel from plastic waste through pyrolysis.

Jayswal et al. [4] designed, fabricated, and tested a waste plastic pyrolysis plant. The authors designed and modeled a plant in 3D CAD software, SolidWorks, and a batch reactor was used to pyrolyze LDPE at a reactor base temperature of approximately 600°C, and the vapor produced was directed to a horizontal, counter-flow shell and tube condenser to be condensed into oil. It was reported that factors like the plastic type, the cracking temperature, rate of heating, operation pressure of reactor, type of reactor, residence time, use of catalyst, etc. have significant effects on oil yield. It was further reported that a feedstock of 10 kg of plastics produced 6.63 liters of pyrolysis oil and 2.236 kg of char consuming at least 3.169 kg of LPG gas.

Aditya et al. [5] designed a simple pyrolysis reactor for converting plastic wastes to liquid fuel using biomass pellets as a source of heat. The authors fabricated a pyrolysis reactor from a used-refrigerant steel tank with a wall thickness of about 2mm and employed a forced convection by an electric blower which helped them obtain an overall temperature of 412°C. The reactor dimensions were 35 cm wide and about 75 cm height with a capacity of 3 kg of waste plastic per run. The authors used PET-type plastics as their feedstock and they found out that the fuel obtained had the characteristics approaching that of the commercial fuel with a specific gravity of 0.776 and heating value of 46 MJ/kg.

Shukla et al. [6] designed a viable machine for converting waste plastics to mixed oil to be used for domestic purposes. The authors used a machine made of stainless steel, a temperature-controlling electric heater, a K-type thermocouple for temperature measurement, a gasket for providing the mechanical seal and filling spaces between two surfaces, and insulating materials to control heat loss. The reactor design was obtained by using CAD software. The authors obtained mixed oil, hydrocarbon gas, and carbon black charcoal using mixed plastics as the feedstock which did not include PET and PVC. The authors found out that plastics were converted to lighter fractions at 425°C in the presence of zeolite catalysts even at a lower residence time of 30 minutes.

Pranay et al. [7] designed and fabricated a machine that was used for the extraction of base oil from plastics. The authors designed a machine that comprised the reactor assembly, condensing chamber, vapor line assembly, and water collecting unit. The reactor wall thickness was 5mm and the heater capacity of 2KW. The authors concluded that the products from this pyrolysis process are oil, hydrocarbon gases, and carbon charcoal or char. From their experimental readings, the weight of char decreased with an increase in residence time. Furthermore, the volume of oil increased with an increase in residence time.

Firke et al. [9] designed and fabricated a pyrolysis unit made from stainless steel that was used to generate fuel from plastic waste. The authors highlighted that simple thermal degradation ranged from 120 to 400°C temperatures. Further conclusions on the study showed that each of the liquid products obtained had low sulfur levels but varied from each other. Also, mixed plastics give a higher yield of fuel than if a certain type of plastic is pyrolyzed independently.

Zhang et al. [10] produced liquid fuels by pyrolysis of plastics in a rotary kiln at 500°C. The authors investigated the filling ratios (0%, 5%, 10%, 15%, and 20%) of heat carriers and the different types of waste plastics on the product spectrum. The authors found the suitable filling ratio of heat carriers for maximum oil production as 15% and liquid oils generated from a mixture of waste plastics were in the gasoline range with a percentage of 89.1%. The authors also highlighted that loading the heat carrier with more plastic waste in the rotary kiln favored the production of olefins and paraffin.

Babajo et al. [15] designed and fabricated a fixed bed co-pyrolysis system that was used to generate liquid fuel from the combination of Jatropha and polystyrene waste. The authors stated that the main part of their co-pyrolysis system was a rector and a condenser and selected a polystyrene type of plastic as their feedstock. The authors also employed a thermocouple as their temperature sensor and a temperature controller to control the temperature from the electric heater. They carried out experiments at temperatures of 450°C, 500°C, and 550°C with a heating rate of 20°C min^{-1} until the reaction reached its completion which was after 30 minutes. The authors found that feed ratio, temperature, and reaction time are the main parameters influencing oil yield.

5. Methodology

5.1. Design Dimensions of a Batch Pyrolysis Reactor

Simulating a Pyrolysis Process

Aspen Hysys V11 simulator was used to simulate polyethylene pyrolysis. The simulation helped in the determination of the dimensions of the reactor as shown in Table 1. The reactor wall thickness was determined from mathematical modeling.

The reactant and product streams were selected from the property environment and added to the component list based on the equation below.

$$35C_2H_4 \longrightarrow H_2+CH_4+C_2H_6+C_2H_4+C_3H_6+C_3H_8+C_4H_{10}+C_8H_{16}+C_{16}H_{32}+C_{28}H_{56}+5C$$

The following components namely; Ethylene, Propylene, styrene, Methane, Ethane, Carbon, Hydrogen, n-Butane, Propane, Cyclopropane, n-Pcycpentan, 1-Hexadecene were selected.

The Peng-Robinson model was implemented to estimate the physical properties of each component.

The process flow diagram (PFD) was developed by picking the parts of the conversion reactor (batch pyrolysis reactor) from the simulator's palette and properly connecting the input and output. The conversion reactor (batch pyrolysis reactor) was picked from the palette's column section. After the flow sheet has been developed, a mass flow rate of 1 kg of plastic waste/hr. was used to simulate it at the optimum temperature of 450°C and 1 atm pressure as the feed to the pyrolysis batch reactor. The top of the pyrolysis batch reactor contained an exit pipe which was employed as a condensing tube to cool the vapor-liquid fraction containing oil whereas; char residue was removed from the bottom of the pyrolysis batch reactor.

This procedure generated the pyrolysis batch reactor dimensions of diameter, height, and volume.

5.2. Experimental Procedure

Plastic wastes were collected, washed, dried then cut into small pieces for easy pyrolysis. 1000 g of shredded plastics was placed into the reactor and heated up to temperatures of 250, 350, and 450°C in the reactor for a residence time of 1 hour. On to the pyrolysis reactor a temperature regulatory system consisting of a thermocouple, contactor, and a temperature controller was set up for setting the different desired temperatures.

The vapors coming from the reactor were condensed employing air and steel condensing pipe to form a condensate or oil.

The condensed liquid fuel from the condensing tube was collected in the fuel collection bottle and measured.

5.3. Determination of the Effect of Temperature on the Amount of Oil Yield and Char Production

1000 g of plastic waste for each of the 3 batches in the reactor was heated at different temperatures of 250, 350, and 450°C while maintaining the residence time of 1 hour.

The temperature was varied employing a contactor and temperature controller. The required temperature was set on the temperature controller and the contactor kept switching on and off in case the temperatures went below or above the set value respectively and the amount of liquid fuel and quantity of char produced at different temperatures were weighed.

5.4. Determination of the Effect of Residence Time on Oil Yield and Char Production

1000 g of shredded plastic waste for each of the 3 batches was heated at 450°C in a batch reactor at different residence times of 40, 50, and 60 minutes. A temperature of 450°C was set on the temperature controller and the contactor kept switching on and off in case the temperatures went below or above the set value respectively and the amount of liquid fuel and quantity of char produced at different residence times were weighed.

6. Results and Discussion

6.1. Batch Pyrolysis Reactor Design Dimensions and Assembly

After sizing the reactor with the given conditions, the dimensions were obtained and presented in Table 1. The batch reactor was assembled as indicated in Figure 1.

Table 1. *Design dimensions of a batch pyrolysis reactor.*

Conversion reactor dimensions	
Parameters	**Cylinder vessel sizing**
Height (m)	0.3252
Diameter (m)	0.2168
Volume (m^3)	1.20E-02
Reactor thickness (mm)	
Wall	2
Ellipsoidal head	2

The rector dimensions obtained from the Aspen Hysys V11 simulator were; diameter (0.2168 m), height (0.3252 m), and volume of 1.20E-02 m^3 for the cylinder vessel. The reactor wall thickness was 2 mm, and an ellipsoidal head of 2 mm (Table 1).

Figure 1. *Complete assembly of the reactor and condensing system from the Nabisunsa stage welding station.*

6.2. Impact of Varying Temperatures on Oil and Char Production

Oil and char amounts produced from LDPE waste plastic pyrolysis at varying temperatures of external heat supplies are presented in Table 2.

Table 2. *Amount of oil and char produced at different temperatures.*

Temperature (C)	Quantity of oil (ml)	Weight of oil (g)	Quantity of char (g)
	132	101.772	600
	180	138.78	520
450	250	192.75	450

At 250°C of external heat supplied to the reactor, 132 mL (101.772 g) of oil was produced while the amount of char produced was 600 g. At 350°C, the amount of oil yield was 180 mL (138.78 g), and 520 g of char was produced (Table 2). The amount of oil produced at 450°C was 250 mL (192.75 g) and the char quantity produced at this temperature was 450 g (Table 2).

The highest amount of oil produced was 250 mL while the lowest amount of oil produced was 132 mL at 450°C and 250°C (Table 2). The lowest char quantity produced was 450 g and the highest was 600 g at 450 and 250°C.

6.3. Effect of Temperature on Conversion Efficiency and Waste Reduction Efficiency

As indicated in Figure 2, the conversion efficiency of oil from waste plastic increased with an increase in the amount of external heat temperature supplied to the reactor. The highest (19.28%) conversion efficiency was achieved at 450°C whereas the lowest (10.18 %) was obtained at 250°C. Similarly, the waste reduction efficiency of waste plastics in oil increased as the external heat temperature was increased with the highest value (55%) obtained at 450°C and the lowest (40%) waste reduction value obtained at 250°C.

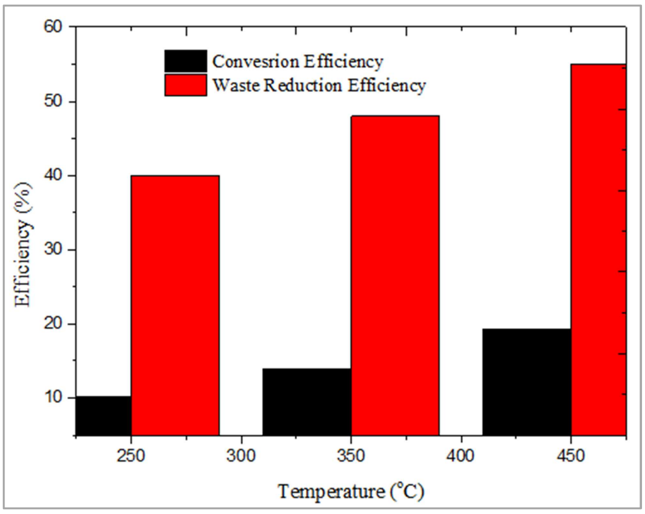

Figure 2. *Effect of temperature on conversion efficiency and waste reduction efficiency.*

Based on the study conducted by Rapsing [11], the pyrolysis reactor had a 78.1% conversion efficiency at 500°C which is not in agreement with the current study where our maximum conversion efficiency obtained at 450°C was 19.28% which is quite lower at relatively the same temperature of external heat supply.

As a result of The current study, it doesn't agree with Rapsing [11] who reported the equipment to have shown 94.3% waste reduction efficiency at 500°C.

The increase in the conversion efficiency and waste reduction efficiency with an increase in the temperature of external heat supplied shows that these two parameters are dependent on the amount of heat supplied to the reactor during the pyrolysis process.

6.4. The Effect of Residence Time on Oil Yield and Char Production

Table 3. *Amount of oil and char produced at a varying residence time.*

Time (Minutes)	Oil quantity produced (ml)	Quantity of oil by weight (g)	Char quantity produced (g)
40	185	142.635	512
50	210	161.91	480
60	250	192.75	450

The highest oil amount produced was 250 mL (192.75 g) while the lowest was 185 mL (142.635 g) at a residence time of 60 and 40 minutes respectively as shown in Table 3. The highest char quantity (512 g) was produced at 40 minutes of residence time while the lowest was 450 g produced at 60 minutes of residence time.

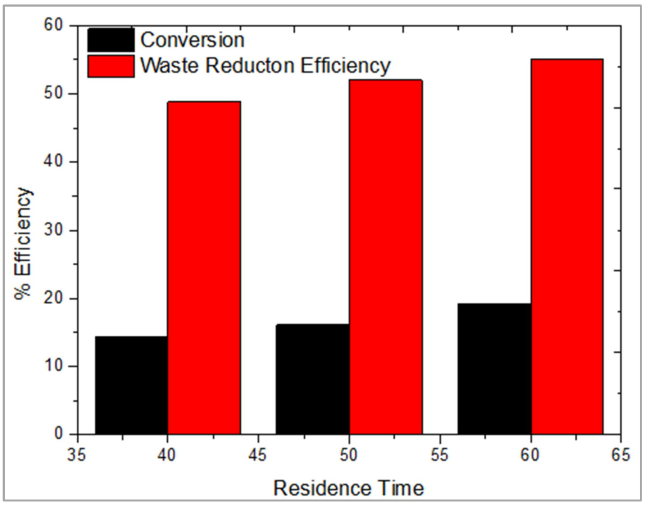

Figure 3. *Effect of residence time on conversion efficiency and waste reduction efficiency.*

The number of plastics converted to oil was lowest at 40 minutes while it was highest at 60 minutes of residence time. The waste reduction efficiency was highest (55 %) at 60 minutes and lowest (48.8 %) at 40 minutes (Figure 3).

The present study results do agree with Aswan et al. [1] who found out that the 86.40% liquid yield was obtained after 90 minutes.

The results indicated that the quantity of waste plastics converted to oil is dependent on the residence time. The higher the residence time, the more the pyrolysis reaction will take place effectively and efficiently to achieve a complete reaction for more oil yield and high waste reduction efficiency.

7. Conclusion

Based on the outcome of the study, the batch pyrolysis reactor was found to be more operational and functional at 450°C and 60 minutes of temperature and residence time respectively. The pyrolysis batch reactor garnered a considerable waste reduction efficiency and a reasonable conversion efficiency using LDPE as a feedstock.

8. Recommendations

The design and performance of the pyrolysis batch reactor were a success. Despite the considerable waste reduction efficiency and conversion efficiency, the design and performance of the pyrolysis batch reactor were not very effective and the following recommendations are suggested:

1) The capacity of the batch pyrolysis reactor should be increased to accommodate more amount of feedstock and preferably stainless steel should be used in the fabrication of the reactor to withstand a higher temperature and prolong the reactor lifespan.
2) Other types of waste plastic feedstock should be used to further study the performance of the reactor.
3) The chemical and physical properties of the produced oil from LDPE and other types of plastic should be fully analyzed to establish its potential practical applications.
4) Upgrading and pilot testing of the pyrolysis batch reactor should be conducted to validate the economic and environmental benefits that the community can gain from it.

Appendix

Pyrolysis reactor, condensing tube, and temperature controlling system.

Figure 4. *A complete setup of a pyrolysis reactor and a temperature-controlling system.*

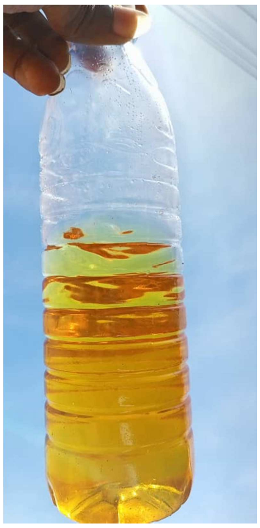

Figure 5. *A sample of oil was obtained from the experiment.*

References

[1] A. Aswan, I. Rusnadi, Fatria, Zurohaina, and R. Daniar, "Re-Design Pyrolysis Reactor Prototype for the Conversion of Plastic Waste into Liquid Fuel," *J. Phys. Conf. Ser.*, vol. 1500, no. 1, 2020.

[2] E. H. Istoto, Widayat, and S. Saptadi, "Production of Fuels from HDPE and LDPE Plastic Waste via Pyrolysis Methods," *E3S Web Conf.*, vol. 125, no. 201 9, pp. 9–12, 2019.

[3] M. Salih, R. Muhammed, R. P. Tms, K. Ct, M. Mk, and F. Poolakkal, "Design and Fabrication of Pyrolysis Unit," *Int. J. Innov. Sci. Res. Technol.*, vol. 3, no. 5, pp. 799–801, 2018.

[4] A. Jayswal, A. Kumar, P. Pradhananga, S. Rohit, and H. Bahadur, "Design, Fabrication and Testing of Waste Plastic Pyrolysis Plant," *Proc. IOE Grad. Conf.*, vol. 5, no. July 2018, pp. 275–282, 2017.

[5] K. Aditya, "Designed a Simple Pyrolysis Reactor for Plastic Waste Conversion into Liquid Fuel using Biomass as Heating Source," 2020, ISSN: 1410-394X.

[6] Y. Shukla, H. Singh, S. Sonkar and D. Kumar, "Design of Viable Machine to Convert Waste Plastic into Mixed Oil for Domestic Purpose," International Journal of Engineering Research and Development, E-ISSN: 2278-067X, P-ISSN: 2278-800X, Volume 12, April 2016, pp. 09-14.

[7] D. Pranay, S. Satpute, S. Ganver, and T. Mate, "Design and Fabrication of Machine to Extract Base Oil from Plastic," 2017, Volume 3, IJARIIE-ISSN(0)-2395-4396.

[8] Suhartono, K. Priyono, R. Ate, A. Iqbal, and Y. Muhamad, "Fuel Oil from Municipal Plastic Waste through Pyrolysis with and without Natural Zeolite as Catalysts," E3S Web of Conferences 73, 01021, pp 1-6, 2018.

[9] M. Firke, "Design and Fabrication of Pyrolysis Unit for Generation of Fuel from Plastic Waste," International Journal of Future Generation Communication and Networking, Vol. 13, No. 2s, 2020, Pp. 769–779, ISSN: 2233-7857 IJFGCN Copyright ©2020 SERSC 769.

[10] Y. Zhang, Y. Wang, and A. Li, "Liquid Oils Produced from Pyrolysis of Plastic Wastes with Heat Carrier in Rotary Kiln." Fuel Processing Technology, 2020.

[11] E. C. Rapsing, "Design and Fabrication of Waste Plastic Oil Converter," vol. 4, no. 2, pp. 69–77, 2016.

[12] C. Abhishek, B. Lohithkumar, I. Ahamed, R. Praveena and M. Amruth, "Waste Plastic Pyrolysis Oil Alternative Fuel for an IC Engine," International Journal of Engineering Research & Technology, ISSN: 2278-0181, pp 1-7, 2019.

[13] M. Aziz, R. Al-khulaidi and M. Rashid, "Design and Fabrication of a Fixed-bed Batch Type Pyrolysis Reactor for Pilot Scale Pyrolytic Oil Production in Bangladesh," IOP Conference Series: Materials Science and Engineering, 184 (2017) 012056.

[14] R. Geyer, J. Jenna, and L. Kara, "Production, Use, and Fate of All Plastics Ever Made," DOI: 10.1126/sciadv.1700782, ISSN 2375-2548, pp. 1-6, 2017.

[15] S. Babajo, J. Enaburekhan, and I. Rufa, "Design, Fabrication and Performance Study of Co-Pyrolysis System for Production of Liquid Fuel from Jatropha Cake with Polystyrene Waste," vol. 25 (3) 407-414, pp. 1-8, March 2021.