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Experimental study of fuel characteristics from plastic waste (HDPE and PP) using the pyrolysis process

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ABSTRACT *This research was conducted to determine the effect of the type of plastic (HDPE and PP) and the effect of varying the diameter of the heat exchanger (1/2-inch, ¾-inch, and 1-inch) on the physical properties of fuel using pyrolysis process. Plastic waste is one of the environmental pollution materials on a global scale, especially in Indonesia, because plastic waste is difficult to decompose in the soil. One way to overcome this is by recycling plastic waste. However, this method is not very effective ; only about a few percent can be recycled, and the rest ends up in landfills. Another way to do this is to use plastic waste to process it into fuel using a pyrolysis process. From the test results, the density and viscosity of the resulting fuel decrease as the heat exchanger diameter increases. PP plastic produces fuel that has a lower density and viscosity but has a higher calorific value than HDPE. Generally, the physical properties of fuel produced from the pyrolysis process of plastic waste are close to the physical properties of gasoline.*

Keywords: *fuel, pyrolysis, plastic, waste, physical properties.*

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I. INTRODUCTION

To address the extensive environmental pollution due to plastic waste, which remains a global issue notably severe in Indonesia because of its slow decomposition in soil, various methods have been considered. One such approach involves recycling plastic waste, as advocated by the Mataram City Cleaning Department (2012). However, research suggests that this recycling method, as indicated by Santoso in 2010, is not as efficient as desired (Alit et al, 2024), resulting in only a fraction of the plastic being recycled (Santoso, 2010), with the majority accumulating in landfills. An alternative solution proposed by Kadir (2012) involves transforming plastic waste into fuel oil through a pyrolysis process.

One type of waste often encountered is plastic waste, which sees increased usage alongside the growth of industries and consumers. Plastic waste management is crucial to preserve environmental equilibrium (Kurniawan and Nasrun, 2014). According to data from the Mataram City Cleaning Service (2012), the waste generation in Mataram City rises annually in line with population growth. Daily waste production stands at 1,287 m3, yet the city's cleaning service can only handle 832 m3/day. This signifies that the government manages just 64.6% of the waste daily, with the remaining 35.4% addressed through additional operational policies. Moreover, some waste is directly eliminated by the community.

Plastic has many advantages over other materials. In general, plastic has a low density, is electrically insulating, has varying mechanical strength, limited temperature resistance, and varying chemical resistance (Wahyudi, 2001). Plastic is also light, easy to design, and cheap to manufacture (Alfiando et al, 2019). Efforts to create alternative energy include converting plastic waste into fuel to replace fossil fuels (Ahmad, 2022). Since plastic originates from petroleum derivatives, during decomposition, it can be returned to hydrocarbons as a basic energy material (Nuryosuwito et al, 2020). The process of recycling plastic waste aims to convert long chain hydrocarbon polymers into shorter chains for use as raw materials in the chemical industry or fuel production.

Okariawan, et al (2011), conducted research on the conversion of used oil into fuel oil using a thermal cracking process at varying heating temperatures and heat exchanger diameters. In the process of making fuel oil from used oil, the thermal cracking process is most effective at temperatures above 300 ^{o}C. From 1000 ml of used oil, an average of 90% is fuel oil and 10% is sediment. Furthermore, physical characteristic testing of the fuel from used oil revealed that the characteristics closest to diesel specifications were found in the oil produced at a heat exchanger diameter of 3/4 inch at a heating temperature of 300 ^{o}C.

Plastic is a polymer that has unique and extraordinary properties. A polymer is a material consisting of molecular units called monomers (Novarini et al, 2021). If the monomers are the same it is called a homopolymer, and if the monomers are different it results in a copolymer. Plastic can be divided into two types, namely thermoset plastic and thermoplastic plastic. Thermoset plastic is a plastic that cannot be recycled because the polymer composition is in the form of a three-dimensional network (Jahiding et al, 2020). Examples are PU (Poly Urethene), UF (Urea Formaldehyde), MF (Melamine Formaldehyde), polyester, epoxy, and so on. Meanwhile, thermoplastic plastic is plastic that can be molded repeatedly in the presence of heat. Thermoplastic plastics include PP, PE, PS, ABS, SAN, nylon, PET, BPT, Polyacetal (POM), PC, cetal (POM), PC, and so on (Harper, 2000).

Polyethylene is a polymer material with stable chemical properties, resistant to various chemicals except halides and strong oxides. PE is typically white, translucent, and has a density ranging from 0.91 to 0.97 gr/cm3 (Erlangga et al, 2023). This material is produced by polymerizing ethylene gas derived from petroleum hydrogen gas added to the breakdown of oil (naphtha), natural gas, or acetylene. Polyethylene is categorized based on its density (Mujiarto, 2005). High-density polyethylene (HDPE) is a thermoplastic form dependent on petroleum, requiring 1.75 kg of petroleum to produce 1 kg of HDPE. HDPE exhibits a density of 0.95-0.97 gr/cm3 and is notably crystalline (90% crystallinity) (Erlangga et al, 2023). Commonly employed in various products and packaging like milk bottles, detergent containers, and water pipes, HDPE is a versatile material (Harper et al, 2003). On the other hand, low-density polyethylene (LDPE) possesses a density of 0.92 gr/cm3 with a melting temperature of 105^{o}C (Erlangga et al, 2023).

Polypropylene, a plastic akin to polyethylene, exhibits enhanced physical strength owing to its lower density (Adoe et al, 2016). This lightweight material has a density of 0.900-0.915 g/cm3 (Erlangga et al, 2023). Polypropylene molecules feature tertiary carbon atoms with main chain methyl groups, where the hydrogen atom linked to a tertiary carbon atom readily reacts with oxygen and ozone, culminating in lower oxidation resistance compared to polyethylene (Panda, 2011).

The conversion of plastic waste into fuel oil, involving tertiary recycling, as noted by Sari (2017), can be accomplished through a cracking process (Rodiansono et al, 2007; Okariawan et al, 2011). The cracking process entails breaking down polymer chains into compounds with reduced molecular weights, yielding products utilized as chemicals or fuel.

II. MATERIAL AND METHODS

In this study, HDPE/P1 plastic waste (from oil bottles) and PP/P2 plastic waste (from drinking water bottles) were the materials utilized. The plastic waste underwent cleaning, cutting into segments, drying, and weighing (1 kg per fuel oil production process) before processing. The research methodology involved an experimental approach, including the construction of pyrolysis equipment and the evaluation of equipment performance by altering the heat exchanger diameter and plastic waste type. Subsequently, tests were conducted on the physical properties of the resulting fuel oil for comparison with standard diesel or gasoline, as well as fuel oil derived from other plastic waste sources.

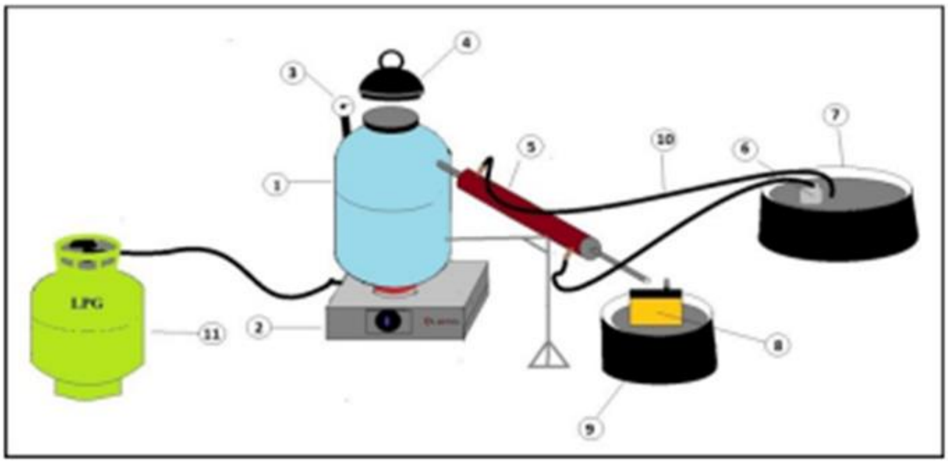

Figure 1. Pyrolysis apparatus; 1 Pyrolysis reactor 2. Heater 3. Thermometer 4. Cover 5. Heat exchanger 6. Pump, 7. Cooling media 8. Condensate reservoir 9. Condensate cooler reservoir 10. Hose 11. LPG fuel.

This research was conducted in two stages. The first stage involved producing fuel oil from plastic waste using a device designed with various types of plastic and different heat exchanger diameters. The plastic waste used in this research came from two different types of plastic: high-density polyethylene (HDPE/P1) oil bottles and polypropylene (PP/P2) drinking water bottles. The heat exchanger diameters varied as follows: D1 = 1/2 inch, D2 = 3/4 inch, and D3 = 1 inch. The second stage focused on studying the physical properties of the produced fuel oil. The fuel oil production process was carried out three times for each type of plastic and each heat exchanger diameter variation. During the production process, each type of plastic was placed into the reactor with a mass of 1 kg. Since the density of P2 is lower than that of P1, P2 filled the reactor space more fully.

Figure 2. Fuel resulting from the pyrolysis process

III. RESULTS

This fuel manufacturing process was carried out three times for each type of plastic and each variation in heat exchanger diameter. During the fuel production, each type of plastic was placed into the reactor with a mass of 1 kg. Data on the manufacturing results, including fuel density, were obtained and are presented in Table 1 below.

Table 1. Density of fuel

Sample	Density (kg/m^3)	Sample	Density (kg/m^3)
	773.0		765.0
P1D1	776.7	P2D1	766.0
	772.0		765.7
Average	**773.9**	**Average**	**765.6**
	770.0		758.0
P1D2	769.0	P2D2	759.0
	772.7		759.7
Average	**770.6**	**Average**	**758.9**
	749.0		731.0
P1D3	748.0	P2D3	732.0
	750.0		734.0
Average	**749.0**	**Average**	**732.3**

The highest fuel density is produced by the HDPE pyrolysis process at a heat exchanger diameter of 1/2 inch (P1D1), with an average value of 773.9 kg/m^3 and the lowest at a heat exchanger diameter of 1 inch (P1D3), with an average value -average of 749.0 kg/m^3. Meanwhile, the highest fuel density is produced by the PP pyrolysis process at a heat exchanger diameter of 1/2 inch (P2D1), with an average value of 765.6 kg/m^3 and the lowest at a heat exchanger diameter of 1 inch (P2D3), with the average value is 732.3 kg/m^3. It should be noted that these values are averages, and variations may occur depending on the conditions of the pyrolysis process and the type of plastic used. The pyrolysis process converts plastic waste into fuel oil, and further understanding of the characteristics of pyrolysis oil can help in further use and utilization.

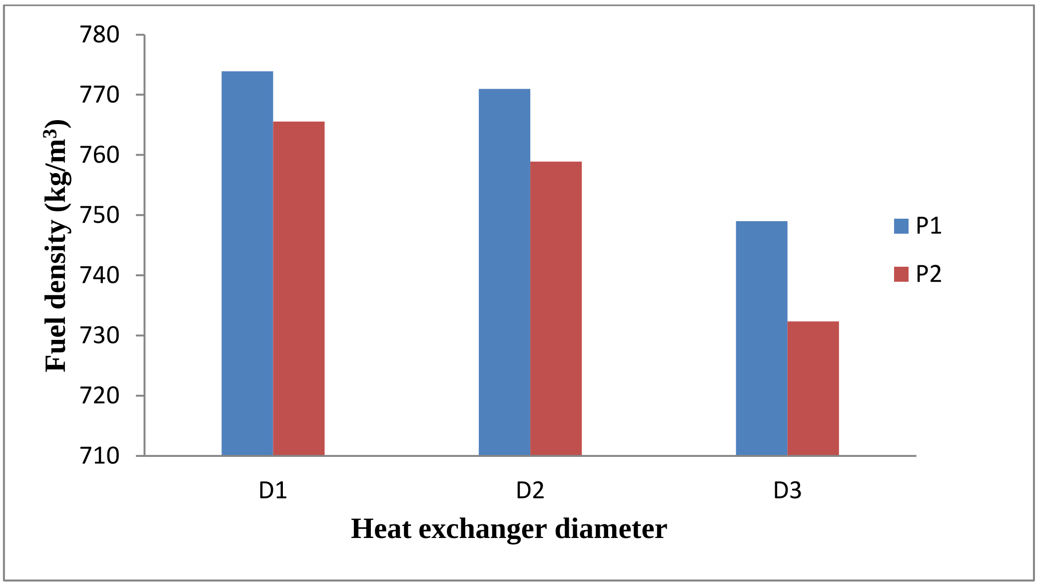

Figure 3. Relationship between plastic waste type and heat exchanger diameter on fuel density

The density of fuel resulting from the pyrolysis process of PP plastic (P2) tends to produce fuel with a lower density compared to the density of fuel from HDPE plastic (P1). In addition, increasing the diameter of the heat exchanger tends to produce fuel with a lower density. The density of the fuel produced can be determined by comparing the mass of the fuel with the volume of fuel resulting from the pyrolysis process. The highest fuel density value was produced by the HDPE pyrolysis process with a heat exchanger diameter of 1/2 inch (P1D1), with an average value of 773.9 kg/m^3 and the lowest was with a heat exchanger diameter of 1 inch (P1D3), with a value of an average of 749.0 kg/m^3. Meanwhile, the highest fuel density value was produced by the PP pyrolysis process at a heat exchanger diameter of 1/2 inch (P2D1), with an average value of 765.6 kg/m^3 and the lowest at a heat exchanger diameter of 1 inch (P2D3), with an average value of 732.3 kg/m^3.

In general, the density of the fuel produced is smaller than the base material (plastic type). The lower the density of the material used, the lower the density of the fuel produced. The density value of the fuel oil produced is closely related to the reactor temperature during the process of making fuel from plastic waste. The higher the reactor temperature, the higher the density of the fuel produced. Meanwhile, the lower the reactor temperature, the lower the density of the oil produced. HDPE has a longer and more complex polymer chain structure compared to PP polymer chains which tend to be shorter and simpler, so that during the pyrolysis process HDPE produces oil with a higher density than PP. So, differences in molecular structure and operating temperature during pyrolysis affect the density of the oil produced. HDPE produces higher density oil due to the complexity of its molecules

Santoso (2010) carried out tests on the properties of pyrolysis fuel and performance tests on stoves fueled with pyrolysis oil from plastic waste. From this research, the properties of the pyrolysis fuel tested included density, viscosity and heating value. The average density value for PP plastic is 727.5 kg/m^3 and the average density value for LDPE plastic is 755.0 kg/m^3.

Table 2. Viscosity of fuel

Sample	Viscosity (mPa.s)	Sample	Viscosity (mPa.s)
	1.44		1.32
P1D1	1.44	P2D1	1.24
	1.44		1.24
Average	**1.44**	**Average**	**1.27**
	1.40		1.20
P1D2	1.40	P2D2	1.16
	1.40		1.20
Average	**1.40**	**Average**	**1.19**
	1.24		1.19
P1D3	1.36	P2D3	1.04
	1.24		1.16
Average	1.28	**Average**	**1.13**

In viscosity testing, data is taken at the end of the research process by measuring the viscosity value where the viscosity value is the force required to move a plane of a certain area at a certain distance and within a certain time. The tool used is a Brookfield viscometer with spindle number 2 (spindle number 0.2 on the tool), spindle speed 100 rpm and dial reading torque 10%. Fuel viscosity data was collected three times for each type of plastic and variation in heat exchanger diameter and then the average was taken. The highest fuel viscosity value from HDPE plastic was found to be an average of 1.44 mPa.s with a hear exchanger diameter of ½ inch (P1D1), while the lowest viscosity was an average of 1.28 mPa.s with a hear exchanger diameter of 1 inch (P1D3). The highest viscosity value for fuel from PP plastic was obtained at 1.27 mPa.s at a heat exchanger diameter of ½ inch (P2D1) and the lowest viscosity value on average was 1.13 mPa.s at a heat exchanger diameter of 1 inch (P2D3).

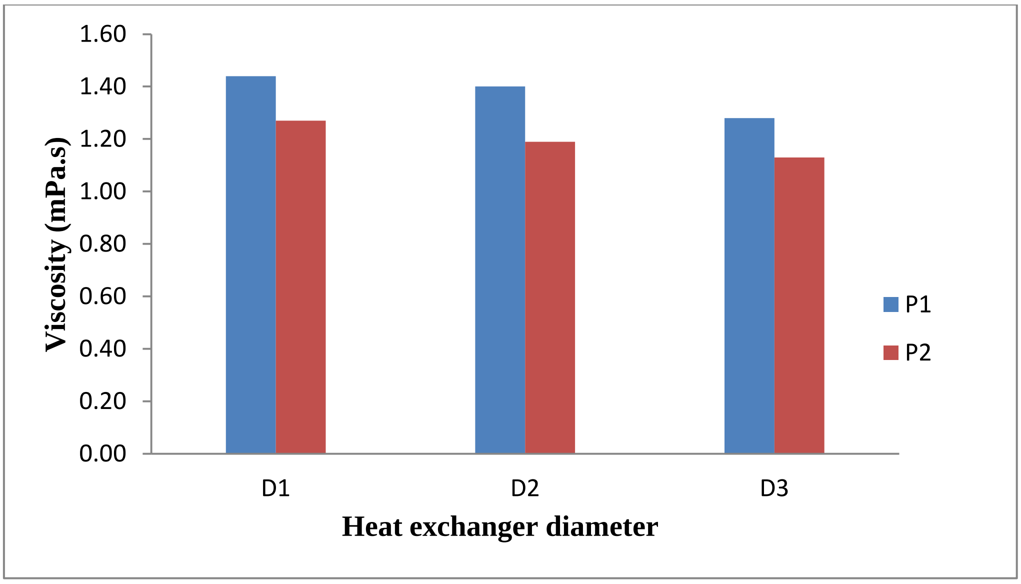

Figure 4. The relationship between the type of plastic and the diameter of the heat exchanger on the viscosity of fuel from plastic waste.

Figure 4 shows the average value of fuel viscosity for each type of plastic and variations in heat exchanger diameter. The highest viscosity values were obtained from the pyrolysis process of HDPE (P1) and PP plastic (P2) when using a heat exchanger diameter of 1/2 inch, namely 1.44 mPa.s and 1.27 mPa.s respectively. Meanwhile, the smallest average viscosity values of the HDPE (P1) and PP plastic (P2) pyrolysis processes when using a heat exchanger diameter of 1 inch are respectively 1.28 mPa.s and 1.13 mPa.s. It can be seen that the viscosity of the fuel produced in each type of plastic has a similar trend, namely decreasing as the heat exchanger diameter increases. On the other hand, fuel viscosity is influenced by the density of the fuel, where the higher the fuel density, the higher the viscosity. Meanwhile, the lower the density of the fuel, the lower the viscosity. PP plastic produces fuel with a slightly lower viscosity compared to HDPE. This difference can be caused by the molecular structure and chemical composition of each plastic (Mara and Nuarsa, 2024). PP has simpler and less branched polymer chains, so its pyrolysis fuel oil has a lower viscosity. HDPE, with its more complex molecular structure, produces a fuel with a slightly higher viscosity. This is also supported by research by Santoso (2010) where the average viscosity value for PP plastic types is lower than the average viscosity value for LDPE plastic types.

Table 3. The calorific value of fuel

Sample	Calorific value (cal/gr)	Sample	Calorific value (cal/gr)
	10735		10897
P1D1	10634	P2D1	10884
	10812		10888
Average	**10733**	**Average**	**10890**
	10855		10958
P1D2	10873	P2D2	10940
	10826		10938
Average	**10851**	**Average**	**10945**
	10983		11091
P1D3	10988	P2D3	11065
	10979		11031
Average	**10983**	**Average**	**11062**

In testing the calorific value, data was taken at the end of the research process using an IKA C200 digital bomb calorimeter. Data was collected three times for each type of plastic and variation in heat exchanger diameter and then the average was taken. Where the research results can be seen directly on the IKA C200 digital bomb calorimeter. The highest calorific value of fuel was obtained from HDPE pyrolysis, an average of 10983 cal/gr with a hear exchanger diameter of 1 inch (P1D3) and the lowest calorific value was obtained at a hear exchanger diameter of ½ inch (P1D1). Meanwhile, the highest calorific value of PP plastic pyrolysis fuel is an average of 11062 cal/gr at a heat exchanger diameter of 1 inch (P2D3) and the lowest calorific value is at a ½ inch diameter hear exchanger (P2D1), namely an average of 10890 cal/gr.

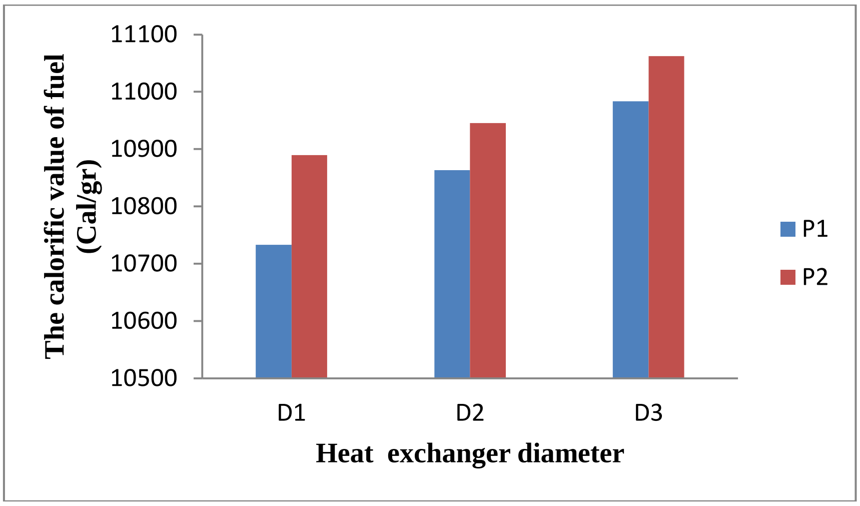

Figure 5. The relationship between the type of plastic and the diameter of the heat exchanger on the calorific value of fuel from plastic waste.

From Figure 5, it can be seen that the average fuel calorific value produced for HDPE plastic (P1) at heat exchanger diameters of 1/2 inch, 3/4 inch and 1 inch respectively is 10733 cal/gr, 10851 cal/gr. and 10983 cal/gr. Meanwhile, the average fuel calorific value produced for PP (P2) plastic type at heat exchanger diameters of 1/2 inch, 3/4 inch and 1 inch respectively is 10890 cal/gr, 10945 cal/gr and 11062 cal /gr. The difference in the calorific value of the fuel from the plastic waste studied is because the types of HDPE (P1) and PP (P2) plastic have different chemical contents and constituent elements so that the calorific value produced is also different.

The calorific value of fuel is related to the density of the fuel. It can be seen that the calorific value of the fuel produced for each type of plastic and variation in heat exchanger diameter has the same trend, namely increasing as the density value decreases. Because the calorific value of fuel oil is inversely proportional to its density. The higher the density of the fuel, the lower the calorific value. Meanwhile, the lower the density of the fuel, the higher the calorific value.The calorific value of a fuel refers to the amount of energy released when a known volume of gas is completely combusted. The calorific value of fuel is a measure of fuel quality. To measure the calorific value, a calorie bomb is used. This tool can determine how much heat energy the fuel produces during the combustion process. HDPE produces fuel with a fairly high calorific value. This heating value indicates how much energy can be released when HDPE oil burns completely. These values are averages, and variations may occur depending on the conditions of the pyrolysis process and the type of plastic used. The higher the calorific value, the more efficient the fuel is in producing energy. The calorific value of the fuel resulting from the pyrolysis process of HDPE waste (P1) is lower than plastic PP waste (P2).

The density, viscosity and heating value of PP plastic fuel in this study are slightly greater than the density, viscosity and heating value of fuel in research conducted by Alit et al (2024), Santoso (2010). This difference is caused by differences in the design of the research equipment used, especially in heat exchangers, Santoso (2010) used a helical tube type heat exchanger with temperature variations in the fuel manufacturing process of 300^oC-450^oC. Meanwhile, this research uses a tube and shell heat exchanger with variations in the diameter of the heat exchanger tube.

Based on the analysis carried out and comparing the physical properties of fuel from plastic waste with petrol and diesel fuel, in general it can be concluded that the physical properties of fuel from plastic waste are close to the physical properties of gasoline.

IV. DISCUSSION AND CONCLUSION

Based on the results and the discussion, it can be concluded that the physical properties of the fuel from each type of plastic, the density and viscosity of the fuel produced from the pyrolysis process decrease as the heat exchanger diameter increases. PP plastic produces fuel that has a lower density and viscosity but has a higher heating value than HDPE. The fuel produced from the pyrolysis process of plastic waste has physical properties that are close to gasoline specifications.

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