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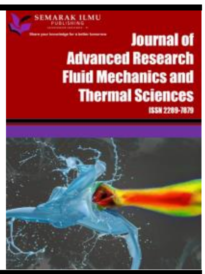

Potential of Pyrolytic Oil from Plastic Waste as an Alternative Fuel Through Thermal Cracking in Indonesia: A Mini Review to Fill the Gap of the Future Research

Janter Pangaduan Simanjuntak[1,*], Bisrul Hapis Tambunan[1], Junifa Layla Sihombing[2]

[1] Mechanical Engineering Department, Universitas Negeri Medan, Medan 20221, North Sumatera, Indonesia
[2] Natural Science Department, Universitas Negeri Medan, Medan 20221, North Sumatera, Indonesia

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ABSTRACT

This article aims to review the potential and feasibility of pyrolytic oil from plastic waste (POPW) as a substitution fuel for conventional fossil fuels. Pyrolytic oil can be generated from plastic waste through the thermal cracking process. In addition to overcoming the global plastic waste problem, recovering plastic waste into alternative fuels can also reduce the consumption of fossil-based fuels. The research on POPW production and utilization of internal combustion engines (ICE) was reviewed and discussed to determine their potential and suitability for fuel substitution. Currently, plastic materials can be easily found in various product packaging, ranging from food and beverage packaging to shopping bags and appliances. When they are no longer utilized, this plastic becomes garbage and will be very harmful to humans and the environment. Therefore, it needs a correct way to proceed and minimize the impact caused by plastic waste. In fact, there are seven types of plastic waste in the polymer groups that must be handled via the pyrolysis process to avoid plastic pollution. literature survey, research on POPW via the pyrolysis process, and its usage is thoroughly found to be booming and growing very rapidly. Co-pyrolysis is known to be the most potential and suitable way to produce high-quality POPW, which is suitable to be used to fuel the ICE and also the stationary industrial engine.

1. Introduction

Indonesia is one of the countries that deal with waste. Especially for the city of Medan with a waste product of nearly 2000 tons/day. When compared to Malaysia with a waste production of 49,670 t/day, Indonesia is a country with high waste production. Until now, the most preferred waste management is to throw it in a landfill. Both Indonesia and Malaysia consider this method to be the most cost-effective with a low level of pollution compared to the pollution caused by coal-fired power plants [1]. Of the total waste generated, plastic waste is the most.

* *Corresponding author.*
E-mail address: janterps@unimed.ac.id

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The utilization of plastic materials globally continues to grow because it has many advantages compared to other materials [2]. As a result, about 300 million tons of plastic are produced every year [3]. As a developing country, also uses lots of plastics, such as in the industrial sector, health, hospitality, and general use by the public. In the health sector, the use of plastic materials is very dominant. As evidenced during the COVID-19 pandemic, global medical waste made from plastic reached approximately 20.5 million tons [4]. After use, these materials are generally wasted as garbage, may be arbitrary or become an embarrassment in landfills, and frequently end up in the sea as marine debris, causing significant problems for marine organisms [5].

Indonesia, like the rest of the world, was dealing with a serious plastic waste problem. Reporting from several sources indicates that waste generation in Indonesia reaches 64 million tons per year, as much as 15% of which is plastic waste, and 5% is unprocessed and wasted in the sea. According to additional data, Indonesia produces 4.82 billion plastic bottles year and up to 10 billion plastic bags annually, or up to 85,000 tons of plastic bags, which are then released into the environment. This number puts Indonesia in second place as the country with the largest amount of plastic pollution in the sea after China [6]. This condition is getting worse due to the import of plastic waste required for industrial needs, where plastic waste imports in 2018 reached 320 thousand tons, an increase of up to 150% from the previous year. As a result, pollution due to plastic in Indonesia has increased and the quality of the environment will be threatened.

Due to undeveloped knowledge and technology, the handling of plastic waste has become very slow. If not handled properly, it is predicted that plastic waste in Indonesia will reach 12 billion tons by 2050. Evidently, the research proved that the waste that ends up in the sea is mostly plastic waste [7]. Another study conducted in 2019 also stated that of the total waste of 9 major cities studied in Indonesia, 14.6% was plastic waste [8].

In Indonesia, efforts to reduce the impact of plastic waste are still dominated by the 3R; reducing imports and plastic production; reuse, and recycling to be used as products of economic value. PT. Veolia Services Indonesia is a PET-type plastic recycling industry with a 25,000 tons/year capacity. This industry was built on the mandate of Law Number 3 of 2014 concerning Industry [9] and implemented through Government Regulation Number 14 of 2015 concerning the National Industrial Development Master Plan (RIPIN) of 2015–2035.

Waste processing in both household and industries are expected to be able to strengthen the implementation of the circular economy, which has just been implemented in Indonesia as has been done by Germany [10]. The principle of a circular economy is the reuse of residual consumer goods to maximize economic value to zero waste [11-12] and can support the government's efforts to overcome the problem of plastic waste in the sea by up to 70% by 2025. A theory related to the treatment of waste through combustion, where the thermal energy obtained can be stored for household hot water purposes [13]. According to research conducted by Nursyuhada *et al.,*[14] the method of burning waste is the most superior in waste management. However, this method only proceeds a small part of the amount of waste; most of it, including plastic waste, is still wasted, having a significant negative environmental impact.

Several countries in the world have tried to make plastic waste more valuable than throwing it into landfills or burning it to produce thermal energy because plastic has a low heating value similar to petroleum and even greater than coal. However, pollution and emissions that arise must be taken into account because plastic materials have more toxic content than fossil fuels and biomass, so that plastic combustion can be one of the treatment options for plastic waste [15]. A study reported that thermal energy of 6,348 kW/kg could be obtained from plastic waste through combustion [16]. However, during combustion, especially of PVC-type plastic, it also emits harmful substances into the air, such as carbon monoxide, dioxins and furans, volatiles, and other particles that are very dangerous for humans and the environment [17].

The pyrolysis method is currently the most effective way to manage plastic trash since it may generate chemicals and crude oil instead of thermal energy [18]. Furthermore, current energy availability has begun to cause concern because it is still dependent on fossil fuel energy sources and is anticipated to be unable to full fill energy needs in the future. Therefore, the exploration and exploitation of alternative energy sources are urgently needed immediately. In addition to renewable energy sources, converting plastic waste into fuel has the potential to be a significant solution since it can simultaneously address the issue of plastic waste volume and the issue of energy supply.

Globally, the production and utilization of plastics will increase due to their superior characteristics, such as: being lightweight, easy to use, low production costs, corrosion resistance, and also long service life [19]. Various kinds of necessities, ranging from packaging bottles, packaging bags, household appliances, including eating and drinking utensils, and various other items, are made of plastic-based materials. However, after utilization is completed, these things become useless and are usually thrown away as garbage. Slowly but surely, the plastic waste that accumulates over time will become a very serious problem and threaten human civilization in this world. Plastic will become a tough enemy of the world because it takes a very long time to decompose naturally compared to organic matter.

Plastic waste is included in the category of non-biodegradable waste which causes very chronic environmental problems [11] and takes 500 years to decompose [20]. Therefore, an appropriate solution is needed to turn plastic waste into something more useful than throwing it into a landfill. Plastic waste actually has a high potential economic value if it is processed properly. Then the accumulation and environmental pollution can be reduced. Plastic can be processed into more valuable things, one of which is to become an alternative fuel as a substitute for the main fuel [21].

This study was raised based on the facts, which require appropriate solutions and handling related to crucial problems caused by plastic waste. Relevant sources, literature reviews, and studies of previous research that have been carried out by researchers underlie the efforts of the research team to find the solutions that contribute to solving the waste problem in Indonesia. Utilization of plastic-based liquid fuels cannot necessarily be implemented, so the potential and feasibility of the fuel must be assessed or at least reviewed from the results of research that has been widely carried out. The following should be studied, such as; environmental issues, social acceptance, waste problems, feedstock, ergo environmental, economic development, and product commercialization [21-22].

There have been numerous initiatives to create alternative energy from plastic garbage. However, none of them became a reality and contributed to the provision of additional energy for national energy. Similar to fuels based on fossil materials, fuels made from plastic also have a heating value, almost the same as fossil fuels. The type of plastic and physical properties of liquid fuel that will be used in certain uses for machinery or other equipment must be known ahead of time in order to achieve optimal combustion results [23-24].

The objective of this article is to explore the literature related to the generation of crude plastic oil by the pyrolysis method and its application to the internal combustion engine. Data and information related to the technology and quality of crude oil produced will be used for the initiation of processing pyrolysis-clean plastic waste. It is hoped that the implications of this study can provide input on whether waste processing is feasible with the pyrolysis method, which has the implications of solving the problem of environmental pollution due to plastic waste and its products can reduce dependence on the main energy source, namely fuel sourced from fossils.

2. Literature Review
2.1 Plastic

In this section, a number of research findings are presented as possible and discussed in relation to efforts to produce bio-oil plastics. Plastics are known as polymers, formed due to the bonding between hundreds to thousands of monomers that began to be produced in the 1950s. In addition to low prices, this material can be used in various fields, so its development is very rapid. In 2015, global production reached 380 Mt/year [25]. The thermoplastic group of plastics, which includes polyethylene terephthalate (PET), high, low, and linear low-density polyethylene (HDPE, LDPE, and LLDPE), polyvinyl chloride (PVC), polypropylene (PP), and polystyrene (PS), is the most commonly used type of plastic.

Actually, not all plastic can be recycled, so coding is done on the packaging to find out the identity of the plastic. In 1988, the Society of Plastic Industry (SPI) in the United States released the code. Seven RIC (Resin Identification Code) codes were issued by SPI. after receiving ISO approval (International Organization for Standardization), the 7 codes must be included in the form of a symbol on every product that uses plastic materials, including products originating from Indonesia. Table 1 shows the polymer groups and examples of commercial plastics. This code will help in terms of collection and sorting, types of plastic, examples of commercial items made from plastic, and processes that can be carried out in handling plastic waste. In general, the pyrolysis method can convert all types of thermoplastics into liquid oil [26-30].

Table 1
Polymer groups and commercial plastic

Polymer groups	Commercial plastic
Polyethylene terephthalate 1 PET	Water bottles, soda bottles, soft drink bottles, shampoo bottles, wash mouth bottles, and peanut bottle jars
High-density polyethylene 2 HDPE	Milk, water, and juice bottles, detergent bottles, yogurt and margarine tubs, grocery bags, shampoo bottles, cereal box liners
Polyvinyl chloride 3 PVC	Plumbing pipes, clear food packaging, shrink wrap, plastic children's toy, tablecloths, vinyl flooring, and blister packs
Low-density polyethylene 4 LDPE	Brad bags, frozen food bags, dry cleaning bags, newspaper bags, produce bags, paper milk cartoons, and hot/cold beverage cups
Polypropylene 5 PP	Ketchup bottles, yogurt and margarine containers, furniture, luggage, and winter clothing insulation
Polystyrene 6 PS	Toys, rigid packaging, refrigerator trays, CD cases, take-out containers, cups/plates, and packing chips
Bioplastic 7 OTHER	Polycarbonates, nylon, acrylic, CD, baby bottle, and headlight lens

2.2 Bio-Oil Plastic Production

Figure 1 shows the current state of plastic waste management trends. Landfilling is usually the last effort where plastic waste that is no longer valuable is disposed of a landfill. Recovering is generally defined as processing plastic waste with a thermal process to produce liquid fuel. Unlike Indonesia, European countries process their plastic waste into fuel oil, which is categorized as secondary fuel through a thermal recovery process. Denmark and Switzerland are the two countries that process plastic waste into oil. Almost all plastic waste is converted into fuel [31].

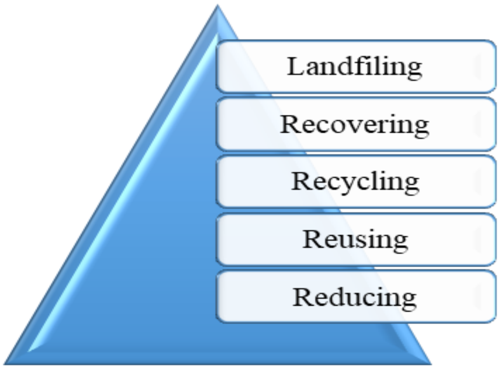

Fig. 1. Plastic waste treatment hierarchy

The Indonesian government continues to encourage activities related to the research and development of plastic waste into alternative fuels so that it is worthy of being a source of energy for the community and industry or providing fuel to internal combustion engines. Using the findings of the analysis of the immediate and long-term effects of the type of plastic, it was found from Table 2 that plastic contains an average volatile content of 96.69% wt., so the recovery process with the pyrolysis method will have the potential to be carried out to obtain liquid oil.

Table 2
Proximate and ultimate analysis of the thermoplastic [32]

Type of Plastic	Moisture (%Wt)	Fixed Carbon (%Wt)	Volatile (%Wt)	Ash (%Wt)
PET	0.535	10.47	89.29	0.01
HDPE	0	0.02	99.19	0.79
PVC	0.77	5.745	94.26	0
LDPE	0.3	0	99.65	0.2
PP	0.165	0.69	96.46	2.77
PS	0.274	0.16	99.56	0
Other	0.065	1.18	98.42	0.5

The origin of plastic material is also made from fossils, so it can be restored to its original form by decomposition or pyrolysis. Plastic is very sensitive to temperature, so it is easy to decompose as desired. Pyrolysis, therefore, comes with a very precise and seeded process to convert plastic waste back into raw fuel [33]. Pyrolysis is one of the thermochemical methods, which is a process with a high temperature without the use of oxygen, which is usually within the temperature range of 250–500 °C and can be used to decompose or convert hydrocarbon-based materials into light molecules [34]. To obtain high-quality pyrolytic oil from plastic waste (POPW), a high pyrolysis temperature of up to 900 °C is sometimes required. Products from plastic pyrolysis come in the form of crude oil that contains many fuel kinds, including diesel and gasoline [35]. The yields and quality of the POPW must meet the fuel standards required by internal combustion engines, especially the physical character and energy content possessed. Matters which are directly related to the amount of production and quality of POPW are briefly described in Figure 2 below.

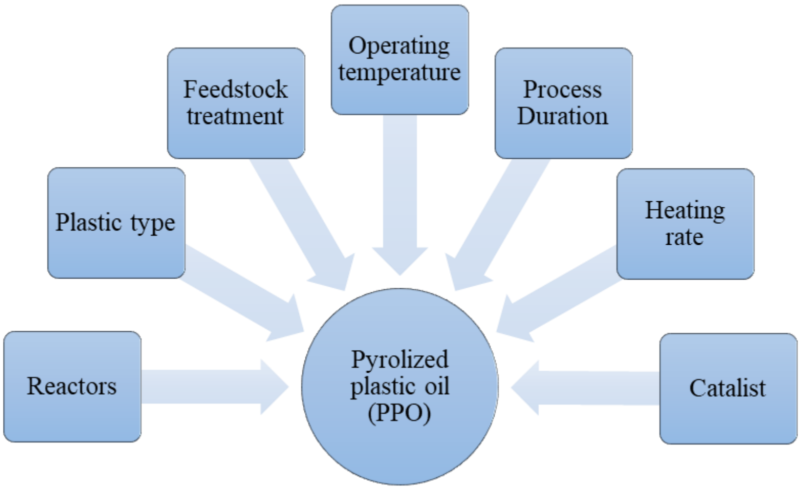

Fig. 2. Parameters related to the POPW production quality

There are seven decisive parameters in producing crude oil from plastic waste. In this section, it is discussed the most difficult parameters to control, which are known through the number of recent studies that have been conducted. According to the heating methods, the different types of reactors that can be utilized for the pyrolysis process are fluidized beds, fixed beds, spouted beds, rotating kilns, or packed beds [35-36]. Each type of reactor has benefits and drawbacks. One of the essentials for the pyrolysis process is high heat transfer rates. The fluid bed reactor has the most potential as shown in Figure 3 because it is known to have good hydrodynamic flow. Using heat carrier materials such as sand so that the heat transfer and distribution are better [37]. In addition, the fluidized bed reactor can be scaled to an industrial scale [38]. Whereas, the packed bed reactor also has high performance when the hydrodynamic flow of combustion air is made more evenly distributed [39-40].

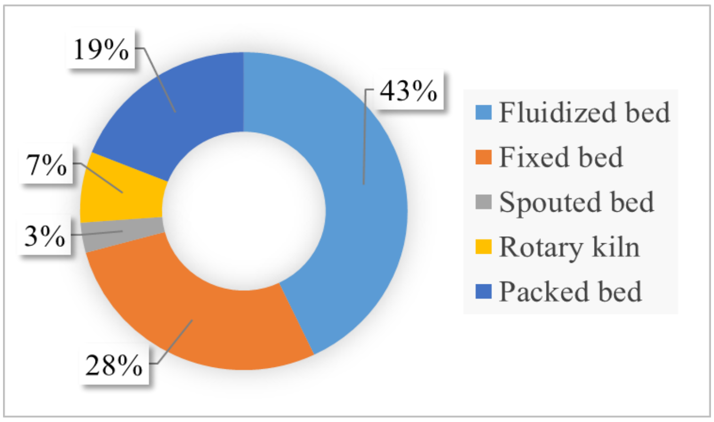

Fig. 3. Research trend based on the reactor type

In pyrolysis, there are three heating methods that are always used by researchers; the fast, medium, and slow heating methods. When the main purpose is to produce pyrolysis oil, then slow pyrolysis is used. These three methods greatly affect the yield and quality of POPW. In addition, the product and POPW quality are also strongly influenced by the temperature and operating time [41-42] In addition to the pyrolysis of plastic types individually [43-44], combined pyrolysis of all plastics or co-pyrolysis is also presented [45-46]. Figure 4 shows the research on pyrolysis plastics where the pyrolysis of co-pyrolysis is the most popular. The advantage is that it does not require a sorting system such as the recycling process. The combination of all plastics in the feedstock can be processed because the goal is to produce liquid.

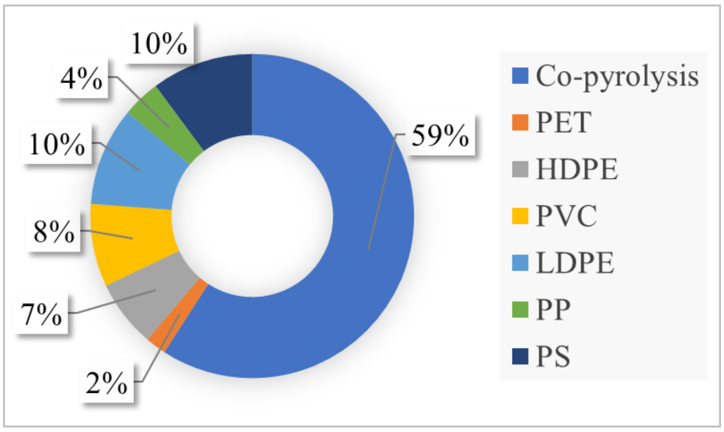

Fig. 4. Research focuses on energy recovery of plastic wastes

Some of the pyrolyzed oil which has been found needs to be characterized as having used internal combustion engines. Some notes state that the fuel content of the resulting POPW still contains a lot of impurities and the probability of cetane number is still low. To obtain fuel with characteristics such as diesel, the distillation process must be carried out at a temperature according to the boiling point of the diesel and the time used [47].

2.3 The Characteristic of POPW

The POPW product obtained must be close to the characteristics and heating value of diesel fuel. Table 3 and Table 4 show the characteristics of POPW, which are very similar to diesel fuel, and the heating value of each plastic type, respectively.

Table 3
Plastic fuel vs. diesel fuel characteristics

Property	PPO [48]	Diesel [48]	Euro IV Diesel [49]
Density at 30 ^{0}C in gm/cc	0.835	0.840	0.807
Ash content, %	0.00023	0.045	-
Gross calorivic value (kJ/kg)	44.340	46.500	43.41
Kinematic viscosity. Cst at 40 ^{0}C	2.52	2.0	2.64
Cetane number	51	55	55.2
Flashpoint, ^{0}C	42	50	-
Fire point, ^{0}C	45	57	-
Carbone residues, %	82.49	26	-
Sulfur content, %	0.030	0.045	-
Distillation temperature, ^{0}C at 58%	344	328	-
Distillation temperature, ^{0}C at 95%	362	340	-

Table 4
The heating value of each PPO plastic type

Plastic-type	CV (MJ/kg)	Reff
Polyethylene-terephthalate (PET)	43.42	[50]
High-density polyethylene (HDPE)	44.50	[51]
Polyvinil chloride (PVC)	15-25	[15]
Low-density polyethylene (LDPE)	36.50-39.80	-
Polystyrene (PS)	41.40-41.80	[52]
Polypropylene (PP)	44.5	[53]
Bioplastic	31.53	-

3. Recent Development of POPW Utilization in ICE

Along with the increasing fuel requirements and the global warming issue, the POPW can be a target to be developed to increase the supply of fuel needs, especially for motorized vehicles [54]. A number of tests of POPW must be carried out to determine its potential to replace fossil fuels, although to replace 100% is not convincing. Although several research findings reported that the performance of internal combustion engines (ICE) using 100% POPW is similar to that achieved by using pure diesel, the emissions produced are still greater [55]. This makes an even harder effort because it is reported that the use of 100% pyrolysis oil from waste tires cannot fuel the ICE engine but can reduce emissions compared to emissions produced using pure diesel fuel [56]. One of the indicators of a fuel that is suitable for use is its low emission content. According to research, emissions from the transportation sector are the second-largest contributor to Indonesia's overall greenhouse gas emissions, after those from the industrial sector. The four largest contributors to emissions can be seen in the chart shown in Figure 5 below.

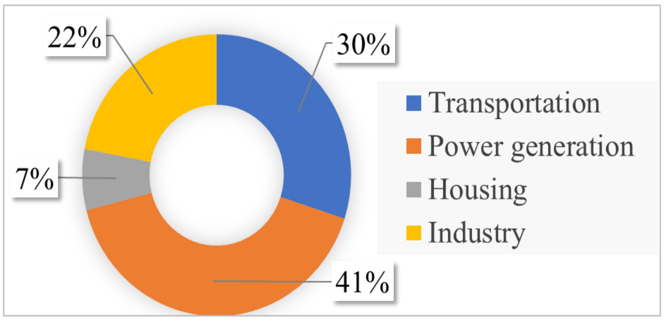

Fig. 5. The largest contributor to emission by sector [57]

In addition, it is hoped that there will be a decrease in emissions if plastic fuel is mixed with diesel. Currently, Indonesia applies the Euro-4 emission standard with the emission threshold as shown in Table 5 below. As a result, all research findings must refer to the established threshold.

Table 5
The emission threshold value of Euro-4

Fuel	NOx (gr/km)	CO (gr/km)	HC+NOx (gr/km)	PM (gr/km)
Petrol	0.08	1	0.1	-
Diesel	0.25	0.5	0.3	0.025

One of the efforts that can be made is to mix POPW with diesel fuel without modifications to the engine geometry. It is reported that 20% of POPW can be mixed with diesel fuel to improve the performance of diesel engines [58]. The density of diesel does not have much effect on engine performance, so mixing POPW with diesel can be done, and according to the results of the study, the density of the mixture of POPW with diesel is not too different and tends to be the same [59].

4. Challenges and Opportunities

Energy conservation and diversification efforts are the main keys to energy security. This effort aims to divert attention from petroleum as the main source of energy so that additional energy sources are found and will maintain the stability of the energy supply in the future. As a comparison, a literature review related to energy diversification from biomass states that biomass in Indonesia is sufficient to support energy availability by gasification processing using a downdraft-type gasifier. As much as 3 MJ/m^3 of combustible gas products can be produced from biomass classified as wood using a downdraft reactor that can be used to replace fossil fuels in internal combustion engines [60]. The diversification and development of bio-oil from plastic as a fuel substitution in Indonesia is very promising compared to biomass because the heating value of plastic bio-oil is greater than biomass. However, efforts to produce bio-oil from plastic waste have begun to be carried out, and trials have been carried out, but have not yet obtained promising results. Until now, Indonesia has not used liquid fuel from the pyrolysis of plastic waste. Therefore, efforts continue to be made to obtain fuel oil from plastic waste that is close to the characteristics of premium fuels. In addition, the government encourages energy source diversification activities to produce a future energy mix that is more varied.

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