# Feasibility Study of Plastic Waste Pyrolysis from Municipal Solid Waste Landfill with Spent FCC Catalyst

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**ABSTRACT**

Globally, there is growing concern about the problem of plastic waste. The majority of plastic waste is dumped into landfills, where it occupies space, reducing landfill capacity and causing a variety of environmental issues. Plastic waste pyrolysis has gained popularity because it can reduce the volume of plastic waste while also producing alternative fuels. This study assessed the feasibility of producing fuel oil from plastic waste using the catalytic pyrolysis process. Polyethylene (PE), polypropylene (PP), and polystyrene (PS) waste samples were collected from municipal solid waste (MSW) landfills on Samui Island, Surat Thani Province, Thailand. Pyrolysis was carried out in a 3-L bench-scale reactor at 450ºC using a 3% spent FCC catalyst. PE, PP, PS, and mixed plastic waste were used as feedstocks. The results showed that the pyrolysis of PS produced the most liquid product (91.44 wt%), whereas the pyrolysis of PE produced the highest percentage of diesel range product (36.60 wt%). Furthermore, the results of the analysis revealed that the characteristics of diesel from improved PE pyrolysis oil by naphtha removal were similar to those of commercial diesel B7. According to the cost-benefit analysis, the operating costs of pyrolysis oil and improved diesel were 0.37 and 0.65 USD/L, respectively, which were lower than the current market price of diesel B7. The findings of the study demonstrated the feasibility of converting plastic waste from MSW on Samui Island into alternative energy using eco-friendly and cost-effective technology.

## 1. INTRODUCTION

Samui Island is one of Thailand's most popular tourist destinations. The increasing number of residents and visitors contributes to a large volume of solid waste. According to the report of the TISTR (2020), the major component of municipal solid waste (MSW) on Samui Island was plastic waste, which accounted for 40.4% and 64.4% of new and old MSW, respectively. Since plastics degrade slowly, they take up a lot of space, resulting in overflowing landfills. In addition, leachate, toxic dyes, and additives in plastic products have a negative impact on the environment (Miandad et al., 2017a; Yansaneh and Zein, 2022).

Although several approaches have been implemented for MSW management on Samui Island, there are still many problems and obstacles. These include landfills that have reached their maximum capacity, leachate contamination from landfill sites to the nearby environment, and the MSW incinerator that has been out of order since 2012. To solve the problems, the municipality has transported the waste to be disposed of outside the area with a large budget. However, the accident in which a ferry capsized during MSW transportation from Samui Island to Surat Thani Province in August 2020, causing 60 tons of MSW to sink into the sea (Bangkok Post, 2020; Thai PBS, 2020), has raised concerns.

Currently, pyrolysis technology is growing in interest. This technology involves the thermal degradation of complex molecules into smaller molecules at temperatures ranging from 300 to 600°C in the absence of oxygen (Singh et al., 2019; Zhang et al., 2020; Lee et al., 2021). This method reduces a massive amount of MSW and can potentially convert

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plastics to more valuable chemicals and fuels (Hakeem et al., 2018; Maafa, 2021).

A number of studies have been documented on the factors affecting the yield and distribution of pyrolysis products. Miandad et al. (2017b) conducted the pyrolysis of polystyrene (PS), polypropylene (PP), polyethylene (PE), and polyethylene-terephthalate (PET) at 450°C for 75 min of retention time and found PS provided the maximum liquid yield, while PE pyrolysis converted plastic into wax instead of liquid products. While the thermal and kaolin catalytic pyrolysis of PP waste was conducted in a horizon glass reactor at 450°C for 30 min of retention time, 67.48 wt% and 79.85 wt% of the liquid products were obtained, respectively (Hakeem et al., 2018), whereas plastic bag pyrolysis in a fixed bed reactor at 500°C with three catalysts (ZSM-5, dolomite, and kaolin) showed that non-catalytic pyrolysis provided the largest amount of liquid products (Chaiphet et al., 2022). These studies demonstrated that the distribution and yield of pyrolysis oil depend on several factors, such as temperature, type of catalyst, reactor type, and feedstock characteristics.

According to the above-mentioned MSW management issue on Samui Island, pyrolysis could be an alternative method for Samui Island MSW management. However, since the yield and characteristics of liquid products and the cost-effectiveness of this approach have not been evaluated, this research aimed to determine the feasibility of using catalytic pyrolysis to convert plastic waste from Samui Island's MSW into fuel. The results provided the information necessary for the relevant organizations to select the appropriate means of MSW management that facilitate the environmental and economic sustainability of Samui Island.

## 2. METHODOLOGY

### 2.1 Study site

Samui Island, Thailand's third-largest island, is a municipality in Surat Thani Province. The island is situated off the east coast of Thailand between latitudes N9°24' to N9°36' and longitudes E99°54' to E100°06', which cover an area of around 227 km$^2$ as shown in Figure 1 (Nazaruddin, 2020). In 2021, the population in the Samui Island municipality was 68,698 (Koh Samui City, 2021).

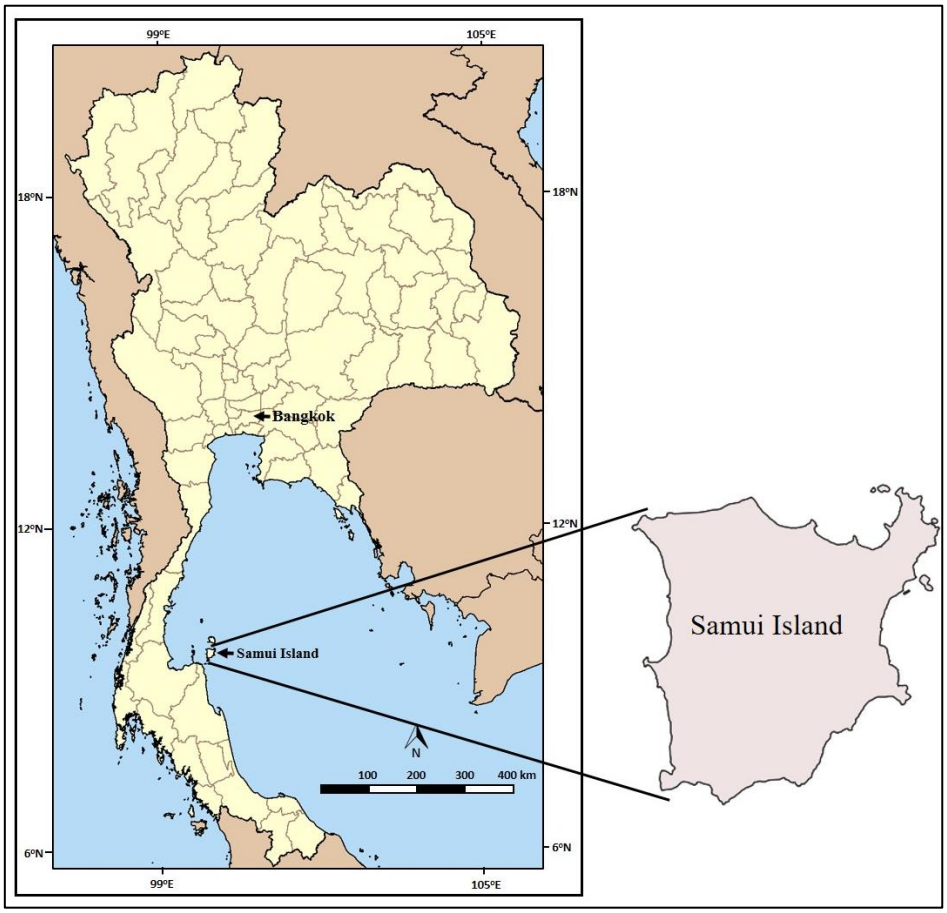


**Figure 1.** Map of Samui Island, Surat Thani Province, Thailand

### 2.2 Raw material survey and preparation

Municipal plastic waste samples were randomly collected from Samui Island Landfill in April 2022. PE, PP, and PS were the three major types of plastic in the landfill in the ratio of 80:15:5 wt%. Thus, this study conducted the pyrolysis based on the types of plastic and the mixed plastic ratio in terms of mixed plastic waste. All samples were shredded to less than 3 cm and dried to less than 1% moisture content.

### 2.3 Reactor system and experimental set-up

The pyrolysis experiments were carried out in a 3-L bench-scale horizontal cylindrical reactor comprised of 316 stainless steel materials with a 10 cm internal diameter, 2 cm thickness, and 39 cm length. The center shaft was equipped with an agitator and a compartment for inserting a thermocouple to monitor the temperature inside the reactor. The reactor was heated via an electrical furnace, and nitrogen gas was used to carry the obtained product vapor to the condenser. A counter-current heat exchanger and the chiller were installed to support cool water for the heat exchanger. The schematic diagram of the reactor is shown in Figure 2.

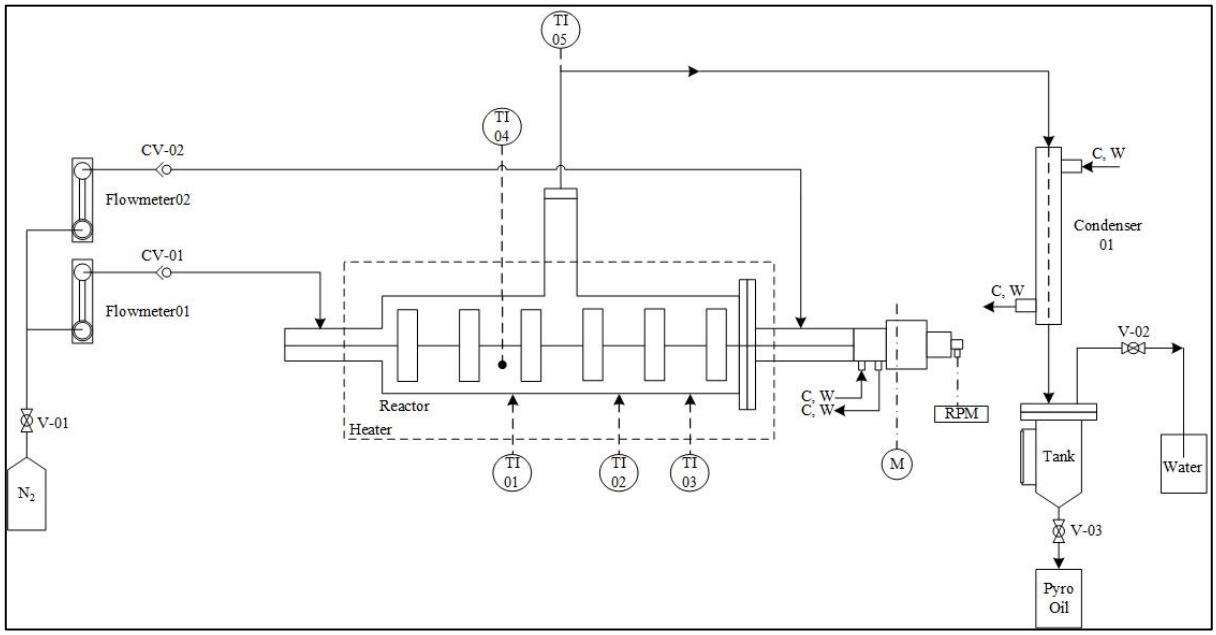


**Figure 2.** The schematic diagram of the reactor

The pyrolysis experiment was carried out at a reaction temperature of 450ºC with 3 wt% spent FCC catalyst in the feed. A total of 250 g of PE, PP, and PS and mixed plastics of PE, PP, and PS in a ratio of 80:15:5, which was the plastic ratio in the Samui Island Landfill, were used to determine the effect of the plastic types on the yield and selectivity of the product. Two thermocouples were used to indicate the reaction temperature (RT) and the oil vapor's temperature (VT) over time at TI04 and TI05, respectively. The pyrolysis oil product was collected gradually until the reaction ended. The carbon residues that remained in the reactor were collected and weighed. Finally, the mass balance was used to calculate the gas product.

### 2.4 Analytical methods

Ash content, moisture content, volatile matter, and fixed carbon of plastic waste samples were determined by proximate analysis according to ASTM D3172-3175. Carbon, hydrogen, nitrogen, and sulfur were determined by ultimate analysis according to ASTM D5373. Meanwhile, heating value and thermal degradation temperature were determined via the bomb calorimeter and TGA, respectively.

The composition of liquid products from the pyrolysis process was analyzed by a Simulated Distillation Gas Chromatography (DGC; Agilent 7890 model) equipped with a DB-1 column (J&W Scientific) and simulation distillation software. The heating value, viscosity, and acidity of pyrolysis liquid products were analyzed following the ASTM standards. The quality of improved pyrolysis oil was compared with diesel standards to assess the possibility of using it as an alternative fuel.

### 2.5 Cost-benefit evaluation of plastic waste pyrolysis

The cost-benefit analysis focused only on the pyrolysis of plastic waste to produce a liquid product with the same quality and characteristics as diesel fuel. The cost-benefit analysis was based solely on the estimated monthly operational costs of the plastic waste pyrolysis process and income from diesel sales. PE plastic waste with a moisture content of 0.77 wt% was used as the feedstock for the pyrolysis process at a rate of one ton per day.

## 3. RESULTS AND DISCUSSION

### 3.1 Characteristic of plastic waste samples

In April 2022, 30 kg of plastic waste samples were randomly collected from the landfill. The plastic waste samples contained 80% PE, 15% PP, and 5% PS. Table 1 presents the proximate and ultimate results of plastic waste samples. The PP had the highest gross calorific value, fixed carbon, and hydrogen content, whereas the PS had the highest volatile matter and carbon content. In the meantime, the moisture content, ash, nitrogen content, and sulfur content of mixed plastic waste were the highest among PP, PS, and PE.

**Table 1.** Proximate and ultimate analysis of plastic waste samples

| Parameters | Methods | Unit | PP | PS | PE | Mixed plastic |
|---|---|---|---|---|---|---|
| Gross calorific value | ASTM D5865 | cal/g | 10,381.47 | 9,843.51 | 9,824.28 | 9,718.4 |
| Moisture content | ASTM D3172 | wt% | 0.77 | 0.22 | 1.03 | 1.11 |
| Volatile matter | ASTM D3173 | wt% | 95.19 | 99.57 | 93.24 | 93.05 |
| Ash | ASTM D3174 | wt% | 2.03 | 0.11 | 5.66 | 5.68 |
| Fixed carbon | ASTM D3175 | wt% | 2.01 | 0.10 | 0.07 | 0.16 |
| Carbon content | ASTM D5373 | wt% | 82.22 | 92.00 | 77.55 | 78.97 |
| Hydrogen content | ASTM D5373 | wt% | 13.84 | 8.34 | 12.81 | 12.77 |
| Nitrogen content | ASTM D5373 | wt% | 0.14 | 0.05 | 0.21 | 0.24 |
| Sulfur content | ASTM D4239 | wt% | UD | 0.002 | 0.015 | 0.024 |

Remark: UD refers to Undetectable

### 3.2 Thermogravimetric analysis of plastic wastes

The degradation temperatures of individual and mixed plastic wastes were determined using TGA. In Figure 3, all plastic degradation temperatures began around 300°C (as shown on the TG line in solid lines). PE degraded slowly initially until it reached 450°C then the degradation occurred rapidly. While PP, PS, and mixed PE/PP/PS degradation occurred rapidly after reaching 440, 425, and 390°C, respectively. As shown on the DTG line, the peaks of the dashed lines showed that the maximum temperatures for PS, PP, PE, and mixed PE/PP/PS degradation were 414.0, 467.7, 480.2, and 470.3°C, respectively. PE had the highest maximum degradation temperature, followed by mixed PE/PP/PS, PP, and PS. The differences in pyrolysis temperatures between plastic types are caused by the polymer structures of each plastic (Gałko and Sajdak, 2022).

Figure 4 depicts the RT and VT against the reaction time. The PS experimental results showed that when the desired RT (solid line) was reached at 450ºC, the VT rapidly rose (dashed line). A rapid increase in the oil vapor temperature in PS pyrolysis indicated that PS cracked easily to produce pyrolysis oil and gas products when compared to PP, PE, and mixed PE/PP/PS; corresponding to TGA results, the PS degradation reaction occurred at a lower temperature when compared to other plastics. Figure 5 depicts the differential oil and accumulative oil against reaction times. It was clearly observed that the differential oil receiving of all samples conformed to the oil vapor's temperature with time, as mentioned in Figure 4. PS had a reaction termination time of 120 min, whereas PP, PE, and mixed plastics had times of 210, 240, and 225 min, respectively.

PS degrades more easily than other plastics (Maafa, 2021). As shown in Figure 6, PS has a long-chain hydrocarbon molecular structure with alternating carbon centers attached to phenyl groups. PS plastic degradation is typically caused by end-chain scission, followed by beta scission, which can occur at low temperatures (Singh et al., 2019). Meanwhile, PE had the highest peak pyrolysis temperature compared to the others. PE requires higher temperatures to degrade than other plastics (Rizzarelli et al., 2016; Miandad et al., 2017b) due to its structure being linear and symmetrical without a functional group, resulting in a higher crystalline structure. Furthermore, cracking may occur only on both sides of the polymer chain's end, resulting in

small molecular hydrocarbon products (Cheng et al., 2022). The study results also exhibited that the reaction temperature of mixed PE/PP/PS (80:15:5) was higher than PS and comparable to PP and PE. This is caused by the composition of the plastics used as feedstock, which contributes to the interaction of the mixed polymers that affects the onset temperature, peak decomposition temperature, and endset temperature (Yu et al., 2016; Anene et al., 2018).

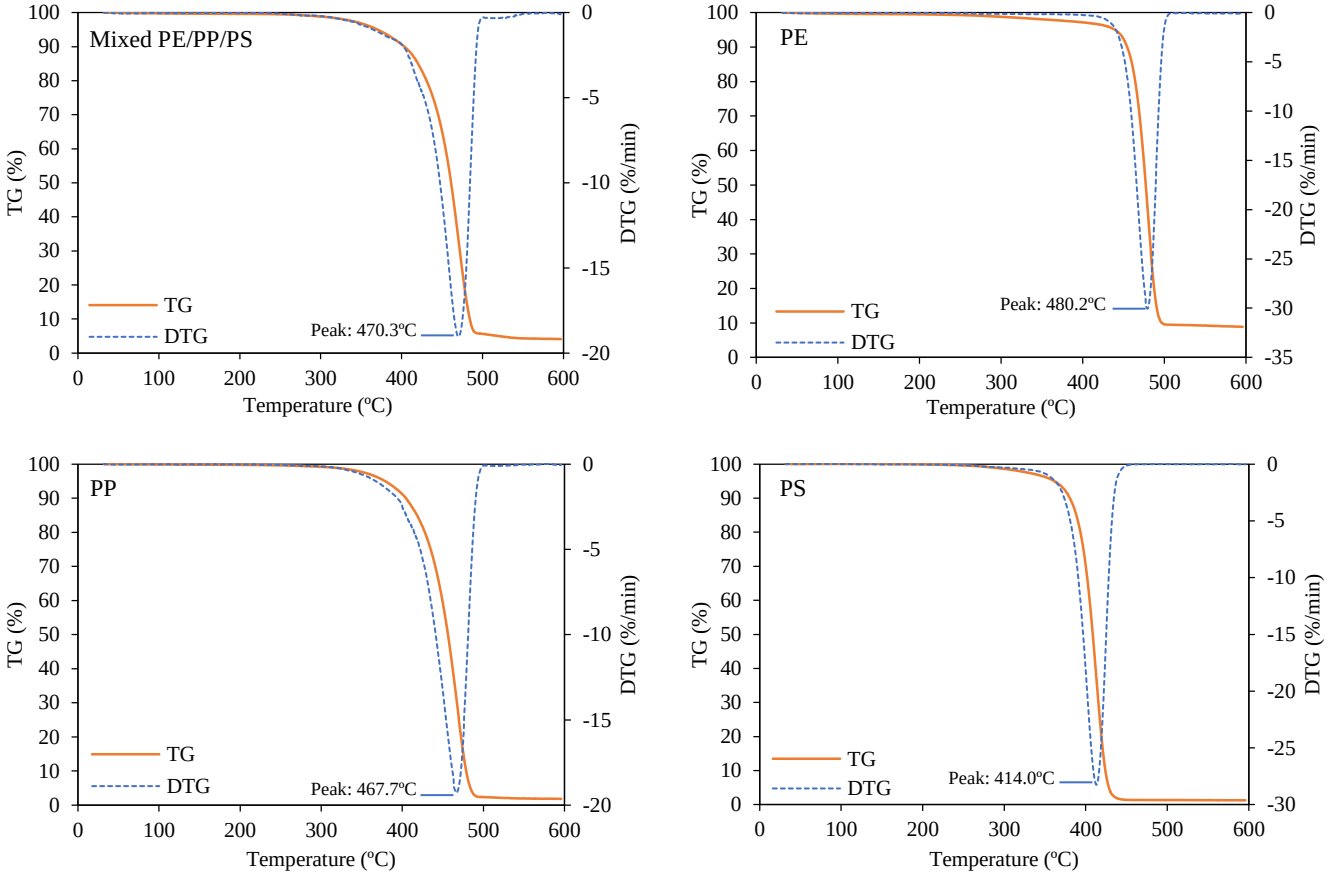


**Figure 3.** The TGA results (TG refers to Thermogravimetric; DTG refers to Differential Thermogravimetric)

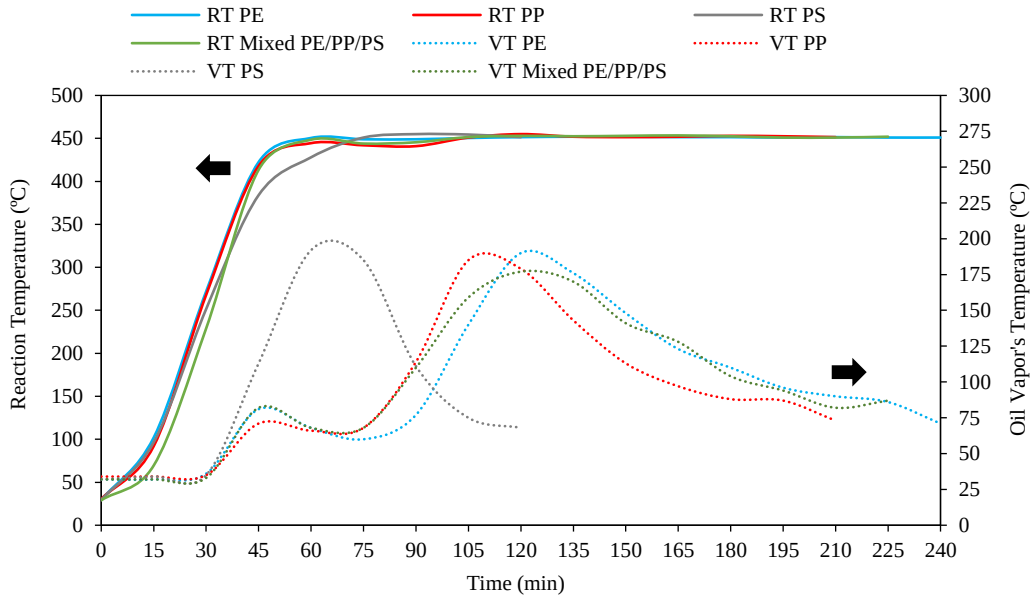


**Figure 4.** The reaction temperature (RT) and the oil vapor's temperature (VT) against reaction time

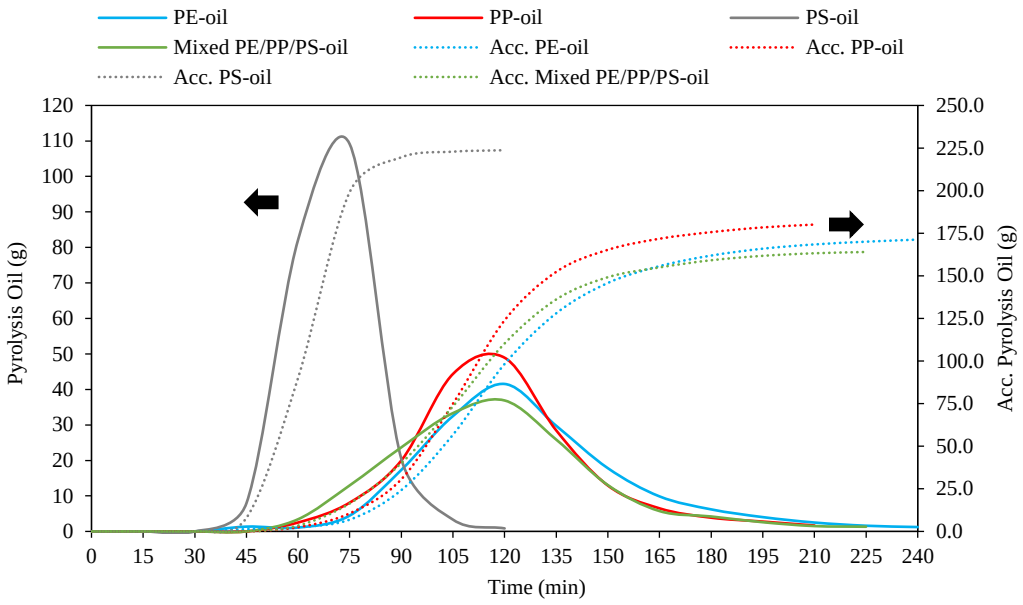


**Figure 5.** Differential and accumulative oil against reaction time

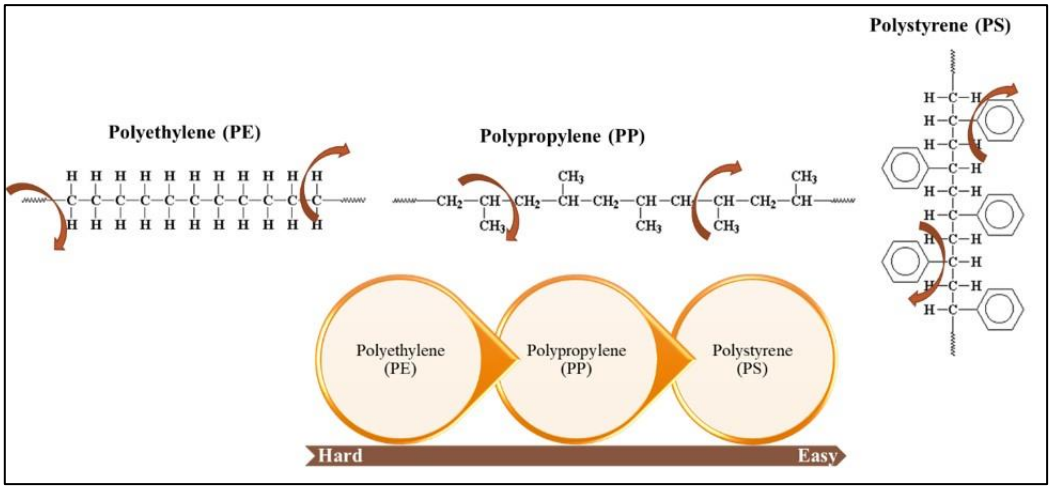


**Figure 6.** Molecular structures of PE, PP, and PS (Maafa, 2021)

Plastic molecular structures also influence reaction times. In this study, the time required for the complete pyrolysis reaction of PS was the shortest, which was 120 min, whereas the time required to complete the pyrolysis reactions of PP, PE, and mixed PE/PP/PS was 210, 240, and 225 min, respectively. Furthermore, a 3% catalyst was used in the reaction condition, which improved the cracking of polymers, particularly PS, leading to the conversion into styrene over catalysts at relatively low temperatures via simple thermal cracking (Maafa, 2021).

### 3.3 Yield and distribution of pyrolysis products

Figure 7 presents the maximum liquid yield from the pyrolysis of PS at 91.44 wt%, while the pyrolysis of PE, PP, and mixed PE/PP/PS yielded 72.65, 73.75, and 69.19 wt%, respectively. Furthermore, PS plastic waste produced the least amount of gas and carbon residue. This is consistent with previous research showing that pyrolysis of PS produced the most liquid product with the least amount of gas and char when compared to PE and PP (Miandad et al., 2017b; Palmay et al., 2022). However, when compared to individual plastics, mixed plastic waste pyrolysis produced the lowest yield of liquid product and the highest yield of carbon residue and gas products. The proportion of plastic types in the mixed feedstock has a significant impact on the oil yield of mixed plastic waste (Kusenberg et al., 2022; Palmay et al., 2022; Zein et al., 2022).

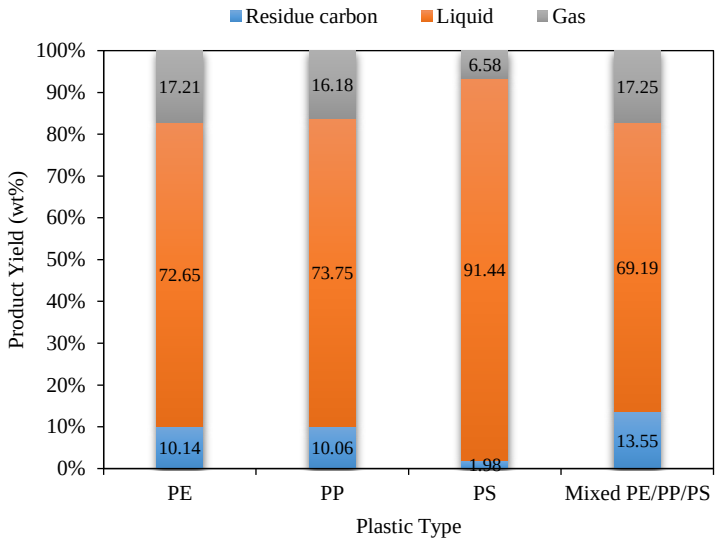


**Figure 7.** Effect of the plastic types on yield of pyrolysis product

Figure 8 exhibits the variation in the composition of pyrolysis oil derived from each feedstock type. The percentage of naphtha ($C_5$-$C_{12}$), kerosene ($C_{12}$-$C_{15}$), diesel ($C_{15}$-$C_{33}$), and long residue varies in the range of 39.55-72.25%, 0.35-18.70%, 24.00-36.60%, and 3.40-6.80%, respectively. In liquid products, pyrolysis of PS yielded the highest percentage of naphtha range, followed by diesel range, long residue, and kerosene range, whereas pyrolysis of PE yielded the highest percentage of naphtha range, followed by diesel range, kerosene range, and long residue. When PS was mixed with PE and PP, the light hydrocarbon molecule decreased while the heavy hydrocarbon molecule increased. These findings confirmed the previously reported influence of plastic type and plastic waste composition on the yield and formation of certain hydrocarbon groups (Al-Salem et al., 2017; Miandad et al., 2017a; Santaweesuk and Janyalertadun, 2017).

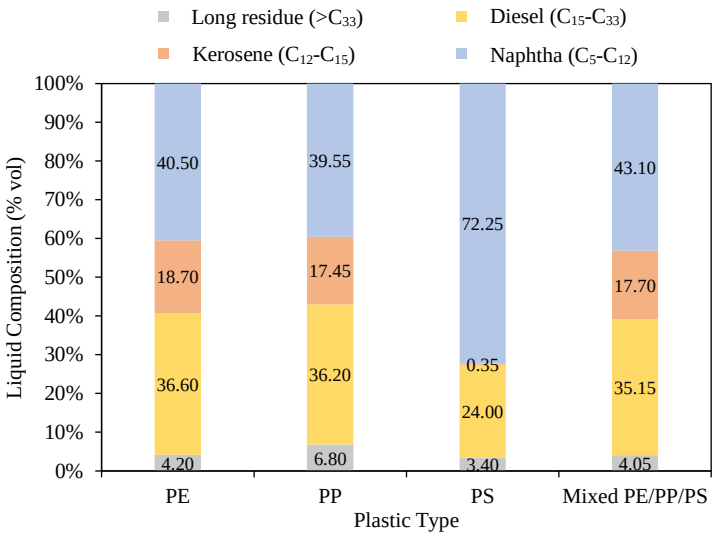


**Figure 8.** Effect of the plastic types on selectivity of pyrolysis product

### 3.4 Characteristic of improved diesel from pyrolysis oil

Normally, the naphtha composition in commercial diesel B7 is around 10 wt%, which contributes to high performance in diesel engines. In this study, the pyrolysis oil of PE contained 40.50 percent naphtha. Excess naphtha was evaporated at temperatures ranging from 120 to 150ºC in the same reactor. Naphtha vapor was condensed by keeping the condenser temperature at 20ºC until the naphtha

product was obtained. The remaining pyrolysis oil in the reactor was a diesel product with a naphtha content similar to diesel B7 (around 10 wt%). Furthermore, the liquid diesel composition from the pyrolysis process, as shown in Table 2, had a relative value to commercial diesel B7.

### 3.5 Application of pyrolysis oil from plastic waste

According to the improved pyrolysis oil, its properties were close to those of diesel B7, so the oil could be used as a fuel for diesel engines. However, before use, pyrolysis liquid oils should be upgraded through various methods such as distillation, refining, and blending with conventional diesel. Various studies have reported on the use of pyrolysis oil in diesel engines for electricity generation (Rehan et al., 2016; Kassargy et al., 2018; Lee et al., 2021) and the use of pyrolysis oil or blended pyrolysis oil with conventional diesel as a transportation fuel (Faussone, 2018; Jahirul et al., 2022; Uebe et al., 2022). Furthermore, because of the high-value chemical potentials of pyrolysis oils, they could be used in industries such as the browning and flavoring of wood adhesives (Kunwar et al., 2016) and could be a source of precursor chemicals in plastic, including biocompatible and biodegradable plastic industries (Lu et al., 2021; Mahari et al., 2022).

**Table 2.** Characteristics of diesel after improvement and commercial diesel

| Characteristic | Methods | Diesel after improvement | Commercial diesel B7 |
|---|---|---|---|
| 1. Density at 15°C (kg/m$^3$) | ASTM D 1298 | 809.60 | 827.48 |
| 2. Kinematic viscosity at 40°C | ASTM D 445 | 1.45 | 3.74 |
| 3. Heat value (MJ/kg) | ASTM D 240 | 45.376 | 44.864±0.295 |
| 4. API gravity | ASTM D 1298 | 43.10 | 39.5 |
| 5. Distillation (°C) | ASTM D 86 | | |
| • IBP | | 140.00 | 206.59 |
| • T10 | | 191.00 | 251.70 |
| • T50 | | 280.00 | 316.18 |
| • T90 | | 364.00 | 375.34 |
| • FBP | | 435.00 | 398.21 |
| 6. Cetane index | ASTM D 976 | 63.58 | 68.89 |
| 7. Flash point (°C) | ASTM D 93 | 55.00±1.20 | 81.50±0.70 |
| 8. Acid value (mg KOH/g) | ASTM D 664 | 0.15 | 0.3 |
| 9. Liquid composition | ASTM D 2887 | | |
| • Naphtha | | 12.70 | 12.20 |
| • Kerosene | | 23.30 | 21.10 |
| • Diesel | | 55.40 | 57.20 |
| • Long Residue | | 8.60 | 9.50 |

IBP=Initial Boiling Point; FBP=Final Boiling Point; T10, T50, T90=10, 50, 90 % recovery temperature (°C), respectively (ASTM International, 2020)

### 3.6 Cost-benefit evaluation of plastic waste pyrolysis

As previously mentioned, the study's target pyrolysis product is diesel. In terms of the cost-benefit analysis presented in Table 3, it was focused only on the cost of pyrolysis operations and the income from diesel based on the current diesel price. A total of 21,795 L of pyrolysis oil were produced from 1 ton/day, or 30 tons/month, of PE plastic waste pyrolysis. Following the removal of the excess naphtha, the process will produce 13,730 L/month of diesel fuel (with a 10% loss during operation). The total operating cost of pyrolysis oil will be 8,144.69 USD/month, or 0.37 USD/L. While the operating cost for diesel production will be added up for naphtha separation and additives, the total cost will be 8,859.89 USD/month or 0.65 USD/L. Based on the current market price of diesel, which is 1.01 USD/L, the monthly income from selling diesel will be 13,931.96 USD (PTT OR, 2023). However, this benefit is not included in the naphtha revenue evaluation. In addition, the carbon residue and gas products, mainly ethane and propane, can be recycled as fuel for heating the reactor on pilot and commercial scales, leading to a lower operation cost.

Furthermore, because a large amount of plastic waste will be pyrolyzed, this project will assist Samui Municipality in overcoming solid waste problems, resulting in sustainable solid waste management, which corresponds to SDG 6: Water and Sanitation and SDG 11: Sustainable Cities and Communities.

**Table 3.** Monthly expenditure and income

| Items | Quantity | Cost per unit | Total (USD) |
|---|---|---|---|
| PE plastic waste1 (ton/day × 30 days) | 30tons | 877.12 USD/ton | 2,613.73 |
| Catalyst | 900 kg | 0.15 USD/kg | 130.69 |
| Bleach substances | 763 kg | 0.87 USD/kg | 664.6 |
| Electricity | 692.15 units | 0.13 USD/unit | 88.87 |
| Workforce | 4persons | 726.04 USD/month/person | 2,904.15 |
| Maintenance cost | | | 871.24 |
| Others | | | 871.24 |
| Total cost for pyrolysis oil | | | 8,406.06 |
| Cost per liter of pyrolysis oil (USD/L) | | | 0.37 |
| Adding up cost of improvement from pyrolysis oil to diesel grade | | | |
| Separating | 21,795 L | 0.15 USD/L | 316.47 |
| Additives (Cetane improver, PPD) | 13,730 L | 0.029 USD/L | 398.74 |
| Total cost for diesel | | | 8,859.79 |
| Cost per liter of diesel product (USD/L) | | | 0.65 |

Remark: Monthly expenditure and income calculated based on 1-month pyrolysis operation with 30 tons/month of PE plastic waste. 1 baht=0.029 USD (January 3rd, 2023)

## 4. CONCLUSION

The pyrolysis of municipal plastic wastes from Samui Island landfill was carried out in a 3-L bench-scale reactor at a temperature of 450ºC with a 3 wt% spent FCC catalyst loading. PE, PP, PS, and mixed plastic waste were used as feedstock. Although catalytic pyrolysis of PS plastic waste yielded the most liquid products, catalytic pyrolysis of PE plastic waste yielded the most diesel-range products. The properties of the improved pyrolysis oil after naphtha removal were quite similar to commercial diesel B7. Furthermore, the operation cost of plastic waste pyrolysis and liquid product improvement was less than the market price of diesel fuel. This study demonstrated that plastic pyrolysis is a feasible and cost-effective intervention for addressing Samui Island's plastic waste problem.

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