

# Characterization of Synthetic Oil Produced from Medical Mask Waste by Pyrolysis Using a Silicon Dioxide (SiO<sub>2</sub>) Catalyst

Abdul Azis <sup>1✉</sup>, Dwi Yudha Meydiansyah <sup>2</sup>, Herman Saputro <sup>3</sup>, Ngatou Rohman <sup>4</sup>, Aris Purwanto <sup>5</sup>, Riyadi Muslim <sup>6</sup>

(1,2) Master's Program in Mechanical Engineering Education, Yogyakarta State University, Yogyakarta, Indonesia

(3,4) Mechanical Engineering Education, Sebelas Maret University, Surakarta, Indonesia

(5) Mechanical Engineering, Surabaya State University, Surabaya, Indonesia

(6) Manufacturing Engineering Technology, Vocational School, Sebelas Maret University, Surakarta, Indonesia

**Abstract:** The increasing demand for fossil fuels, particularly petroleum, has contributed to the depletion of fossil energy reserves and highlights the need for alternative energy sources. One potential alternative is synthetic oil produced from waste materials, including used medical masks. This study aims to evaluate the effect of pyrolysis temperature and SiO<sub>2</sub> concentration on the characteristics of synthetic oil produced from medical mask waste based on liquid yield, calorific value, density, and flash point. An experimental method with quantitative analysis was employed. Pyrolysis was conducted at temperatures of 200 °C and 300 °C using three SiO<sub>2</sub> concentration variations: 0% (100% medical mask waste), 1% SiO<sub>2</sub> + 99% medical mask waste, and 2% SiO<sub>2</sub> + 98% medical mask waste. The produced synthetic oil was filtered and characterized based on liquid yield, calorific value, density, and flash point. The results showed that the highest liquid yield was obtained at 300 °C with 2% SiO<sub>2</sub> addition, reaching 55.666%. The highest calorific value was obtained at 200 °C with 2% SiO<sub>2</sub> addition, reaching 9674.54 cal/g. The lowest density value of 0.76205 g/cm<sup>3</sup> was obtained at 300 °C with 1% SiO<sub>2</sub> addition, while the highest flash point value of 152.5 °C was obtained at 300 °C without SiO<sub>2</sub> addition. These results indicate that pyrolysis temperature and SiO<sub>2</sub> concentration influence the yield and physicochemical properties of synthetic oil derived from medical mask waste.

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## INTRODUCTION

The increasing demand for fossil fuels driven by population growth has raised concerns regarding the depletion of non-renewable energy resources. Previous studies have highlighted that the growing global energy demand, coupled with declining fossil fuel reserves, has accelerated the need for alternative energy sources (Capellan-Perez et al., 2014). This global energy challenge is also reflected at the national level, particularly in developing countries such as Indonesia. Based on data from the Indonesia Energy Outlook, in 2019 the national fuel demand reached 465.7 million barrels/year. This need has not been met by domestic production of fuel oil, which averages 278.1 million barrels/year. Resulting in an average import of fuel oil of 165.4 million barrels or around 35% of the national need each year.

The high dependence on imported fuel, combined with the continuous depletion of petroleum resources, has intensified the urgency to develop alternative and sustainable energy sources. In this context, waste-to-energy (WTE) conversion has emerged as a promising approach to address both

energy shortages and environmental issues. One potential source of alternative energy that can be used as fuel oil is mask waste, especially medical masks. The increasing use of masks, especially disposable medical masks, during and after the Covid-19 pandemic has created another problem, namely an increase in medical mask waste in the environment. According to data from the Ministry of Environment and Forestry of Indonesia (KLHK) from the start of the Covid-19 pandemic in March 2020-February 2021 there were 6,417.95 tons of medical waste (Kriswibowo et al., 2021). Medical masks are made of non-woven materials such as polypropylene, polyethylene or cellulose which are known for their resistance to natural degradation (World Health Organization, 2020). This characteristic makes medical mask waste a persistent environmental pollutant, while at the same time providing potential as a hydrocarbon-rich feedstock for fuel production.

The improper management of medical mask waste has led to its accumulation in the environment, posing serious environmental and public health risks. In many cases, medical mask waste is disposed of through open dumping or uncontrolled burning, which can result in soil and water contamination as well as the release of hazardous pollutants (Selvaranjan et al., 2021). From a thermochemical perspective, medical masks represent a promising feedstock for fuel production due to their high polymer content, particularly polypropylene, which consists of long-chain hydrocarbons suitable for conversion into liquid fuels. Previous studies have demonstrated that plastic waste containing polypropylene can be effectively converted into fuel products with properties comparable to conventional fuels (Islami et al., 2020).

Therefore, the conversion of medical mask waste into synthetic fuel has attracted increasing research interest as a dual-solution approach to address both waste management and energy challenges. Among various conversion technologies, pyrolysis has been widely recognized as an effective method for transforming plastic-based waste into liquid hydrocarbons under oxygen-limited conditions. Medical masks containing polypropylene can be used to manufacture fuel. This is because polypropylene has a hydrocarbon group. The fuel produced is in the form of synthetic fuel oil (Synthetic-Oil). Synthetic-Oil or synthetic fuel oil is a fuel consisting of chemical compounds derived from artificial processing of synthetic materials. Therefore, the processing of medical mask waste into synthetic-oil is the main topic of research and development. One way that is used is through the process of pyrolysis.

Pyrolysis has been widely studied as an effective method for converting plastic waste into valuable fuel products (Qureshi et al., 2020). According to previous review studies, the pyrolysis of plastics such as polyethylene and polypropylene can produce liquid hydrocarbons with properties similar to conventional fuels, influenced by process parameters such as temperature, heating rate, and catalyst type (Capellan-Perez et al., 2014). Pyrolysis is a chemical decomposition through a fast or slow heating process without oxygen content. The pyrolysis process is often used in the manufacture of fuel oil because it has advantages compared to other processing processes. According to (Islami et al., 2020) pyrolysis has the advantages of low energy required, the process takes place without the need for pressure, and there are no pollutants and contaminants in the final product. The pyrolysis process can be carried out with or without a catalyst. The use of catalysts has the advantage of increasing the quality of fuel products (Bemis et al., 2012). Previous studies have shown that catalytic pyrolysis using low-cost catalysts such as bentonite can significantly improve fuel properties, accelerate reaction time, and produce liquid fuels comparable to commercial gasoline and diesel, which can be directly used in internal combustion engines (Budsareechai et al., 2019). Various types of catalysts are often used for

the degradation of polypropylene into fuel, including silicone dioxide ( $\text{SiO}_2$ ). The  $\text{SiO}_2$  catalyst has the advantage of having a high particle area, improving product quality and no contaminants affecting yield (Price et al., 2019).

Despite the growing interest in the pyrolysis of plastic waste for fuel production, previous studies have primarily focused on high-temperature processes and conventional catalysts, with limited attention given to the optimization of low-temperature pyrolysis of medical mask waste using silica-based catalysts. In addition, the influence of catalyst concentration on fuel properties such as heating value and density has not been thoroughly investigated. Therefore, this study aims to evaluate the effect of pyrolysis temperature and silicon dioxide ( $\text{SiO}_2$ ) catalyst concentration on the characteristics of synthetic oil derived from medical mask waste. This research specifically investigates relatively low-temperature conditions (200°C and 300°C) combined with varying catalyst concentrations (0%, 1%, and 2%) to analyze their impact on key fuel properties, including heating value and density. This study is expected to contribute to the development of sustainable waste-to-energy technologies, particularly in the utilization of pandemic-related plastic waste.

## RESEARCH METHOD

### Methods

In this study using the experimental method. The research activities carried out included making storage mask, collecting medical mask waste, treating medical mask waste, pyrolysis of medical mask waste, Characteristic testing of synthetic-oil and data analysis. Data analysis is carried out with quantitative descriptive with a comparative approach. The measured data were analyzed comparatively to find solutions to problems through comparisons of causal relationships with the elements studied.

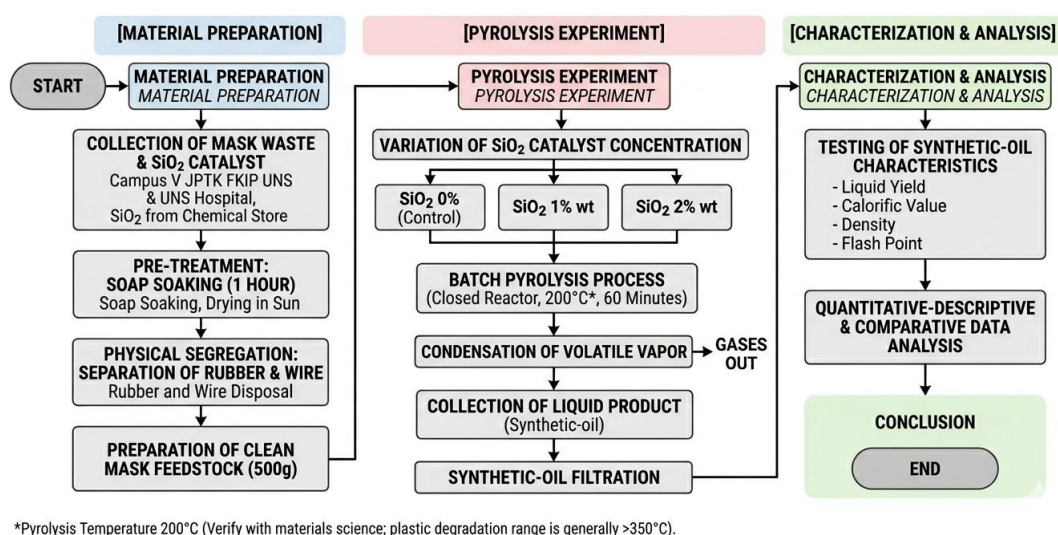


Figure 1. Flowchart Experimental Research Method

The experiment used two pyrolysis temperature levels, namely 200 °C and 300 °C, and three  $\text{SiO}_2$  concentration levels, namely 0%, 1%, and 2%. These variations resulted in six treatment combinations. The 0%  $\text{SiO}_2$  treatment served as the control, while the 1% and 2%  $\text{SiO}_2$  treatments

were used to evaluate the effect of catalyst concentration on the characteristics of the synthetic oil. Each experimental treatment was tested in three independent replicates, designated as Replicate I, Replicate II, and Replicate III. The data presented in the results represent the mean values obtained from the three replicates.

The pyrolysis temperatures of 200 °C and 300 °C were selected to represent two relatively low-temperature operating conditions for evaluating the effect of SiO<sub>2</sub> on medical mask waste conversion. Previous studies have reported liquid product formation from polypropylene-rich plastic waste at approximately 300 °C, while pyrolysis studies of waste masks have also reported substantial liquid production in the 300–350 °C range (Hujuri & Gumma, 2010). Therefore, 300 °C was selected as the higher temperature condition relevant to polypropylene-rich feedstock conversion, while 200 °C was selected as a lower-temperature condition to evaluate the effect of SiO<sub>2</sub> on synthetic oil formation and characteristics at a reduced operating temperature.

The experimental design in six treatment combinations as presented in Table 1.

Table 1. Experimental treatment combinations

| Treatment | Pyrolysis temperature (°C) | SiO <sub>2</sub> concentration (%) |
|-----------|----------------------------|------------------------------------|
| T1        | 200                        | 0                                  |
| T2        | 200                        | 1                                  |
| T3        | 200                        | 2                                  |
| T4        | 300                        | 0                                  |
| T5        | 300                        | 1                                  |
| T6        | 300                        | 2                                  |

## 1. Preparation of Medical Mask Waste

### Material Collection

Medical mask was collected in two places, such as Campus V JPTK FKIP UNS and UNS Hospital. Mask waste was checked and collected weekly and the next step is taken in the research process. We obtained the silicon dioxide catalyst from a chemical store in Surakarta, Central Java, Indonesia. We obtained a insulated jacketed batch pyrolysis reactor, previously designed and fabricated at the Mechanical Engineering Education Workshop, Sebelas Maret University, Surakarta.

### Treatment of medical mask waste

Steps for sorting and washing medical mask waste. Mask waste that has been collected from all storage masks is then sorted and wash using soap for 1 hour. Masks other than medical masks are segregated and not used in research. Next steps is drying and separating masks from rubber and wire. The soaked medical mask is then rinsed and dried in the sun to dry. After that the rubber and wire parts are separated from the mask. Rubber and wire parts were not used in the study.



Mask waste washed process



Mask waste dried process



Mask waste sorted process

Figure 2. Treatment and process of mask waste

## 2. Experiment Set-Up Pyrolysis of medical mask waste

The experimental setup used in this study consisted of a laboratory-scale batch pyrolysis system, as shown in Figure 3. The system comprised a closed cylindrical reactor positioned inside a furnace unit, which served as the primary heating source for the thermal decomposition process. The reactor was supported by a steel frame structure to maintain stability during operation.

The generated pyrolysis vapors were transferred from the reactor through a horizontal connecting pipe to a condensation unit. The condenser was designed as a vertical cylindrical column equipped with an external cooling medium, allowing efficient heat exchange and phase conversion of the volatile compounds into liquid products.

The condensed liquid (synthetic oil) was collected at the bottom section of the condenser, while non-condensable gases were discharged through an outlet. This configuration enabled controlled thermal degradation under oxygen-limited conditions and ensured effective separation between liquid and gaseous products during the pyrolysis process. Experimental steps of pyrolysis of medical mask waste is burned in a pyrolysis reactor tube with a composition of 500 g medical mask and 0 g SiO<sub>2</sub> (without catalyst). Pyrolysis temperature 200°C for 60 minutes. This step is carried out the same for SiO<sub>2</sub> catalyst concentrations of 1% and 2%.

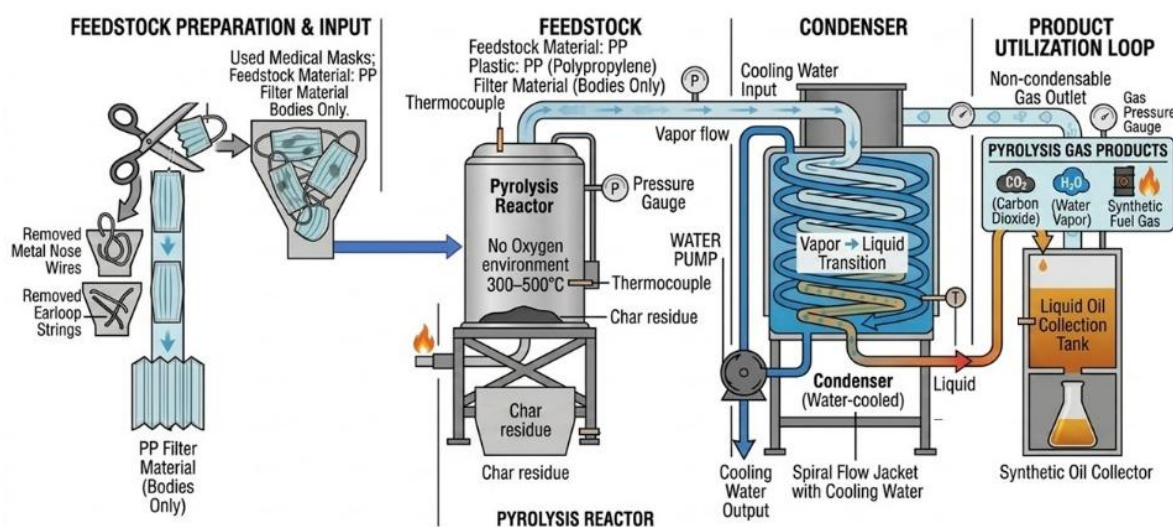


Figure 3. Schematic diagram of the pyrolysis experimental apparatus

### 3. Pyrolysis of medical mask waste

The pyrolysis process was conducted at two temperature levels, 200 °C and 300 °C, with a processing time of 60 minutes for each treatment. SiO<sub>2</sub> was added at concentrations of 0%, 1%, and 2% based on the weight of the medical mask waste. The addition of SiO<sub>2</sub> was intended to facilitate the thermal degradation of medical mask waste during the pyrolysis process. SiO<sub>2</sub> acts as a catalyst that promotes the breakdown of hydrocarbon chains into smaller compounds, thereby affecting the formation and yield of liquid synthetic oil.

The experimental treatment operational procedures was conduct 500 g of prepared medical mask waste was placed in the batch pyrolysis reactor. The pyrolysis process was conducted under oxygen-limited conditions. The resulting pyrolysis vapors were transferred to the condenser, where they were cooled and condensed to obtain the synthetic oil.

The pyrolysis parameter processes presented on Table 2.

Table 2. Pyrolysis Operational Condition

| Parameter                      | Condition                          |
|--------------------------------|------------------------------------|
| Feedstock                      | 500 g medical mask waste           |
| Temperature                    | 200 °C and 300 °C                  |
| Processing time                | 60 min                             |
| SiO <sub>2</sub> concentration | 0%, 1%, 2%                         |
| Atmosphere                     | Oxygen-limited                     |
| Reactor                        | Batch pyrolysis reactor            |
| Product recovery               | Vapor condensation → synthetic oil |

### 4. Characteristic Testing

The next step in this research is that synthetic-oil will be filtered and tested to find the characteristic value. At this stage, the optimal synthetic oil will be sought based on liquid yield, calorific value, density and flash point.

## Material

### 1. Medical Mask

Medical masks waste were used as the primary feedstock in this study. The masks consisted predominantly of non-woven polymer materials, mainly polypropylene (PP), which is widely reported as the major component in disposable medical masks (World Health Organization, 2020). Fadare & Okoffo (2020) further confirmed that the multilayer structure of disposable medical masks—including the outer layer, melt-blown filter layer, and inner layer—are all polypropylene-based, making them highly resistant to natural biodegradation while simultaneously representing a polypropylene-rich feedstock well-suited for thermochemical conversion. The high polypropylene content provides a high hydrocarbon content suitable for thermal cracking into liquid fuels, making it suitable for thermochemical conversion processes such as pyrolysis (Aisien et al., 2021). The collected masks were further processed prior to the experiment, as described in the subsequent section.



Figure 4. Mask waste resulting from treatment

## 2. Silicone Dioxide

Silicon dioxide ( $\text{SiO}_2$ ) was used as a catalyst in this study due to its high surface area and its ability to enhance the thermal degradation of polymeric materials during pyrolysis. Previous studies have reported that catalytic pyrolysis can significantly improve cracking efficiency and increase the yield and quality of liquid fuel products compared to non-catalytic processes. Silicon dioxide ( $\text{SiO}_2$ ) was used as a catalyst in this study. The catalyst was selected due to its high surface area and its effectiveness in enhancing the thermal degradation of polymeric materials during pyrolysis. In this study,  $\text{SiO}_2$  was applied with concentration variations of 0%, 1%, and 2% by weight of the feedstock.



Figure 5. Silicon dioxide powder used as a catalyst

Bemis et al., (2012) conducted a pyrolysis study using polypropylene plastic waste with the addition of various catalysts namely  $\text{SiO}_2$ , Zeolite,  $\text{CaO}$  and Fe. The result is that the  $\text{SiO}_2$  catalyst has effect on reaction temperature, reaction time and product yield percentage as follows:

Table 3. Effect of catalyst on the pyrolysis of polypropylene plastic waste

| Test Parameters                               | The catalyst used |                |         |              |        |
|-----------------------------------------------|-------------------|----------------|---------|--------------|--------|
|                                               | No catalyst       | $\text{SiO}_2$ | Zeolite | $\text{CaO}$ | Fe     |
| First drop temperature ( $^{\circ}\text{C}$ ) | 150               | 130            | 133     | 135          | 166    |
| Last drop temperature ( $^{\circ}\text{C}$ )  | 160               | 160            | 195     | 180          | 166    |
| Total reaction time (minutes)                 | 240               | 100            | 113     | 105          | 110    |
| Liquid product volume (mL)                    | 30                | 33             | 31      | 32           | 32     |
| Product density (g/mL)                        | 0.7206            | 0.7236         | 0.7235  | 0.72         | 0.7203 |
| Product percentage (%)                        | 72.06             | 79.59          | 74.76   | 76.80        | 76.83  |

## RESULTS AND DISCUSSION

The changes in synthetic oil characteristics observed at different pyrolysis temperatures and SiO<sub>2</sub> concentrations are related to the differences in polymer degradation mechanisms and product distribution during thermal conversion. Temperature determines the amount of energy supplied to the polymer matrix, affecting the cleavage of polypropylene molecular chains. Within the investigated temperature range, increasing the pyrolysis temperature increases the thermal energy supplied to the polymer matrix promotes random chain scission, resulting in the formation of smaller hydrocarbon molecules and increasing the amount of volatile products that can be condensed into liquid oil. Excessive thermal severity may also enhance secondary cracking reactions, which convert part of the liquid hydrocarbons into lighter compounds and non-condensable gases, thereby influencing the final characteristics of the produced oil (Ahmad et al., 2015; Al-Salem et al., 2017).

The variation in SiO<sub>2</sub> concentration also affects the conversion behavior of medical mask waste during pyrolysis. The addition of silica-based materials can influence the interaction between polymer chains and solid surfaces, improving heat transfer and modifying the degradation pathway of polypropylene-derived intermediates. Previous studies have reported that silica-containing catalytic systems can alter polypropylene degradation behavior by enhancing polymer-surface interaction and improving the selectivity of hydrocarbon products (Panda & Singh, 2011). Therefore, differences in pyrolysis temperature and SiO<sub>2</sub> concentration may result in variations in the quantity and physicochemical characteristics of the recovered synthetic oil.

### Volume of Synthetic-Oil

From the research that has been done, synthetic-oil is obtained from medical mask waste with the following details.

Table 4. Volume of Synthetic-oil Medical Mask Waste

| No | Sample                                                      | Volume of synthetic-oil (ml) |     |     |         |
|----|-------------------------------------------------------------|------------------------------|-----|-----|---------|
|    |                                                             | Testing                      |     |     | Average |
|    |                                                             | I                            | II  | III |         |
| 1  | 100% Medical Mask Waste Temperature 200 °C                  | 135                          | 140 | 140 | 138.33  |
| 2  | Medical Mask Waste + 1% SiO <sub>2</sub> Temperatur 200 °C  | 180                          | 175 | 180 | 178.33  |
| 3  | Medical Mask Waste + 2% SiO <sub>2</sub> Temperature 200 °C | 210                          | 215 | 200 | 208.33  |
| 4  | 100% Medical Mask Waste Temperature 300 °C                  | 170                          | 180 | 185 | 178.33  |
| 5  | Medical Mask Waste + 1% SiO <sub>2</sub> Temperature 300 °C | 260                          | 275 | 270 | 268.33  |
| 6  | Medical Mask Waste + 2% SiO <sub>2</sub> Temperature 300 °C | 280                          | 290 | 265 | 278.33  |

Based on the data in Table-2, the average liquid volume of Synthetic-Oil in medical mask waste ranges from 138.33 ml to 278.33 ml. The highest liquid synthetic-oil volume was found in samples with a temperature variation of 300 °C with the addition of 2% SiO<sub>2</sub>. Meanwhile, the lowest volume of liquid synthetic-oil was found in samples with a temperature variation of 200 °C at 100% medical mask waste (0% SiO<sub>2</sub>).

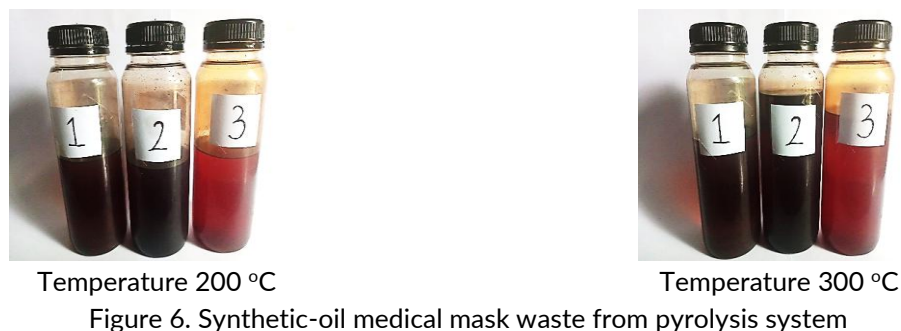


Figure 6. Synthetic-oil medical mask waste from pyrolysis system

Number 1,2 and 3 in Fig. 6. shows that 1 for samples without SiO<sub>2</sub>, 2 for samples with 1% SiO<sub>2</sub> and 3 for samples with 2% SiO<sub>2</sub>. After the volume is obtained, the first test is the yield value test.

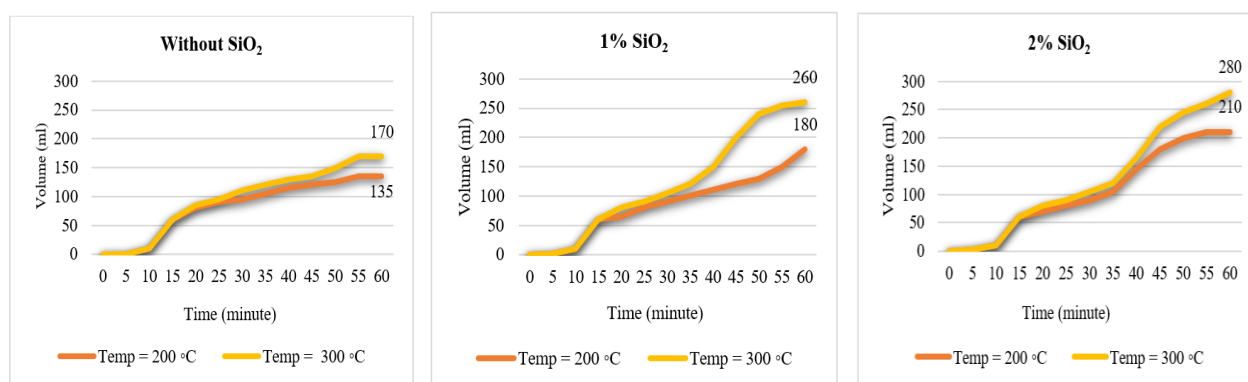


Figure 7. Graph of the volume synthetic-oil from the pyrolysis process of medical mask waste

### Liquid Yield of Synthetic-Oil

Liquid yield testing is carried out to find the percentage ratio of the mass of medical mask waste to the volume of liquid oil produced. Yield of Synthetic-oil calculateusing the formula:

$$\text{Yield (\%)} = \frac{\text{Liquid Volume (ml)}}{\text{Raw Material Mass (gr)}} \times 100 \dots\dots (1)$$

Based on the research that has been done to find out the optimal variations in combustion temperature and SiO<sub>2</sub> concentration based on the yield of liquid synthetic-oil from medical mask waste, it can be described in Figure 8.

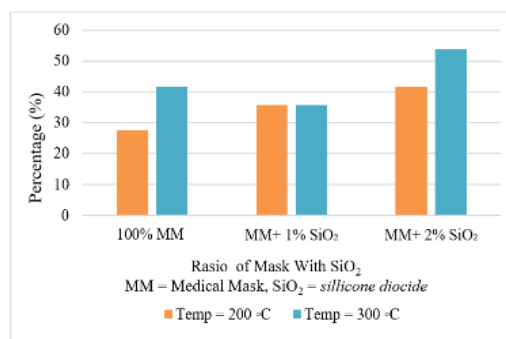


Figure 8. Graph of Liquid yield percentage of synthetic-oil medical mask waste

Based on the data presented in Fig. 8. the highest liquid synthetic-oil yield was found in the sample with a temperature variation of 300 oC with the addition of 2% SiO<sub>2</sub>. Meanwhile, the lowest yield of liquid synthetic-oil was found in samples with a temperature variation of 200 oC at 100% medical mask waste. The yield of liquid synthetic-oil ranges from 27.666% to 55.666%. Based on the results of synthetic-oil liquid yields, the highest yield with a percentage of 55.666% was found in samples with a temperature variation of 300 oC with the addition of 2% SiO<sub>2</sub>.

Table 5. Comparison of Synthetic-Oil Liquid Yield with Other Research

| No | Researcher                   | Research Materials                 | Liquid yield of synthetic-oil (%) | Temperatur of pyrolysis (°C) |
|----|------------------------------|------------------------------------|-----------------------------------|------------------------------|
| 1  | Results of This Research     | 100% MM (T=200°C)                  | 27.666                            | 200                          |
|    |                              | MM + 1% SiO <sub>2</sub> (T=200°C) | 35.666                            | 200                          |
|    |                              | MM + 2% SiO <sub>2</sub> (T=200°C) | 41.666                            | 200                          |
|    |                              | 100% MM (T=300°C)                  | 35.666                            | 300                          |
|    |                              | MM + 1% SiO <sub>2</sub> (T=300°C) | 53.666                            | 300                          |
|    |                              | MM + 2% SiO <sub>2</sub> (T=300°C) | 55.666                            | 300                          |
| 2  | (Ramadhani & Kholidah, 2019) | Styrofoam                          | 32.706 % - 36.758 %               | 500                          |
| 3  | (Riandis et al., 2021)       | HDPE Plastic                       | 11.07 % - 20.87 %                 | 450                          |

Note: MM = Medical Mask, SiO<sub>2</sub> = silicon dioxide

Based on Table 3. These results are higher than the synthetic-oil liquid yield of styrofoam waste with a combustion temperature of 500 °C, which is 32.706% to 36.758% (Ramadhani & Kholidah, 2019) and higher than the liquid synthetic-oil yield of LDPE plastic waste with a combustion temperature of 450 °C namely 11.07% to 20.87% (Riandis et al., 2021). This finding is further supported by Qureshi et al., (2020), who reported that the liquid yield from polypropylene pyrolysis generally falls within the 40–75% range across various temperature conditions, confirming that the yield obtained in this study at 300 °C with 2% SiO<sub>2</sub> (55.666%) is within the competitive range despite operating at a substantially lower temperature than most reported studies.

The yield of synthetic-oil from medical mask waste with the addition of 2% SiO<sub>2</sub> catalyst and a temperature of 300 °C has the highest percentage compared to synthetic-oil from HDPE plastic at 450 and Styrofoam waste at 500. This is due to the content of 73.33% polypropylene (PP) in medical masks can be converted more optimally at a maximum temperature of 300 °C into oil and the presence of a SiO<sub>2</sub> catalyst can lower the reaction temperature so that the pyrolysis process is faster thereby increasing the quality of fuel products. The progressive increase of liquid yield is attributable to consistent with the findings of Palmay et al., (2023), who demonstrated that silica-alumna catalysts lower the activation energy of polypropylene chain scission, accelerating the cracking reaction at sub-optimal thermal conditions and shifting product selectivity toward liquid-phase hydrocarbons. The addition of SiO<sub>2</sub> was associated with an increase in liquid yield under the investigated conditions.

## Calorific Value of Synthetic-Oil

The test of calorific value of synthetic-oil uses a bomb calorimeter with the following details:

- 1) Set up tools and test materials.
- 2) Synthetic-oil 100% medical mask waste weighing 0.6 g is put into the sample test container.
- 3) Prepare a 10 cm long wire and then weigh the wire.
- 4) Attach the wire to the bomb calorimeter.
- 5) The test sample container containing the synthetic-oil of mask waste is put into the bomb calorimeter.  
The wire is dipped a little into synthetic-oil then closed tightly.
- 6) Enter oxygen gas with a pressure of 5 atm into the tool and then release it again.
- 7) Enter oxygen gas with a pressure of 10 atm into the tool and then release it again.
- 8) Put 2 L of water into the water container, then put it in the mantle.
- 9) Put the bomb calorimeter into a container of water, then close it tightly.
- 10) Turn on the bomb calorimeter and the current flowing in the wire.
- 11) Record the initial temperature on the thermometer.
- 12) At 4.58 seconds, the current converter is pressed for 3 seconds.
- 13) Data is recorded every 1 minute.
- 14) After finishing, weigh the remaining wire from the combustion process.
- 15) The data obtained is then processed with the formula:

$$\text{Wire burn factor} : F_k = m_k \times \Delta H_k \dots\dots\dots (2)$$

$$\text{Combustion calorific value} : \Delta H_s = \frac{(\Delta T \times c) - Fk}{m_s} \dots\dots\dots (3)$$

### Note

- $F_k$  : Corection factor  
 $m_k$  : The mass of wire is burning (g)  
 $\Delta H_k$  : Wire burning calorific value (1.400.000 kal/g)  
 $\Delta H_s$  : Sample burning calorific value (kal/g)  
 $\Delta T$  : The difference between the highest and lowest temperatures (°C)  
 $c$  : Calorific capacity (2138,360 kal/ °C)  
 $m_s$  : The mass of sample (g)

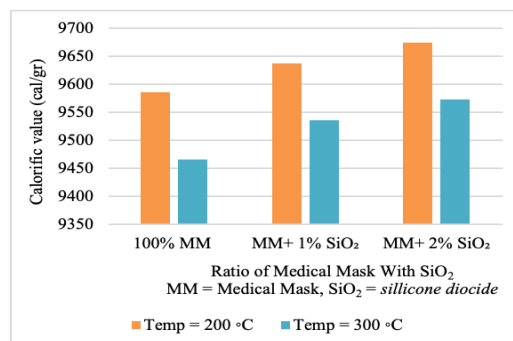


Figure 9. Graph of calorific value of synthetic-oil medical mask waste

The data presented in Figure. 9 indicate that the calorific value increased with increasing SiO<sub>2</sub> concentration at both pyrolysis temperatures. However, increasing pyrolysis temperature from 200°C

to 300°C resulted in a decrease in calorific value under all SiO<sub>2</sub> concentrations. At 200 °C, the calorific value shows a gradual rise from the 100% medical mask sample to mixtures containing 1% and 2% SiO<sub>2</sub>. A similar trend is observed at 300 °C, where all samples exhibit higher calorific values compared to those at 200 °C. The highest calorific value was obtained at 200°C with 2% SiO<sub>2</sub> addition, reaching 9674.54 cal/g. Based on the research findings, the addition of SiO<sub>2</sub> catalyst increases the heating value of the synthetic oil, a higher catalyst concentration consistently leads to an increase in the resulting heating value. Overall, the calorific value ranges from approximately 9465.82 to 9674.54 cal/g, confirming the potential of this material as an alternative fuel source.

Table 6. Comparison calorific value of synthetic-oil with others fuel

| No | Researcher              | Research Materials                  | Calorific value (cal/g) |
|----|-------------------------|-------------------------------------|-------------------------|
| 1. | Result of This Research | 100% MM (T=200 °C)                  | 9586.02                 |
|    |                         | MM + 1% SiO <sub>2</sub> (T=200 °C) | 9636.86                 |
|    |                         | MM + 2% SiO <sub>2</sub> (T=200 °C) | 9674.54                 |
|    |                         | 100% MM (T=300 °C)                  | 9465.81                 |
|    |                         | MM + 1% SiO <sub>2</sub> (T=300 °C) | 9535.46                 |
|    |                         | MM + 2% SiO <sub>2</sub> (T=300 °C) | 9572.91                 |
| 2. | (Islami et al., 2020)   | Diesel (Pertamina)                  | 10334.861               |
| 3. | (Almu et al., 2014)     | Nyamplung Seeds & Rice              | 3431.00 s/d 4792.40     |
|    |                         | Husk                                |                         |

Note: MM = Medical Mask, SiO<sub>2</sub> = silicone dioxide

This result is higher than the calorific value of nyamplung seed bio-oil and rice husk, which is 3431.00 to 4792.40 cal/g (Almu et al., 2014). The calorific value of synthetic-oil from medical mask waste is close to the calorific value of diesel fuel, namely 43.27 MJ/kg = 10334.861 cal/g (Islami et al., 2020). In comparison, Budsareechai et al., (2019) reported calorific values of 40–46 MJ/kg (approximately 9,559–10,990 cal/g) for catalytic synthetic oil from polypropylene-dominant plastic waste at higher process temperatures (400–550 °C). The relatively lower calorific values obtained in this study (9,465–9,674 cal/g) are attributable to the lower pyrolysis temperature applied (200–300 °C), which limits the extent of thermal cracking and produces heavier hydrocarbon fractions. Based on the data obtained from the test results, a pyrolysis temperature of 200 °C produces a higher heating value than a pyrolysis temperature of 300 °C. This result is inversely proportional to (Islami et al., 2020) which stated that the increase in heating value was in line with the increase in pyrolysis temperature.

This inverse relationship between pyrolysis temperature and calorific value observed in the present study may be explained by the selective volatilization mechanism at low temperatures. Sharuddin et al., (2017) in their systematic review of plastic-derived liquid fuels, noted that at relatively low pyrolysis temperatures, thermal cracking predominantly produces medium-chain hydrocarbons with higher energy density per unit mass, whereas at elevated temperatures, secondary cracking reactions become dominant, converting these medium-chain compounds into lighter, lower-calorific gaseous fractions and thereby reducing the overall energy content of the residual liquid product. This mechanism provides a plausible explanation for the higher calorific value observed at 200 °C compared to 300 °C in the present study, despite the general trend reported in the literature for high-temperature pyrolysis regimes.

Miandad et al., (2016) reported calorific values of 42–45 MJ/kg for PP synthetic oil at 300–500 °C, which are higher than the values obtained in this study (≈39.6–40.5 MJ/kg). The lower calorific

values in the present study reflect the less complete thermal cracking achieved at 200–300°C compared to higher-temperature processes, resulting in the predominance of heavier, less-volatile hydrocarbon fractions with slightly lower energy density per unit mass.

The increase in SiO<sub>2</sub> catalyst concentration is in line with the increase in the heating value of the synthetic-oil produced. The improvement in calorific value may be associated with catalytic effects of SiO<sub>2</sub> reported in previous studies, so that the pyrolysis process is faster as a result the increase in the heating value is also higher (Bemis et al., 2012). A low calorific value will result in a low ignition level of the fuel so that the fuel is difficult to burn completely. Based on the test results, the optimal synthetic-oil calorific value was found in the mask waste sample with a 2% SiO<sub>2</sub> concentration at a pyrolysis temperature of 200 °C.

### Density of Synthetic-oil

The test density uses a pycnometer with the following details:

- 1) Prepare tools and test materials
- 2) The mass of the 20 ml pycnometer is weighed empty.
- 3) 100% synthetic-oil medical mask waste is put into the pycnometer bottle until it is full then closed tightly.
- 4) Clean the synthetic-oil liquid that gets on the outer wall of the pycnometer bottle.
- 5) The total mass of the pycnometer containing synthetic-oil is weighed.
- 6) The pycnometer is cleaned and dried
- 7) The density value is calculated by the formula  $\rho = \frac{m_2 - m_1}{v}$  ..... (4)

Note

- $\rho$  : Liquid density (g/ml)  
 $m_2$  : The mass of empty pycnometer (g)  
 $m_1$  : The mass of the pycnometer contains synthetic-oil (g)  
 $v$  : Synthetic-oil volume on the pycnometer (ml)

Based on the results of the density synthetic-oil test that has been carried out, the data is presented in Figure 10.

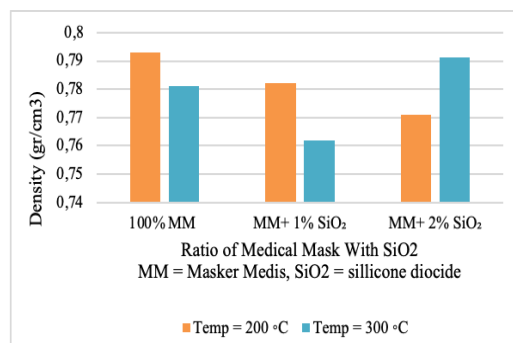


Figure 10. Graph of density of synthetic-oil medical mask waste

Based on the data Figure 10, the density value of synthetic-oil from medical mask waste ranges from 0.76205 to 0.7929 g/cm<sup>3</sup>. The density values did not show a completely linear trend with increasing pyrolysis temperature and SiO<sub>2</sub> concentration. This behavior indicates that density is influenced by the distribution and composition of hydrocarbon fractions formed during pyrolysis. This

happens because the increasing temperature causes the molecules to move freely so that the intermolecular forces weaken and the density decreases (Fardhyanti et al., 2017). In addition, determining the level of SiO<sub>2</sub> catalyst concentration affects the density value. the SiO<sub>2</sub> catalyst functions to accelerate the decomposition reaction and shorten the hydrocarbon chains, making it easier to condense to produce synthetic oil (Ramadhani & Kholidah, 2019).

The density of the synthetic oil did not exhibit a strictly linear response to either pyrolysis temperature or SiO<sub>2</sub> concentration. This behavior is reasonable because the density of pyrolysis oil is primarily determined by the composition and molecular-weight distribution of the condensed hydrocarbon fractions rather than by process temperature or catalyst concentration alone. Catalytic cracking can favor the formation of lower-molecular-weight hydrocarbons, resulting in lower liquid density, whereas differences in reaction severity and product selectivity may also increase the proportion of heavier condensable compounds. Hakeem et al., (2018) reported that catalytic polypropylene pyrolysis produced a lower-density liquid than thermal cracking because enhanced chain scission generated lighter and less waxy products. Similarly, Eldahshory et al., (2023) demonstrated that changes in catalyst type and catalyst-to-polypropylene ratio altered the distribution of light and heavy hydrocarbon fractions.

Table 7. Comparison density of synthetic-oil with other fuels

| No | Fuel Type                          | Density (g/cm <sup>3</sup> ) |
|----|------------------------------------|------------------------------|
| 1. | 100% MM (T=200°C)                  | 0.7929                       |
| 2. | MM + 1% SiO <sub>2</sub> (T=200°C) | 0.7823                       |
| 3. | MM + 2% SiO <sub>2</sub> (T=200°C) | 0.7709                       |
| 4. | 100% MM (T=300°C)                  | 0.78115                      |
| 5. | MM + 1% SiO <sub>2</sub> (T=300°C) | 0.76205                      |
| 6. | MM + 2% SiO <sub>2</sub> (T=300°C) | 0.79125                      |
| 5. | Gasoline and others                | 0.715 – 0.770                |
| 6. | Diesel and others                  | 0.815 – 0.870                |

Note: MM = Medical Mask, SiO<sub>2</sub> = silicone dioxide

Based on Table 5, The density value is close to the density value of gasoline-type fuel with a value of 0.715 to 0.770 g/cm<sup>3</sup> (Miandad et al., 2016). This result is also in ageement Olalo (2021) who reported that pyrolytic oil from polypropylene-based municipal plastic waste exhibited density values in the range of 0.82–0.87 g/cm<sup>3</sup> at pyrolysis temperatures of 400–500 °C. The lower density values observed in the present study are attributable to the lower process temperatures (200–300 °C) employed, which promote the formation of lighter hydrocarbon fractions with reduced intermolecular forces, consistent with the explanation provided by the reduction in density at elevated temperatures. The optimal synthetic-oil density values were found in samples with a temperature variation of 300 °C with the addition of 1% SiO<sub>2</sub> catalyst. The density values obtained in the present study are in close ageement with those reported by Miandad et al., (2016) for polypropylene synthetic oil at comparable process temperatures (300 °C), where density values of 0.780–0.820 g/cm<sup>3</sup> were recorded. The slight deviation in the present study – particularly the lower density at 300 °C with 1% SiO<sub>2</sub> (0.76205 g/cm<sup>3</sup>) –can be attributed to the catalytic effect of SiO<sub>2</sub> in promoting the formation of lighter hydrocarbon fractions through enhanced chain scission, which effectively reduces the average molecular weight and consequently the density of the liquid product.

### Flash Point of Synthetic-oil

The flash point test uses a flash point tester with the following details:

- 1) Prepare tools and test materials.
- 2) Open the sample cup cover.
- 3) Pour the 100% synthetic-oil sample of medical mask waste up to the mark, which is 75 ml.
- 4) Place the cup into the heating block and close it tightly again.
- 5) Setting the flash point tester by entering the testing temperature.
- 6) Start the test by simultaneously pressing the up and down arrow keys.
- 7) When the temperature is between 23–28 °C. The stirrer is turned off and the flame is turned on by sliding the sample cup cover and the flame supply from the burner nozzle.
- 8) Every 1 °C increase, turn on the fire like step (7).
- 9) If the sample ignites and burns the vapor in the cup clearly, then the temperature at this condition is referred to as the flash point.
- 10) The test result data is recorded.
- 11) Turn off the tool and clean the sample cup.

Based on the results of the flash point synthetic-oil test that has been carried out, the data is presented in Figure 11.

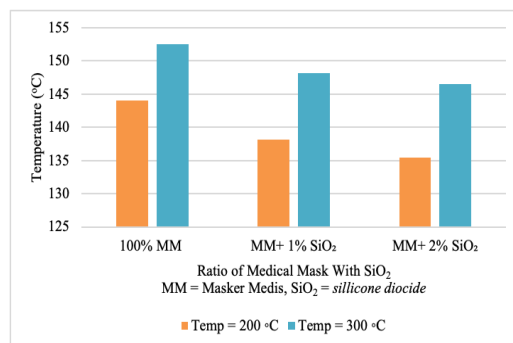


Figure 11. Graph of flash point of synthetic-oil medical mask waste

Based on the data presented, the results of the synthetic-oil flash point test ranged from 135.5 °C to 152.5 °C. This result is higher than PS (polystyrene) plastic synthetic oil, which is 35 °C (Fardhyanti et al., 2017). Pyrolysis temperature of 400–500 °C. Differences in flash point values can occur due to differences in types, composition of raw materials and pyrolysis temperatures used. In this study, increasing pyrolysis temperature from 200 °C to 300 °C increased the flash point values for all SiO<sub>2</sub> concentrations. Meanwhile, increasing SiO<sub>2</sub> concentration resulted in lower flash point values, indicating that catalyst addition affected the produced synthetic oil. The lower the flash point of a fuel, the easier it is to burn. The use of a catalyst also has an effect on reducing the flash point value in fuel. Based on the data from the flash point test results in Figure 9, it shows that the increasing concentration of the SiO<sub>2</sub> catalyst causes the flash point value to decrease which indicates that the fuel is more flammable.

The flash point value of synthetic-oil from medical mask waste is higher than that of PS plastic because the pyrolysis temperature of medical mask waste is 200–300 °C lower than the pyrolysis temperature of PS plastic waste, which is 400–500 °C. So based on the results of this flashpoint test, synthetic-oil from medical mask waste is closer to diesel fuel which has a minimum flash point of 55

°C (Pertamina). In this study, lower synthetic-oil flash point values were found in medical mask waste samples with the addition of 2% SiO<sub>2</sub> catalyst at a pyrolysis temperature of 200 °C, whereas the highest flash point occurred in the sample without SiO<sub>2</sub> at 300 °C. These findings indicate that elevated temperatures contribute to a higher flash point. Furthermore, the addition of the SiO<sub>2</sub> catalyst is effective in lowering the fuel's flash point. Future research should investigate the upgrading of synthetic oil through fractional distillation or hydrotreatment processes, which have been shown by Moonsin et al., (2025) to be effective in reducing the flash point of plastic-derived synthetic oil to levels suitable for direct blending with commercial diesel or gasoline.

Table 8. Comparison flash point of synthetic-oil with other fuels

| No | Fuel Type                          | Flash Point (°C) |
|----|------------------------------------|------------------|
| 1. | 100% MM (T=200°C)                  | 144              |
| 2. | MM + 1% SiO <sub>2</sub> (T=200°C) | 138.2            |
| 3. | MM + 2% SiO <sub>2</sub> (T=200°C) | 135.5            |
| 4. | 100% MM (T=300°C)                  | 152.5            |
| 5. | MM + 1% SiO <sub>2</sub> (T=300°C) | 148.2            |
| 6. | MM + 2% SiO <sub>2</sub> (T=300°C) | 146.5            |
| 7. | Plastic PS                         | 35               |
| 8. | Diesel and others                  | Min 55           |
| 9. | Gasoline and others                | -15              |

Based on the results of the fuel characteristic test, the character of synthetic oil from medical mask waste is close to that of gasoline, and the addition of SiO<sub>2</sub> catalyst is able to increase the quality of synthetic-oil and concentration levels which produce the high synthetic fuel, namely the concentration of 2%. while the temperature that produces the synthetic fuel for medical mask waste is 200 °C.

## CONCLUSION

Based on the research results, it can be concluded variations in pyrolysis temperature and SiO<sub>2</sub> concentration resulted in differences in the characteristics of synthetic oil produced from medical mask waste. The highest liquid yield of 55.666% was obtained at a pyrolysis temperature of 300 °C with the addition of 2% SiO<sub>2</sub>. The highest calorific value of 9674.54 cal/g was obtained at 200 °C with 2% SiO<sub>2</sub> addition among the tested treatments. The lowest density value of 0.76205 g/cm<sup>3</sup> was obtained at 300 °C with 1% SiO<sub>2</sub>, while the highest flash point value of 152.5 °C was obtained at 300 °C without SiO<sub>2</sub> addition. These results show that variations in pyrolysis temperature and SiO<sub>2</sub> concentration are associated with changes in the yield and physicochemical properties of synthetic oil derived from medical mask waste.

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