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The Effect of ZSM-5 Zeolite and Dolomite Catalysts on the Performance of Plastic Waste Pyrolysis

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ABSTRACT

The increasing volume of waste in Indonesia, particularly plastic waste, has led to significant environmental challenges due to its continuous accumulation. Pyrolysis offers a sustainable alternative to conventional disposal methods, such as landfilling and incineration, which are known to contribute to pollution. Pyrolysis is a thermochemical decomposition process carried out in an oxygen-deficient environment, converting plastic waste into valuable products, including gas, oil, and char. These products have various applications: the gas can be used as a fuel, the oil as a liquid fuel, and the char as a solid fuel. This study investigates the pyrolysis of three types of plastic feedstocks: high-density polyethylene (HDPE), polypropylene (PP), and a 50:50 mixture of HDPE and PP. The catalysts employed were ZSM-5 zeolite, dolomite, and a mixed catalyst comprising ZSM-5 zeolite and dolomite, with a catalyst-to-feedstock ratio of 0.2:1. The results revealed that the highest oil yields were achieved using the ZSM-5 zeolite catalyst, producing 243 ml from HDPE, 370 ml from PP, and 380 ml from the HDPE-PP mixture. Conversely, the dolomite catalyst yielded the lowest oil production, with 82 ml from HDPE, 20 ml from PP, and 282 ml from the HDPE-PP mixture. Additionally, the ZSM-5 zeolite catalyst demonstrated a consistent increase in the oil production rate every 10 minutes across all feedstocks. These findings highlight the effectiveness of ZSM-5 zeolite in enhancing oil yield during pyrolysis, offering a viable pathway for converting plastic waste into valuable energy resources.

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1. INTRODUCTION

In the current industrial era, the use of plastics and fossil fuels has become integral to daily life. However, the global issues surrounding plastic waste accumulation and the depletion of fossil fuel reserves are increasingly pressing concerns [1,2]. An alternative solution is needed to address both challenges, and pyrolysis has emerged as a promising method to mitigate these problems [3,4]. Pyrolysis is a recycling method that converts waste into useful products, but its adoption in Indonesia remains limited. Notably, pyrolysis is part of the European Union's 2030 target for large-scale plastic waste management [5].

In Indonesia, the total waste generated in 2022 reached 19.45 million tons, representing a 37.52% reduction compared to 2021’s 31.13 million tons [6,7]. Although plastic can be recycled, each recycling cycle shortens the polymer chains, reducing the material’s quality and lifespan. After several cycles, the plastic may become unsuitable for further production [8,9].

Previous studies have explored pyrolysis under various conditions. For instance, one study processed 1 kg of high-density polyethylene (HDPE) plastic waste mixed with catalysts at different catalyst-to-plastic ratios (0, 0.05, 0.1, 0.15, 0.2, and 0.25) and a reaction temperature of 500°C. The results demonstrated that a catalyst-to-plastic ratio of 0.2 at 500°C optimized oil production, suggesting that pyrolysis has significant potential as a renewable energy alternative. The resulting pyrolysis oil exhibited characteristics similar to conventional fuels [10].

Another study employed zeolite catalysts with 100 grams of polypropylene (PP) plastic, subjected to pyrolysis for 60 minutes at varying temperatures (300°C, 350°C, and 400°C) and catalyst concentrations (5%, 6%, and 7%). The highest liquid yield of 75.69% was achieved at 400°C with 7% zeolite, and the oil's calorific value closely matched that of diesel fuel [11].

Further research combined HDPE and PP plastics in a 50:50 ratio and subjected them to pyrolysis at various temperatures (200°C, 250°C, 300°C, 350°C, 400°C, and 450°C) for 80 minutes. The highest oil yield (350 mL) was achieved at 450°C, with a density of 670–790 kg/m^3, viscosity of 1.611–2.401 cP, and calorific value of 7393.7584–8946.3759 cal/g [12,13]

A more recent study utilized PP plastic and a ZSM-5 zeolite catalyst in a reactor operated between 500°C and 560°C, equipped with four bubble cap trays to collect distilled oil. The maximum liquid yield (68.43 wt%) was obtained at 560°C. Based on API gravity, the trays contained different fractions: gasoline (tray I), kerosene (tray II), and heavier oils (trays III and IV). The results indicated that ZSM-5 increased oil yield and produced a gas composition similar to fossil fuels, as evidenced by density, calorific value, octane rating, and functional group analysis [14].

The distinction of this study lies in its focus on pyrolyzing recycled plastic waste using HDPE, PP, and HDPE-PP blends as feedstocks, along with varying catalysts (non-catalytic, ZSM-5 zeolite, dolomite, and a ZSM-5-dolomite blend). These types of plastics are widely found in society, especially in food and beverage packaging. Previous studies have shown that ZSM-5 enhances oil yield, while dolomite reduces it. By employing a combination of ZSM-5 and dolomite, this study aims to investigate whether the mixed catalysts can improve oil yields compared to non-catalytic, ZSM-5, or dolomite-only processes.

2. METHOD

Fig. 1 shows the experimental apparatus, consisting of: (1) reactor; (2) condenser; (3) water pump; (4) fire chamber; (5) gas source (*elpiji*); (6) thermocouple; (7) cold water container; (8) liquid smoke container; (9) pipe; (10) water pipe; (11) data logger; and (12) laptop.

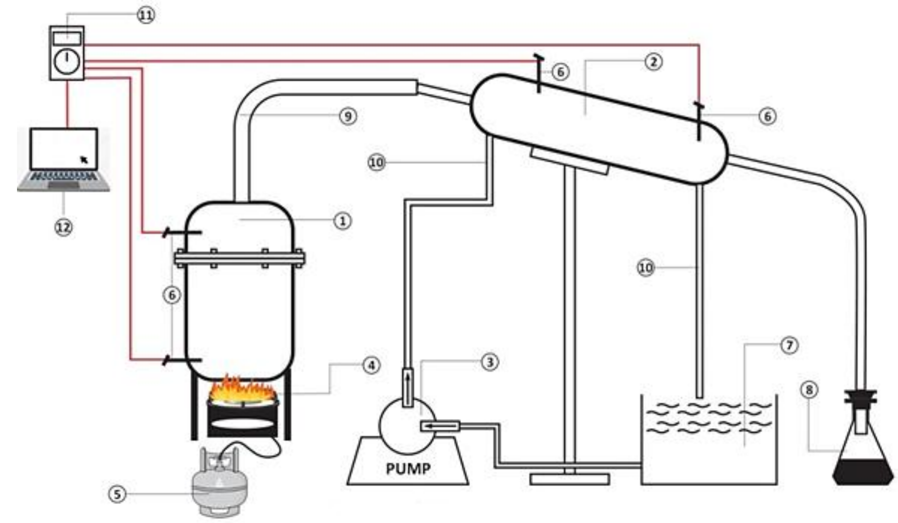

Figure 1. Experimental apparatus.

The study involves several variables to analyze the effectiveness of the pyrolysis process for converting plastic waste into oil and char. The independent variables include the type of catalyst used, which comprises zeolite, dolomite, and a 50:50 mixture of ZSM-5 zeolite and dolomite. The plastic waste materials tested are high-density polyethylene (HDPE), polypropylene (PP), and a mixture of both. The HDPE plastic is shredded into pieces measuring 2–4 cm, while the recycled PP plastic has a length of 3.5–3.8 mm and a diameter of 3.2–3.3 mm. Additionally, the dolomite catalyst is prepared with a particle size of 100 mesh, and the ZSM-5 zeolite catalyst is used in a size range of 1.7–2.5 mm.

The dependent variables observed in this research are the yields of oil and char obtained from the pyrolysis process. The oil yield represents the volume of liquid fuel produced, while the char yield corresponds to the solid residue generated. To ensure consistency and reliability, the pyrolysis process duration is controlled and maintained at 1 hour across all experiments. This comprehensive setup allows for a detailed examination of how variations in catalysts and plastic types influence the efficiency and output of the pyrolysis process.

3. RESULTS AND DISCUSSION

3.1. Oil Yield

The use of ZSM-5 zeolite in the pyrolysis of HDPE plastic produces a higher oil yield, while the use of dolomite as a catalyst results in a lower oil yield. These findings align with the study by Thahir et al. (2021), which demonstrated that ZSM-5 zeolite catalysts enhance oil production during pyrolysis. Similarly, Duanguppama et al. (2023) found that the use of dolomite catalysts results in reduced oil yield.

In the pyrolysis of PP plastic, ZSM-5 zeolite also leads to higher oil production, whereas dolomite reduces the oil yield. Referring to Figure 2, the use of ZSM-5 zeolite catalysts effectively increases the oil yield for several types of plastic feedstock tested. This indicates that ZSM-5 zeolite enhances the decomposition efficiency during the pyrolysis process. Conversely, dolomite catalysts tend to decrease the amount of oil produced. The mixed catalyst of ZSM-5 zeolite and dolomite increases the oil yield for PP and the HDPE-PP mixture but reduces the oil yield for HDPE compared to HDPE processed without a catalyst.

According to Table 1, ZSM-5 zeolite produces a higher oil yield compared to other catalyst variations for HDPE and PP plastics. However, for the HDPE-PP mixture, ZSM-5 zeolite yields less oil than the non-catalyst mixture. This suggests that the catalyst's effectiveness may vary depending on the type of plastic feedstock and its composition.

Table 1. Oil yield.

No	Types of Plastic Waste and Catalyst	Oil yield volume (ml)	Oil density (gr/ml)	Oil yield percentage (%)
1	HDPE non-catalyst	167	0,742	12,39
2	HDPE + Zeolite ZSM-5	243	0,756	18,37
3	HDPE + Dolomite	82	0,772	6,33
4	HDPE + mixture	117	0,726	8,49
5	PP non-catalyst	37	0,755	2,79
6	PP + Zeolite ZSM-5	370	0,76	28,12
7	PP + Dolomite	20	0,966	1,93
8	PP + mixture	184	0,756	13,91
9	HDPE-PP non-catalyst	325	0,748	24,31
10	HDPE-PP + Zeolite ZSM-5	380	0,758	28,80
11	HDPE-PP + Dolomite	282	0,754	21,26
12	HDPE-PP + mixture	365	0,764	27,88

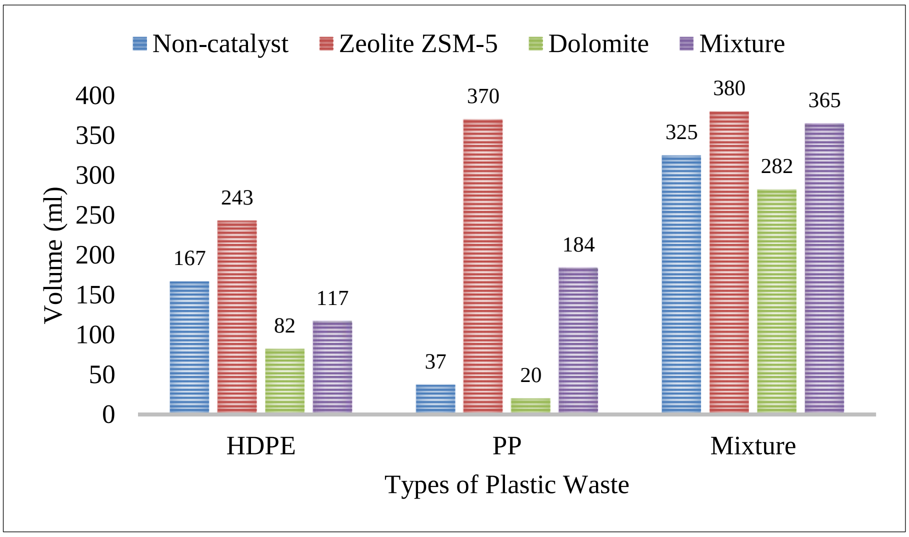

Figure 2. Oil yield of pyrolysis process with variation on types of plastic waste and catalyst.

3.2. Char and Gas Yields

The results in Table 2 and Fig. 3 for char yield reveal significant variations based on the type of plastic waste and catalyst used. For HDPE, the highest char yield was observed when dolomite was used as a catalyst (87.77%), while the lowest char yield was with ZSM-5 zeolite (68.82%). This indicates that dolomite may hinder the complete decomposition of HDPE during pyrolysis, resulting in higher residual char. In contrast, ZSM-5 zeolite facilitates more effective thermal decomposition, reducing char yield and increasing the production of other byproducts.

Similarly, for PP plastic, dolomite resulted in a char yield of 72.97%, which is higher than that observed with ZSM-5 zeolite (57.92%). A similar trend was noted for the HDPE-PP mixture, where ZSM-5 zeolite reduced char yield to 44.12%, compared to 63.22% for dolomite. These results suggest that ZSM-5 zeolite enhances the breakdown of polymer chains, leading to a more significant conversion of plastic into oil and gas products, thereby reducing the char formation.

The gas yield showed an inverse relationship with char yield, further supporting the role of catalysts in influencing pyrolysis behavior. For HDPE, the use of ZSM-5 zeolite resulted in the highest gas yield (12.81%), compared to 5.9% with dolomite. A similar pattern was observed for PP plastic, where ZSM-5 zeolite produced the highest gas yield (13.96%), significantly exceeding the gas yield from dolomite (25.1%). This demonstrates the catalytic efficiency of ZSM-5 in enhancing gas formation during pyrolysis.

For the HDPE-PP mixture, ZSM-5 zeolite also showed the highest gas yield (27.08%), while dolomite resulted in a lower gas yield of 15.52%. The mixed catalyst of ZSM-5 zeolite and dolomite produced intermediate results for both char (54.27%) and gas yields (17.85%), indicating a balanced catalytic effect between the two.

Table 2. Char and gas yields.

No	Types of Plastic Waste and Catalyst	Char Mass (gr)	Char yield (%)	Gas yield (%)
1	HDPE non-catalyst	777,7	77,77	9,84
2	HDPE + Zeolite ZSM-5	688,2	68,82	12,81
3	HDPE + Dolomite	877,7	87,77	5,9
4	HDPE + mixture	825,7	82,57	8,94
5	PP non-catalyst	895,7	89,57	7,64
6	PP + Zeolite ZSM-5	579,2	57,92	13,96
7	PP + Dolomite	729,7	72,97	25,1
8	PP + mixture	704,7	70,47	15,62
9	HDPE-PP non-catalyst	662,5	66,25	9,44
10	HDPE-PP + Zeolite ZSM-5	441,2	44,12	27,08
11	HDPE-PP + Dolomite	632,2	63,22	15,52
12	HDPE-PP + mixture	542,7	54,27	17,85

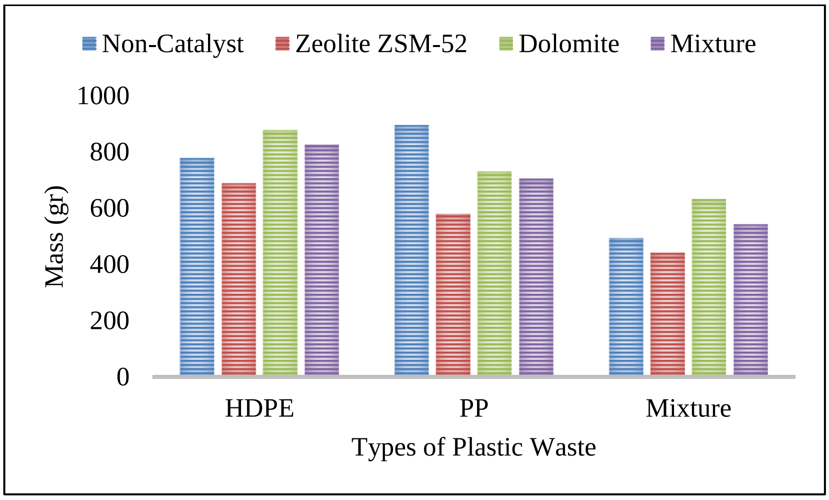

Figure 3. Char and gas yields of pyrolysis process with variation on types of plastic waste and catalyst.

The findings illustrate that the type of catalyst significantly impacts the distribution of pyrolysis products. ZSM-5 zeolite, known for its high acidity and structural properties, promotes cracking reactions that lead to a higher conversion of plastic into gas products while minimizing char formation. On the other hand, dolomite, primarily composed of calcium magnesium carbonate, demonstrates a lower catalytic activity in cracking polymer chains, resulting in higher char and lower gas yields.

The mixed catalyst combines the properties of both ZSM-5 and dolomite, leading to moderate results. For the HDPE-PP mixture, the mixed catalyst produced a relatively balanced char and gas yield, highlighting its potential for applications where a combination of oil and gas products is desired.

Overall, ZSM-5 zeolite emerges as the most effective catalyst for maximizing gas production and minimizing char yield, making it a promising choice for improving the efficiency of pyrolysis processes aimed at producing gaseous fuels.

4. CONCLUSION

The analysis reveals that the use of catalysts in the pyrolysis process for HDPE, PP, and HDPE-PP mixed plastics significantly impacts the resulting oil yield. The ZSM-5 zeolite catalyst proved to be highly effective, producing the highest oil yields for all tested plastic types. Specifically, the oil yields were 243 ml for HDPE plastic, 370 ml for PP plastic, and 380 ml for the HDPE-PP mixture. On the other hand, the use of dolomite as a catalyst led to a considerable reduction in oil yield, with only 82 ml obtained from HDPE plastic, 20 ml from PP plastic, and 282 ml from the HDPE-PP mixture. This highlights the efficiency of ZSM-5 zeolite in enhancing oil production compared to dolomite.

In conclusion, the ZSM-5 zeolite catalyst is highly effective in optimizing both oil yield and production rates during the pyrolysis process, making it a superior choice for converting plastic waste into liquid fuel. Meanwhile, the dolomite catalyst showed limited effectiveness in achieving high oil yields or production rates, indicating its lower suitability for such applications.

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