Optimization polyethylene plastic pyrolysis: Characterization and catalytic activity of ende natural zeolite

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ABSTRACT

This study focuses on optimizing the pyrolysis of polyethylene plastic waste using Ende natural zeolite as a catalyst, activated by 7 M sulfuric acid. Activation significantly enhanced the zeolite's Si/Al ratio, total acidity, and surface area, improving its catalytic properties. Pyrolysis was conducted across temperatures ranging from 350 °C to 500 °C, with catalyst compositions of 5%, 10%, and 15%. The optimal condition was found at 400 °C with 10% catalyst, yielding the highest amount of liquid hydrocarbons suitable for fuel production. The results demonstrate that acid-activated Ende natural zeolite is highly effective in catalyzing the conversion of plastic waste into valuable hydrocarbon products. These findings contribute to developing sustainable waste management strategies by improving pyrolysis efficiency. Future research should investigate the long-term stability of this catalyst and evaluate the performance of different zeolite sources to enhance plastic waste conversion further.

Keywords: *Catalyst, Plastic, Polyethylene, Pyrolysis, Ende natural zeolite*

INTRODUCTION

Plastic waste has become a critical environmental issue, with millions of tons produced globally each year [1]. A significant portion of this waste, particularly single-use plastics and packaging materials, ends up in landfills and oceans, leading to severe pollution and harm to wildlife [2]. Microplastics, which result from the degradation of larger plastic items, have infiltrated ecosystems and food chains, posing risks to human health [3]. Current waste management practices, including recycling, landfilling, and incineration, often fall short due to contamination and low recycling rates, exacerbating the problem [4]. Pyrolysis emerges as a promising solution, converting plastic waste into valuable products such as oil and gas through thermal decomposition. This process not only reduces waste volume but also offers a sustainable method for energy recovery [5]. Research into the optimization of pyrolysis is essential for developing effective strategies to mitigate plastic waste and its environmental impact, making it a crucial area of study for policymakers and industry stakeholders [6].

Zeolite has high surface acidity and features pores that form channels in its framework. This structure makes it highly reactive and suitable for use as a catalyst, capable of selecting reactant sizes in the production of light phase hydrocarbons from pyrolysis products [7]. Indonesia has large reserves of zeolite mineral deposits, including Ende Regency, East Nusa Tenggara [8]. The problem with using zeolite taken directly from nature is that its characteristics vary greatly, because it is very dependent on the environment in which it is formed, namely temperature, pressure, reaction time, concentration and dissolved materials, such as hydrogen ions (H^+), silica, aluminum, alkali and alkaline earth cations [9]. Indonesian natural zeolites primarily consist of mordenite and clinoptilolite types, each with distinct characteristics requiring specific activation methods [10]. Activation can be physical or chemical, depending on the intended application [11]. Physical activation involves reducing grain size or calcination at temperatures above 500 °C, while chemical activation uses acid or alkaline solutions to remove impurities and modify zeolite characteristics [12]. Recent studies have shown that acid treatment produces better quality oil compared to alkaline treatment in palm oil pyrolysis [13]. Acid-activated zeolite catalysts have demonstrated high conversion rates, producing up to 80% polystyrene from used tires and achieving gasoline-quality hydrocarbons of 96.71% from propylene [14]. The performance of natural zeolite catalysts is intrinsically linked to their formation environment and specific reactants [15].

The form of activation selection will also greatly influence the activity of the zeolite as a catalyst [16]. The activity of zeolite catalysts in the pyrolysis of palm oil shows that acid treatment (HCl) produces oil with better quality than alkaline treatment (NaOH) [17]. The activity of the zeolite catalyst in the pyrolysis of used tires with acid treatment is capable of converting up to 80% of polystyrene from used tires with premium-like quality [18]. Therefore, it can be stated that zeolite is suitable for use as a catalyst in this context; the zeolite activation process should be carried out with acid treatment.

The activity of the Aceh natural zeolite catalyst in the pyrolysis of propylene with acid treatment produces quality hydrocarbons such as gasoline of 96.71% [19]. The activity of the Sukabumi natural zeolite catalyst in the pyrolysis of polyethylene with acid treatment produces quality hydrocarbons such as gasoline of 66.71% [20]. Consequently, it can be said that the performance of natural zeolite catalysts is closely linked to the characteristics of their formation environment and the specific reactants involved. In another study, activation of zeolite Y was carried out by treatment with sulfuric acid (H_2SO_4) 7 M at 40 °C produces the best total and surface acidity [21].

The primary objectives of this study are to characterize the physical and chemical properties of Ende natural zeolite activated by H_2SO_4, focusing on changes in the Si/Al ratio, total acidity, surface area, and pore structure. This characterization will provide a comprehensive understanding of how activation influences the zeolite's catalytic properties. Additionally, the study aims to evaluate the catalytic activity of the activated zeolite in the pyrolysis of polyethylene plastic waste at varying temperatures and catalyst compositions. By determining the optimal conditions for hydrocarbon production, this research seeks to identify the most effective parameters for maximizing yield. Furthermore, the study will analyze the impact of the zeolite catalyst on the yield and quality of liquid hydrocarbons produced during the pyrolysis process, comparing the results with existing literature on similar catalysts to highlight advancements in the field. Lastly, the research will assess the environmental implications of using activated zeolite in plastic waste management, emphasizing its potential role in sustainable waste reduction strategies. Through these objectives, the study aims to contribute valuable insights into the effective utilization of natural zeolite as a catalyst in addressing the pressing issue of plastic waste.

EXPERIMENTAL

The zeolite was sourced from Ondorea Village, located in the Nangapanda Sub-district of Ende Regency, East Nusa Tenggara Province, Indonesia. The materials used in this research include natural zeolite from Ende, which is activated and utilized as a catalyst. Ion-free water is employed to wash and clean the zeolite of impurities upon extraction from nature, as well as to neutralize the acidity of the zeolite after the dealumination process. A 7 M solution of H_2SO_4 is used to carry out the dealumination process, simultaneously cleaning impurities and stabilizing the crystal structure of the Ende natural zeolite [21].

The natural zeolite was characterized before and after activation, focusing on several key properties, including crystallinity, Si/Al ratio, total acidity, surface area, pore diameter and volume, and surface morphology. Crystallinity was analyzed both qualitatively and quantitatively; qualitative analysis was performed using Fourier Transform Infrared Spectroscopy (FTIR) over a wavelength range of 4000-500 cm^{-1}, while quantitative analysis was conducted using X-ray Diffraction (XRD) at an angle of 2 theta from 10° to 90°. The Si/Al ratio was determined using Atomic Absorption Spectroscopy (AAS), which involved digesting the zeolite sample in an acid solution and measuring the concentrations of silicon and aluminum. Total acidity was assessed through the gravimetric method, utilizing pyridine gas to interact with acidic sites on the zeolite. The surface area was analyzed using the Brunauer-Emmett-Teller (BET) method, which involved nitrogen adsorption at liquid nitrogen temperature, while the pore volume and diameter were determined using the Barrett-Joyner-Halenda (BJH) method, which analyzes the desorption branch of the isotherm. Finally, surface morphology was examined using Scanning Electron Microscopy (SEM) at a magnification of 10,000X, allowing for detailed visualization of the zeolite's surface features.

Plastic Preparation: The plastic chosen was PE because it is considered the waste with the largest quantity [22]. Plastic is collected from waste disposal sites, then washed and air-dried for several days until completely dry, then cut into sizes ±5 mm^2 [23] of 500 grams for each reaction in pyrolysis.

Plastic pyrolysis: 500 grams of polyethylene plastic was put into the pyrolysis reactor. The pyrolysis process is carried out at a temperature of 350 °C up to 500 °C while turning it on stopwatch. The initial time and temperature are recorded when the oil is first dripped and the pyrolysis process is stopped when the oil no longer drips, then the volume of oil produced is measured [24]. The above process uses a catalyst with a ratio 5%, 10% and 15% of the total weight of polyethylene plastic. The schematic diagram of the pyrolysis apparatus shown in Fig. 1.

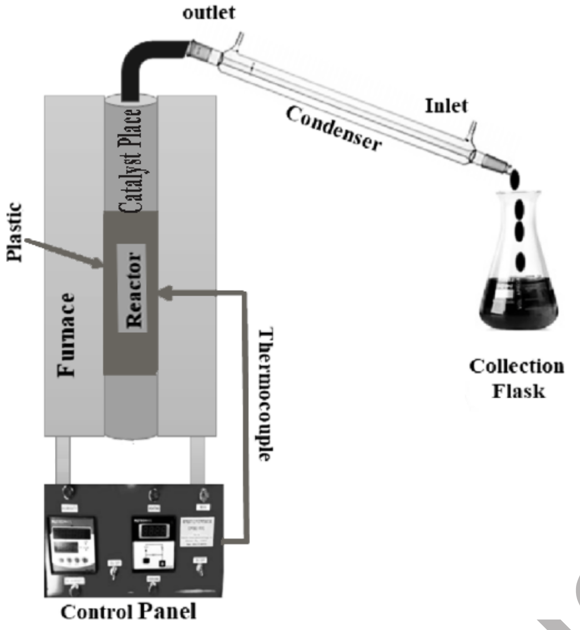


Fig. 1. The schematic diagram of the pyrolysis apparatus

Note: The system includes: (1) a furnace providing heat to the reactor chamber where the pyrolysis reaction takes place, (2) the reactor containing the catalyst bed where thermal decomposition occurs, (3) a thermocouple attached to the reactor for real-time temperature monitoring, (4) a control panel to regulate operational parameters such as temperature and reaction time, (5) a condenser used to cool down the pyrolysis vapors converting them into liquid form, and (6) a collection flask which collects the condensed pyrolysis liquid product.

Data analysis: Experimental data on the pyrolysis process from each sample treatment were processed statistically using surface response analysis following the equation:

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X_i^2 + \cdots \sum_{i<j} \beta_{ij} X_i X_j \; .... \qquad (1)$$

Note: Y= Surface Response, β_0 = intercept, β_i = regression coefficient, β_{ij} = quadratic coefficient, β_{ij} = interaction coefficient, X_iX_j = independent variable.

Significant surface analysis results are tested using the Turkey HSD test (Honestly Significance Diffirence) [25].

RESULTS AND DISCUSSION

Zeolite characteristics: Use of sulfuric acid (H_2SO_4) 7 M with a reflux temperature treatment of 40 °C for the activation of Ende's natural zeolite aims to remove organic and inorganic impurities that cover the surface and pore channels, as well as filling the lack of charge in the zeolite framework with hydrogen ions (H^+) from H_2SO_4 [21]. The presence of H^+ will increase the Bronsted acid sites in the zeolite framework, thus making the zeolite more reactive, and suitable for use as a catalyst [26]. In the process of activation some silica compounds (SiO_2) and alumina (Al_2O_3) will also dissolve and come out of the zeolite framework, thus affecting the Si/Al ratio of Ende natural zeolite [27]. The results of the FTIR analysis are presented in Fig. 2.

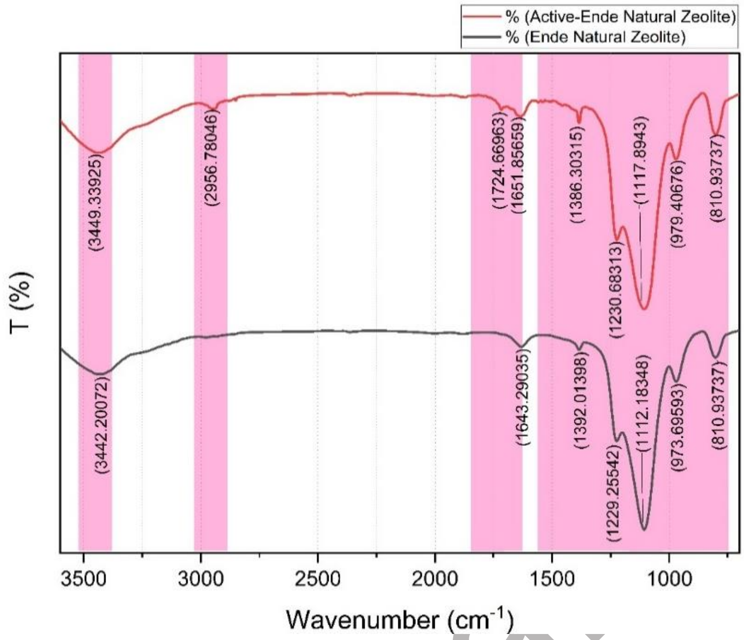


Fig. 2. Results of FTIR analysis of Ende natural zeolite in each acid activation treatment.

Note: FTIR spectra comparing Active-Ende Natural Zeolite (red line) and Ende Natural Zeolite (black line). The graph shows transmittance percentage (T (%)) as a function of wavenumber (cm^{-1}), with characteristic absorption peaks highlighted in pink shaded areas.

Based on the FTIR results presented in the figure, the typical vibration peaks of Ende natural zeolite exhibit significant absorption bands. The absorption peaks at approximately 3449.33 cm-1 and 3522.43 cm^{-1} correspond to the stretching vibrations of the hydroxyl group (O-H). Additionally, an absorption peak at around 1037.39 cm^{-1} is indicative of the silanol group (Si-O) vibrations, while the peaks at 579.39 cm^{-1} and 612.60 cm^{-1} represent the tetrahedral bending vibrations (T-O4). Following activation with a 7 M H_2SO_4 treatment at a reflux temperature of 40 °C, the FTIR spectrum reveals shifts in these absorption bands. Specifically, the O-H stretching vibrations are observed at 3443.64 cm^{-1} and 3528.25 cm^{-1}, while the Si-O vibration is noted at 1068.52 cm^{-1}, and the T-O4 bending vibrations appear at 579.43 cm^{-1} and 629.19 cm^{-1}. These shifts and the increased intensity of the Si-O absorption indicate that the activation process enhances the number of silica atoms within the zeolite framework, suggesting an increase in the Si/Al ratio. Furthermore, the changes observed in the T-O4 bonds imply structural alterations in the Al_2O_3 and SiO_2 components of the zeolite framework [28, 29]. The results of the XRD analysis are presented in Fig. 3.

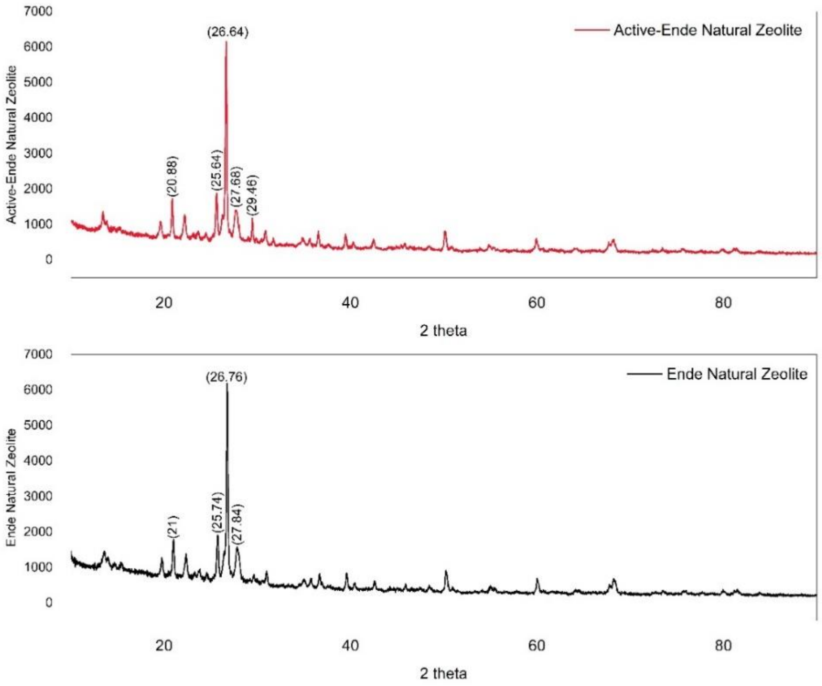


Fig. 3. The results of the XRD analysis of zeolite before and after activation are presented.

Note: XRD patterns comparing Active-Ende Natural Zeolite (red line, top) and Ende Natural Zeolite (black line, bottom). The XRD intensity is plotted as a function of 2 theta, indicating crystallographic phase information.

The XRD (Fig. 3) analysis presented in the figure reveals significant differences between the natural zeolite from Ende and the activated zeolite after treatment. The diffractogram of the natural zeolite (shown in black) exhibits a prominent peak at approximately 26.76°, indicating a stable crystalline structure. This peak suggests that the natural zeolite possesses a good level of crystallinity. In contrast, the diffractogram of the activated zeolite (shown in red) displays a sharper and more intense peak at 26.64°, along with additional peaks at 20.88°, 25.64°, 27.68°, and 29.46°. The increase in peak intensity and the emergence of new peaks indicate that the activation process has enhanced the crystallinity and potentially altered the mineral phases within the zeolite structure. These changes suggest that the activation not only cleanses the zeolite of impurities but also improves its crystalline framework, which may enhance its catalytic properties. Overall, the results align with previous studies that demonstrate how chemical treatments can modify the physical and chemical characteristics of zeolites, thereby increasing their applicability in various fields, including catalysis [29]. This analysis aligns with findings from previous studies, highlighting the impact of activation on the structural properties of natural zeolite. The percentage composition of Si and Al in the zeolite framework in each activation treatment is presented in Table 1.

Table 1. Composition of the Si/Al ratio and total acidity of Ende natural zeolite before and after activation

Mineral	Si/Al Ratio	Total Acid (NH_3/g zeolite)
Ende Natural Zeolite	2.46	1.65
H-Zeolite alam Ende	4.24	7.73

Increasing the Si/Al ratio results in Si-O chemical bonds being shorter than alumina (Al-O) chemical bonds, so that there will be an increase in the surface area and size of the zeolite pore channels [30]. Increasing the size of the pore channels will increase the selectivity of natural catalysts in controlling incoming reactants [31]. Apart from that, the zeolite pore channels also act as microreactors that control the reaction results according to selectivity rules, so that they can produce more hydrocarbons with shorter and lighter bond chains [32]. The results of the analysis of the surface area and pore volume of Ende natural zeolite are shown in Fig. 4.

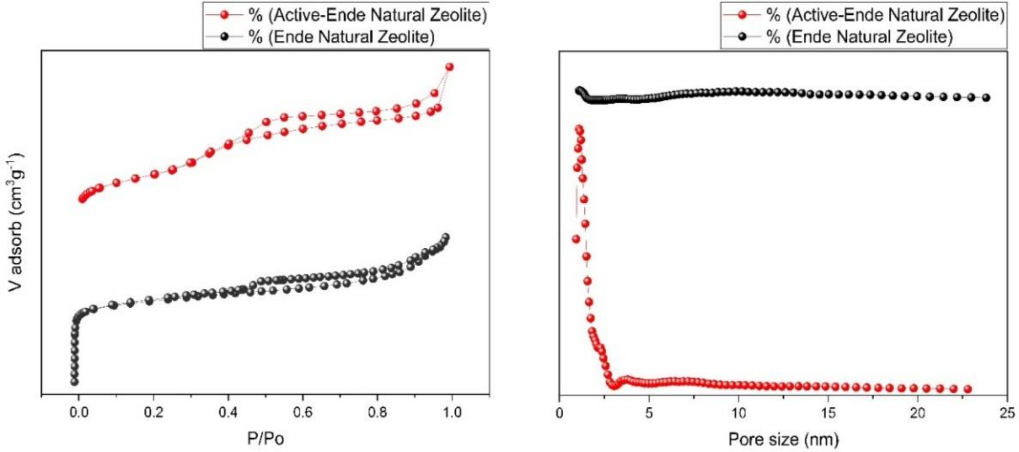


Fig. 4. Results of BET analysis of Ende natural zeolite

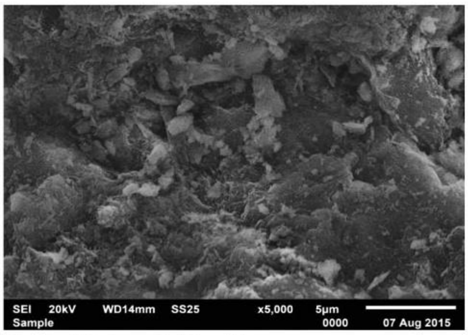
Note: Nitrogen adsorption-desorption isotherms (left) and pore size distribution (right) for Active-Ende Natural Zeolite (red circles) and Ende Natural Zeolite (black circles). The adsorption volume (V adsorb, cm^3/g) is plotted against relative pressure (P/P$_0$) on the left.

The results of the BET (Fig. 4) Isotherm analysis show a comparison of the adsorption capacity between Active-Ende Natural Zeolite (red line) and Ende Natural Zeolite (black line) through a plot of adsorption volume against relative pressure (P/P$_0$). This graph indicates that Active-Ende Natural Zeolite has a higher adsorption capacity than Ende Natural Zeolite, especially in the higher relative pressure range (P/P$_0$ > 0.5). This suggests that Active-Ende Natural Zeolite has a larger surface area and more optimal porosity, allowing it to accommodate more plastic molecules under high-pressure conditions. This difference arises because the H_2SO_4 treatment creates a more open surface pore structure, which increases the accessibility of molecules to the active surface area. Meanwhile, the results of the BJH (Barrett-Joyner-Halenda) analysis show that the pore size distribution of Active-Ende Natural Zeolite is more even and uniform in the range of 2 - 50 nm compared to Ende Natural Zeolite. This indicates that activation with H_2SO_4 successfully increased the pore size and surface area, thereby significantly enhancing the catalyst activity compared to natural zeolite.

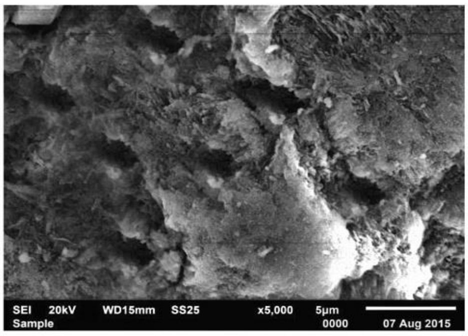
Based on the BET analysis data in Fig. 4, it is evident that activation with H_2SO_4 at a reflux temperature of 40 °C increases the surface area of Ende Natural Zeolite from 43.17 m^2/g to 74 m^2/g, the average pore radius from 11.96 Å to 20.21 Å, and the pore volume from 22 cm^3/g to 72 cm^3/g. One type of natural zeolite found in Indonesia is Bayah natural zeolite. When activated with 1 M H_2SO_4 at a temperature of 90 °C, this zeolite shows an increase in surface area; however, extending the reaction time may compromise its structural integrity [17]. In contrast, using a 7 M H_2SO_4 solution at a temperature of 40 °C is more effective, as it can enhance the surface area by up to 90% without damaging the fundamental structure of the zeolite. The increase in surface area occurs because some of the impurities that originally closed the zeolite pores dissolve in the activating solution, so that the zeolite pores become open and the zeolite's ability to absorb other compounds will automatically improve [33].

The Scanning Electron Microscopy (SEM) (Fig. 5) images provide valuable insights into the surface morphology of the zeolite samples before and after activation. The upper image shows the natural zeolite, revealing a rough and irregular surface texture with a significant presence of agglomerated particles. This morphology suggests a relatively low surface area and limited porosity, which may affect its catalytic performance.

In contrast, the lower image depicts the activated zeolite, which exhibits a more refined and porous structure. The activation process appears to have enhanced the surface area by creating additional voids and increasing the roughness of the surface. This change in morphology is consistent with the results obtained from the Brunauer-Emmett-Teller (BET) analysis, which indicated an increase in surface area following activation. The enhanced porosity and surface area are likely to improve the zeolite's ability to adsorb reactants and facilitate catalytic reactions, thereby increasing its effectiveness in various applications. Overall, the SEM analysis corroborates the BET findings, demonstrating that the activation process significantly alters the physical characteristics of the zeolite, making it more suitable for catalytic purposes.



Ende Natural Zeolite



Active-Ende Natural Zeolite

Fig. 5. Result of the SEM analysis of Ende Natural Zeolite before and after activation

Note: SEM images of Ende Natural Zeolite (top) and Active-Ende Natural Zeolite (bottom) at 5000x magnification. Both images show the surface morphology and microstructural features of the samples with a scale bar of 5 μm.

Effect of zeolite catalyst on pyrolysis reaction

The results of observations of pyrolysis time for each interaction of temperature treatment and catalyst composition are shown in Fig. 6.

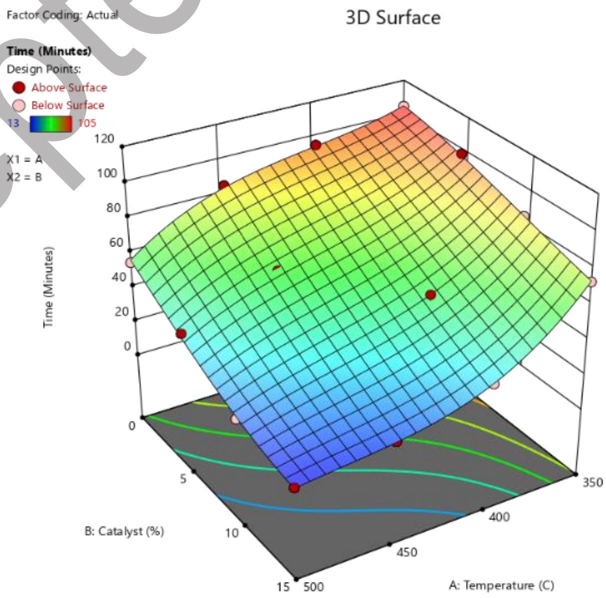


Fig. 6. Effect of temperature and catalyst interaction on pyrolysis time

Note: The surface is color-coded from blue (lowest values) to red (highest values) to enhance visualization of the landscape topology. The red and pink dots denote observed data points used for the model fitting, with red points located above the surface and pink points below.

Based on Fig. 6 it is known that the pyrolysis time will be faster as the temperature and number of catalysts increase. The Turkey test results also show that each temperature treatment and catalyst composition shows significant results (sig. = 0.000 < α = 0.001), but if tested separately it is known that the catalyst composition of 15% does not have a significant effect (sig. = 0.011 > α = 0.001). The existence of active sites in catalyst makes the reaction take place earlier than it should, so that increasing the amount of catalyst will speed up the reaction time [34]. In comparison to studies involving other types of natural zeolite from the Bayah area [17], Ende natural zeolite exhibits limitations in optimizing pyrolysis time. This is likely due to the activation time of 40 °C, which has not yielded optimal results in the dealumination process [35].

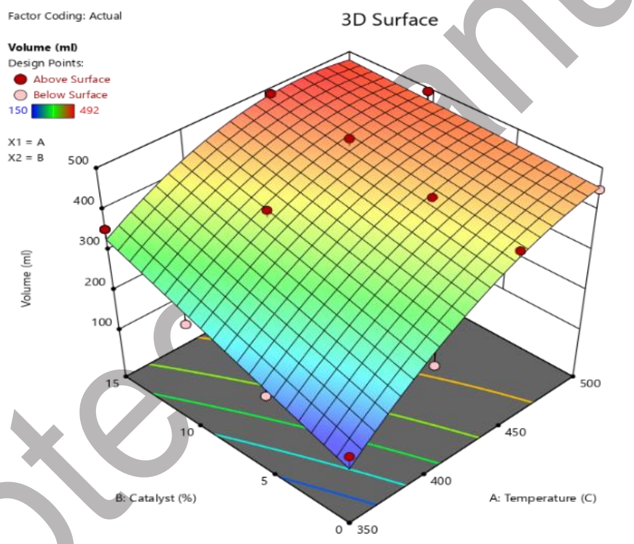


Fig. 7. Effect of temperature and catalyst interactions on the volume of pyrolysis liquid

Note: The surface is color-coded from blue (lowest values) to red (highest values) to enhance visualization of the landscape topology. The red and pink dots denote observed data points used for the model fitting, with red points located above the surface and pink points below.

Based on Fig. 7, it is known that the volume of pyrolysis liquid will increase as the temperature and number of catalysts increase. High operating temperatures can cause the formation of compounds with overly short carbon bonds, resulting in a greater production of gas relative to liquid [24]. Apart from that, too much catalyst will also accelerate the breaking of the hydrocarbon chain, so that increasing the amount of catalyst accompanied by increasing temperature does not produce significantly different results from operating temperatures and catalysts at lower values [36]. This is shown by the Turkey test results that each treatment temperature was 300 °C is not significantly different from other treatments (sig. = 0.050 > α = 0.001), which means that the polyethylene pyrolysis process from plastic waste must be carried out at a temperature above 300 °C to obtain optimal fluid volume. The Turkey test results for catalyst composition also show that each catalyst composition treatment has a significant influence on the volume of pyrolysis liquid, but for compositions of 10% and 15% it is not significantly different (sig. = 0.020 > α = 0.001). This strengthens the previous statement, that a catalyst composition of 10% of the total plastic weight is the best composition. The interaction between temperature and catalyst composition also shows similar results where the interaction between each temperature treatment shows a significant difference with a catalyst composition of 5% and 10% (sig. = 0.000 < α = 0.001), but not with a catalyst composition of 15% (sig. = 0.751 > α = 0.01). Although the results obtained are quite satisfactory, the performance of Ende natural zeolite remains inferior to that of natural zeolite from other regions in Indonesia [35, 37]. However, these results show better performance of synthetic zeolite [38].

Pyrolysis fluid quality: The results of the variance analysis regarding the influence of temperature and catalyst, as well as the influence of the interaction between temperature and catalyst on the viscosity and density of the pyrolysis liquid are shown in Fig. 8.

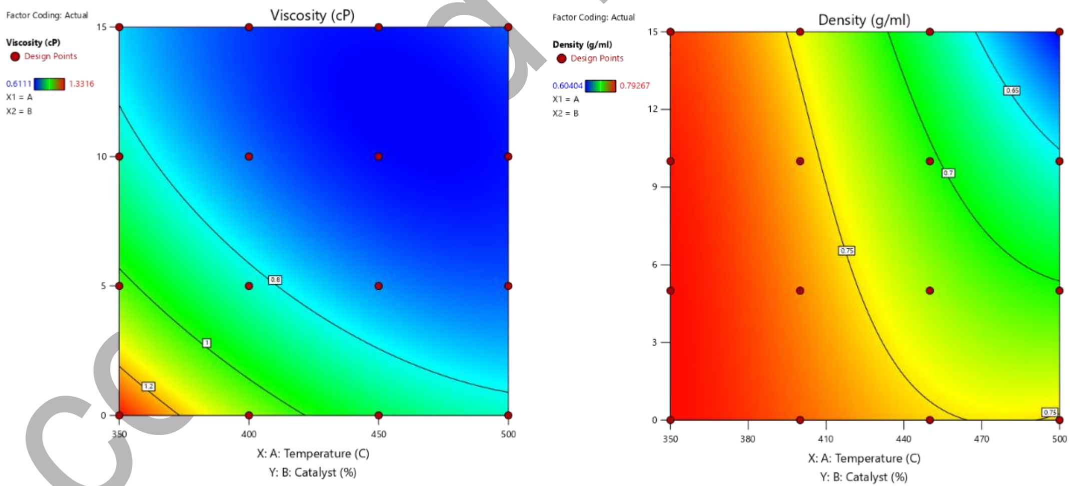


Fig. 8. Effect of temperature and catalyst interaction on viscosity and density

Note: Contour plots depicting the variation of viscosity (left) and density (right) related response variables as functions of two independent variablesand. Both plots include red circular design points representing measured experimental data used for model fitting, with black boundary lines outlining the design space. The contour lines within the plots indicate levels of constant response values, facilitating visualization of trends and interactions between variables.

Based on Fig. 8, it is known that the viscosity value of each treatment is significantly different. The test results also show that the operating temperature of 450 °C to 500 °C at each catalyst amount is the best interaction. The analysis was continued with the Turkey test for the interaction between temperature and catalyst and it was found that each treatment had a significant effect on the viscosity of the pyrolysis liquid (sig. = 0.000 < α = 0.001). The density value of each treatment was significantly different. The test results also show that a temperature of 500 °C at each catalyst amount is the best interaction. The Turkey test for the interaction between temperature and catalyst also shows that each treatment has a significant effect on the density of the pyrolysis liquid (sig. = 0.000 < α = 0.001). Therefore, it is understood that the interactions between temperature and the catalyst play a crucial role in influencing the viscosity and density of the liquid resulting from the pyrolysis of polyethylene from plastic waste. Results of analysis of fraction $C_5 – C_{12}$ content of pyrolysis oil is shown in Fig. 9.

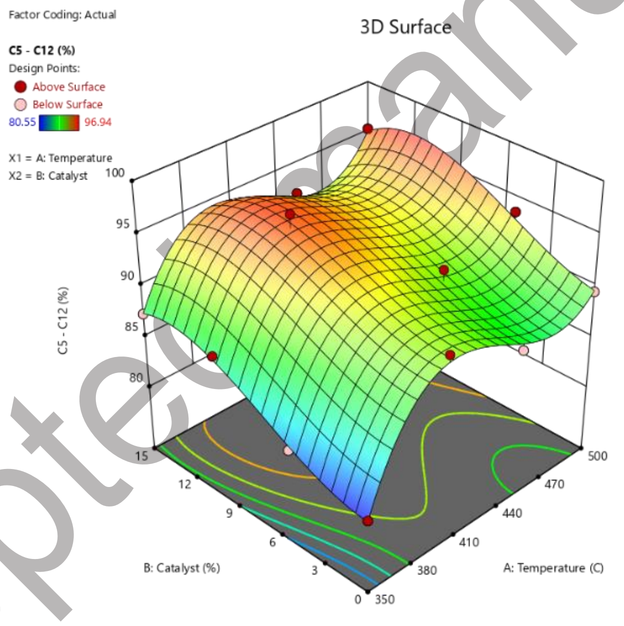


Fig. 9. Effect of temperature and catalyst interactions on the C5 – C12 fraction

Note: The surface is color-coded from blue (lowest values) to red (highest values) to enhance visualization of the landscape topology. The red and pink dots denote observed data points used for the model fitting, with red points located above the surface and pink points below.

Based on Fig. 9, it is known that each temperature and catalyst treatment has a significant effect in forming the gasoline fraction C_5 - C_{12} in the polyethylene plastic pyrolysis process (sig. = 0.000 < α = 0.001). The analysis was continued with the Turkey test for the interaction between temperature and catalyst and it was found that each treatment had a significant effect on the viscosity of the pyrolysis liquid (sig. = 0.000 < α = 0.001). However, there was no significant difference in the results between the treatment at a temperature of 400 °C with a catalyst composition of 10% and that with a 15% catalyst composition (sig. = 0.364 > α = 0.001). Moreover, the temperature of 400 °C is not significantly different from that of 450 °C (sig. = 0.015 > α = 0.001), and a temperature of 500 °C (sig. = 0.131 > α = 0.001).

The catalytic activity tests showed that the activated zeolite exhibited optimal performance at a catalyst composition of 10% and a pyrolysis temperature of 400 °C. Under these conditions, the yield of C_5 - C_{12} hydrocarbons was maximized, producing high-quality liquid hydrocarbons. This finding aligns with previous studies that indicate acid-treated zeolites outperform alkaline treatments in catalytic applications [35, 37]. The analysis of the liquid hydrocarbons produced during pyrolysis indicated that the activated zeolite significantly improved both yield and quality. The results showed that the use of acid-activated zeolite resulted in a higher percentage of gasoline-like hydrocarbons compared to untreated zeolite. This supports the hypothesis that the activation process enhances the catalytic properties of zeolite, making it a viable option for plastic waste management.

While the study provides valuable insights, it is important to acknowledge certain limitations. The variability in the characteristics of natural zeolite from different regions may affect the generalizability of the results. Future research should explore the performance of zeolite from various sources and investigate the long-term stability of the catalyst under operational conditions. The findings of this study have significant implications for sustainable waste management strategies. By optimizing the use of activated zeolite as a catalyst in pyrolysis, we can enhance the conversion of plastic waste into valuable hydrocarbons, contributing to a circular economy and reducing environmental pollution.

CONCLUSIONS

The research results indicate that the combination of activation treatment with sulfuric acid (H_2SO_4) at 40 °C reflux temperature significantly enhances the properties of the zeolite. Specifically, the Si/Al ratio increases from 2.46 to 4.24, total acidity rises from 1.65 NH_3/g zeolite to 7.73 NH_3/g zeolite, and the surface area expands from 43.17 m^2/g to 74 m^2/g. Additionally, the average pore radius increases from 11.96 Å to 20.21 Å, while the pore volume grows from 22 cm^3/g to 72 cm^3/g. The catalyst activity tests reveal that a 10% catalyst composition at a pyrolysis operating temperature of 400 °C is optimal for accelerating reaction time and maximizing the production of C_5 - C_{12} hydrocarbons. The results demonstrate that this specific catalyst composition not only improves the efficiency of the reaction but also significantly increases the yield of the desired hydrocarbon products.

This finding underscores the importance of optimizing catalyst concentration and operating conditions to achieve higher yields, ultimately contributing to more efficient and sustainable pyrolysis processes.

SUPPLEMENTARY DATA

All required data have been included in the manuscript.

AUTHOR CONTRIBUTIONS

This research was designed and conducted solely by the author.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest associated with the publication of this article.

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