



Effect of Zeolite Pre-Treatment on the Performance of a 7-Hole Catalytic Converter

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Abstract

Rice husk ash is a promising silica source for zeolite X synthesis; however, studies comparing different pretreatment methods and their influence on catalytic converter performance remain limited. This study investigated the effect of bleaching and magnetic separation pretreatments on the properties of zeolite X synthesized from rice husk ash and its application in a 7-hole catalytic converter for vehicle exhaust emission reduction. The synthesized zeolite was characterized using XRF, FTIR, XRD, and SEM, while catalytic performance was evaluated based on changes in exhaust gas composition. Both pretreatment methods successfully produced zeolite X with SiO_2 and Al_2O_3 as the main framework components. However, bleaching pretreatment produced zeolite with higher crystallinity (73.39%), better crystal morphology, and a more favorable Si/Al ratio than magnetic separation. When applied in a 7-hole catalytic converter, the bleached zeolite achieved higher reductions of CO, HC, and CO_2 emissions by 65.50%, 67.07%, and 77.55%, respectively, compared to 51.61%, 69.95%, and 38.04% for the magnetic separation zeolite. These findings demonstrate that the pretreatment method significantly affects zeolite quality and catalytic converter performance, with bleaching pretreatment showing superior effectiveness for exhaust emission reduction.

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INTRODUCTION

Zeolites are porous aluminosilicate materials widely used as adsorbents and catalysts due to their high surface area, selective pore structure, and tunable acidity (Dongoran et al., 2021). Among various synthetic zeolites, zeolite X has attracted considerable attention due to its high adsorption capacity and catalytic activity. The synthesis of zeolite X requires silica and alumina sources, which can be obtained from agricultural waste such as rice husk ash. Rice husk ash contains up to 94% silica and therefore has significant potential as a low-cost and sustainable raw material for zeolite synthesis (Krisnawati et al., 2018).

The quality of zeolite synthesized from rice husk ash is significantly influenced by the pretreatment process, which aims to remove

impurities and increase silica availability. Prihastuti et al. (2021) reported that HCl is effective in removing metal impurities from rice husk ash, resulting in higher silica purity. In addition to acid bleaching, magnetic separation has also been applied to reduce magnetic impurities, particularly iron-containing compounds, prior to zeolite synthesis. These pretreatment methods are expected to affect silica purity and subsequently influence the crystallinity, morphology, and performance of the resulting zeolite.

Several studies have reported the successful synthesis of zeolite X from rice husk ash and demonstrated its potential as an adsorbent and catalyst. However, comparative studies evaluating the effects of bleaching and magnetic

separation pretreatments on the characteristics of synthesized zeolite X are still limited. Furthermore, the relationship between the physico-chemical properties of zeolite X obtained from different pretreatment methods and its performance in catalytic converter applications for vehicle exhaust emission reduction has not been comprehensively studied. In addition, Jahro et al. (2025) reported that the 7-hole catalytic converter design improves exhaust gas distribution and increases the contact area between exhaust gases and the catalyst surface, thereby enhancing adsorption and catalytic conversion efficiency.

Therefore, this study aims to compare the bleaching and magnetic separation pretreatments of rice husk ash for the synthesis of zeolite X. The synthesized zeolite was characterized using XRF, FTIR, XRD, and SEM analyses and subsequently applied in a 7-hole catalytic converter to evaluate its effectiveness in reducing vehicle exhaust emissions. The novelty of this study lies in correlating rice husk ash pretreatment methods, zeolite X characteristics, and catalytic converter performance for vehicle exhaust emission reduction.

METHOD

Preparation and Calcination of Rice Husk

Rice husk collected from local agricultural waste was cleaned, dried, and calcined at 600 °C for 3 h to produce rice husk ash. This temperature was selected because it produces highly reactive amorphous silica suitable for zeolite synthesis (Jahro et al., 2024). The resulting ash was sieved through a 200-mesh sieve to obtain uniform particle size.

Magnetic Separation of Rice Husk Ash

Magnetic separation was performed to remove magnetic impurities, particularly iron-containing compounds, from rice husk ash. A total of 20 g of ash was mixed with 100 mL of distilled water and stirred using a magnetic stirrer. The separation process was repeated until no ash was attracted to the magnet. The non-magnetic fraction was used as the silica source for zeolite synthesis and compared with the bleached ash..

Acid Bleaching of Rice Husk Ash

A total of 100 g of rice husk ash was treated with 300 mL of HCl solution, stirred for 30 min, and left for 24 h. HCl was selected because it is effective in removing metal impurities and

increasing silica purity (Prihastuti et al., 2021). The suspension was filtered, washed with distilled water until neutral pH, and dried at 120 °C for 2 h. The treated ash was subsequently characterized using XRF.

Synthesis of Zeolite X

Zeolite X was synthesized by mixing 35 g of pretreated rice husk ash, 18.36 g of Al_2O_3 , and 28.8 g of NaOH in 300 mL of distilled water. The mixture was stirred at 600 rpm for 10 h and aged overnight. Hydrothermal treatment was conducted at 70 °C for 3 h, followed by a second aging step and crystallization under reflux at 120 °C for 8 h with stirring at 300 rpm. These synthesis conditions were adopted from Jahro et al. (2025), who successfully synthesized zeolite X from rice husk ash. The resulting zeolite was filtered, washed to neutral pH, dried at 120 °C, and characterized using XRF, FTIR, XRD, and SEM.

Fabrication of Catalytic Converters Based on Solid Pulp Waste and Zeolite X

The catalytic converter was prepared by mixing zeolite X and solid pulp waste at a mass ratio of 4:5. The homogeneous mixture was molded into a cylindrical monolith (6 cm diameter × 10 cm height) with seven gas-flow channels and dried at room temperature, followed by oven drying at 120 °C for 10 h. The 7-hole design was selected because it can improve exhaust gas distribution and increase the contact area between exhaust gases and the catalyst surface, thereby enhancing adsorption and catalytic conversion efficiency (Jahro et al., 2025). The fabricated catalytic converters were subsequently tested for their ability to reduce vehicle exhaust emissions.

RESULTS AND DISCUSSION

Preparation and Ashing of Rice Husk Charcoal

Rice husk was ashed at 600 °C for 3 hours to remove organic compounds and increase silica content. In the temperature range of 500–700 °C, silica in rice husk ash is generally in the amorphous phase which has high reactivity and is suitable as a raw material for zeolite synthesis (Kang et al., 2018). Combustion at 600 °C has also been reported to produce high amounts of amorphous silica and is therefore considered an optimal condition for zeolite synthesis (Ji et al., 2025). The resulting ash is grayish white, indicating a successful combustion process, as seen in Figure 1.

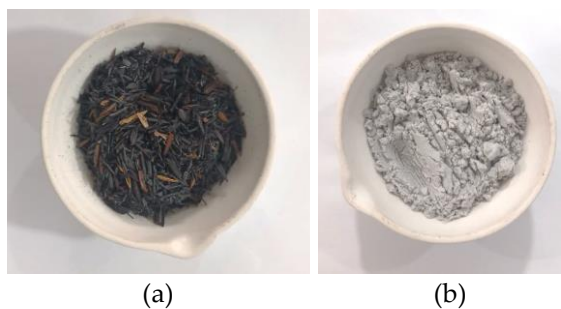


Figure 1. (a) Rice husk Charcoal, (b) Rice Husk Ash after Kiln

From 75 g of rice husk charcoal, an average ash mass of 22.781 g was obtained, corresponding to an ash yield of 30.340%. This yield is consistent with the reported ash content of rice husks and indicates that the combustion process effectively removed organic constituents while retaining the silica-rich inorganic fraction required for zeolite synthesis.

Results of Bleaching and Magnetic Separation of Rice Husk Ash

Based on Figure 2(b), the bleaching process was carried out using 35% HCl to remove inorganic impurities such as Fe_2O_3 , CaO , MgO , and K_2O , which may interfere with the formation of the aluminosilicate framework during zeolite synthesis. HCl was selected because it has been reported to be more effective than other mineral acids in dissolving metal oxides and improving silica purity (Prihastuti et al., 2021). After washing to neutral pH, the average ash mass decreased to 93.45% of its initial mass, corresponding to a mass loss of 6.58%. This reduction suggests that part of the inorganic impurities was successfully dissolved during acid treatment. The removal of these impurities is expected to increase silica availability and promote the formation of a more ordered zeolite framework during synthesis.

Magnetic separation was performed to reduce magnetic impurities in rice husk ash prior to its use as a silica source. The amount of magnetic ash obtained was relatively small (Figure 2a), indicating that strongly magnetic components were present only in minor quantities. However, weakly magnetic and non-magnetic impurities may still remain in the ash and potentially affect the purity of the silica source and the subsequent crystallization process. Therefore, further characterization using XRF analysis was conducted to evaluate the chemical composition of the treated ash.

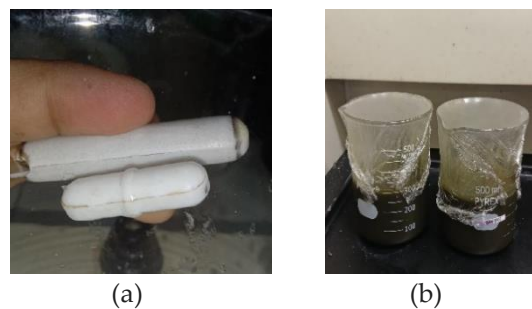


Figure 2. (a) Magnetic Ash Separation, (b) Bleaching Ash Separation

The results of XRF analysis showed that both pretreatment methods produced rice husk ash with high silica content suitable for zeolite X synthesis. The ash obtained from magnetic separation contained 94.50% SiO_2 , while the bleached ash contained 92.59% SiO_2 . The high silica content obtained from both methods confirms that rice husk ash is an excellent silica source for zeolite synthesis. Although the magnetic separation ash exhibited slightly higher SiO_2 content, acid bleaching is expected to provide a cleaner silica source because it removes a broader range of metal oxide impurities through chemical dissolution. The reduction of these impurities may enhance silica reactivity and facilitate the formation of a more ordered aluminosilicate framework during the synthesis process. Overall, both pretreatment methods produced rice husk ash with silica purity above 90%, making them suitable as raw materials for zeolite X synthesis (Salim et al., 2023; Pal et al., 2025).

Zeolite X synthetic results

Zeolite X was successfully synthesized from rice husk ash through stirring, hydrothermal treatment, and reflux processes. The synthesized product appeared as a white powder, as shown in Figure 3, indicating the successful formation of an aluminosilicate material and the absence of significant carbon residues or unreacted precursors.



Figure 3. Zeolite X Synthetic Results

The synthesis process involved NaOH as an activator and mineralizer, which promoted the dissolution of silica and alumina to form soluble silicate and aluminate species. These species subsequently underwent nucleation and crystal growth during the hydrothermal and reflux stages, leading to the formation of the zeolite X framework (Dongoran et al., 2021). The hydrothermal treatment facilitated the rearrangement of aluminosilicate species into an ordered crystalline structure, while the reflux stage promoted further crystal growth and framework stabilization.

After synthesis, the zeolite was washed to neutral pH to remove residual alkali and soluble impurities that could interfere with subsequent characterization and application. The product was then dried at 120 °C to remove physically adsorbed water from the pore system, thereby ensuring a more accurate evaluation of its physicochemical properties (Syaifie et al., 2019).

The resulting zeolite was then characterized using XRF, FTIR, XRD, and SEM analyses to evaluate its chemical composition, framework structure, crystallinity, and morphology.

Characterization Results of Zeolite X synthetic X-ray fluorescence

Analysis of the chemical composition of zeolite resulting from the synthesis of magnetic separation of rice husk ash and bleaching of rice husk ash through spectrometry using X-ray fluorescence equipment produced a spectrum as shown in Table 1.

The results of XRF analysis show that the zeolite synthesized from rice husk ash pretreated with bleaching and magnetic separation in Table 1 is dominated by SiO₂ and Al₂O₃ as the main components of the zeolite aluminosilicate framework. The zeolite synthesized from bleaching ash contains SiO₂ and Al₂O₃ of 60.718% and 33.253%, respectively, with a Si/Al ratio of 1.55, while the zeolite from magnetic separation ash contains SiO₂ and Al₂O₃ of 56.699% and 36.823%, respectively, with a Si/Al ratio of 1.31. Both ratio values are still within the characteristic range of zeolite X, namely 1.1–1.5, although the ratio in the bleaching sample is slightly higher than the ideal range (Fitriyana and Dzulfikar, 2017).

The higher SiO₂ content observed in the bleached zeolite indicates that the HCl pretreatment was effective in dissolving metal oxide impurities that could interfere with

aluminosilicate framework formation. As a result, silica became more available to react with aluminate species during synthesis, promoting the development of a more ordered zeolite framework. In contrast, magnetic separation mainly removed magnetic impurities and may have left non-magnetic oxides in the ash, which could hinder crystallization and reduce the incorporation of silica and alumina into the zeolite structure.

Table 1. Chemical Composition of Synthesized Zeolite

Component	Oxide (Mass%)	
	Zeolite from Bleaching Ash	Zeolite from Magnetic Separation Ash
Al ₂ O ₃	33,253	36,823
SiO ₂	60,718	56,699
P ₂ O ₅	1,075	3,699
K ₂ O	1,556	0,908
CaO	1,245	1,311
MnO	0,041	0,128
Fe ₂ O ₃	0,344	0,081

These compositional differences indicate that the pretreatment method affects the purity of silica and the aluminosilicate framework formation process during synthesis. The bleached zeolite had a higher SiO₂ content and a yield of 74.41%, indicating better impurity removal effectiveness compared to magnetic separation. In contrast, the magnetic separation zeolite still contained some impurity oxides and showed relatively low crystallinity based on the XRD results, which was 35.04%, indicating that some silica and alumina had not been fully integrated into the zeolite crystalline structure. Overall, both pretreatment methods successfully produced zeolite X, but the bleaching treatment provided better product quality based on the silica content, Si/Al ratio, crystallinity, and yield obtained.

Characterization Results of Zeolite

Fourier Transform Infrared Spectroscopy

Based on Figure 4, the FTIR spectrum of the synthesized Zeolite X can be seen with the emergence of four absorption regions at wave numbers (420-300, 500-420, 650-500, 820-750, 1250-950) cm⁻¹ which are typical absorption regions of the zeolite X framework structure (Safitri and Jahro, 2021).

Both spectra exhibit typical absorption bands of zeolite X, indicating the formation of a faujasite-type aluminosilicate framework. The

absorption band in the 1250–950 cm^{-1} region, corresponding to the asymmetric T–O stretching vibration (T = Si or Al), appears at 1058.58 cm^{-1} for the bleached zeolite and 995.27 cm^{-1} for the magnetically separated zeolite.

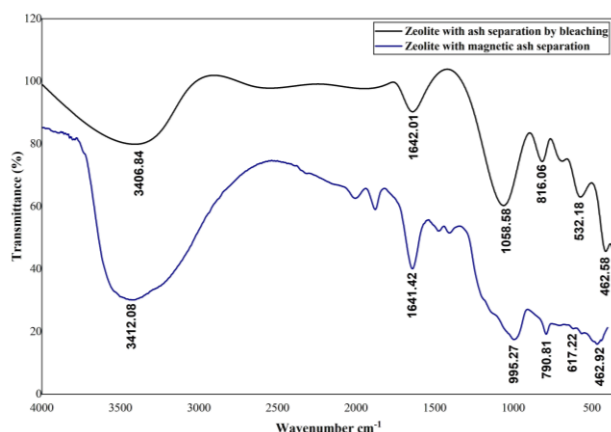


Figure 4. FTIR Spectrum of Synthesized Zeolite

The presence of this band indicates the formation of tetrahedral $[\text{SiO}_4]$ and $[\text{AlO}_4]$ units as the primary constituents of the zeolite framework (Syaifie et al., 2019). The absorption bands at 816.06 cm^{-1} and 790.81 cm^{-1} indicate T–O symmetric stretching vibrations, while the bands at 462.58 cm^{-1} and 462.92 cm^{-1} are associated with Si–O–Si and Si–O–Al bending vibrations.

The presence of these bands confirms the formation of the zeolite X structure in both samples. The distinctive characteristics of faujasite zeolite are also indicated by the appearance of a double-six-ring (D6R) band at 532.18 cm^{-1} for the bleached zeolite and 617.22 cm^{-1} for the magnetically separated zeolite. The D6R band in the bleached zeolite appears more pronounced, indicating a better formation of the typical zeolite X structural units and a higher degree of crystal order (Septiani et al., 2025). The clearer D6R band observed in the bleached zeolite suggests a higher degree of structural ordering within the faujasite framework. This indicates that the removal of impurities during bleaching facilitated the arrangement of silicate and aluminate tetrahedra into the characteristic zeolite X structure, resulting in improved framework integrity and crystallinity (Triyuni et al., 2023).

In addition, the absorption bands in the region of 3406.84–3412.08 cm^{-1} and 1641.42–1642.01 cm^{-1} indicate the O–H stretching vibration and H–O–H bending vibration originating from adsorbed water molecules or crystal water in the zeolite cavity (Muhshi et al., 2024). Overall, both

pretreatment methods successfully produced zeolite X, but the bleached zeolite showed better structural characteristics characterized by stronger T–O vibration bands and the appearance of clearer D6R bands. These results indicate that the bleaching process produces a silica source that is more supportive of the formation of a more regular and crystalline zeolite X framework.

X-ray Diffraction

Comparison of the XRD diffraction pattern of the synthesized zeolite X with the JCPDS standard shows that both samples have good agreement with the characteristic peaks of zeolite X. The bleached zeolite shows peaks at 2θ 12.38°, 13.90°, 24.26°, 26.64°, 31.52°, and 33.11°, while the magnetically separated zeolite appears at 13.93°, 23.31°, 27.43°, 30.07°, 31.44°, and 34.17° (Jahro et al., 2025). These peaks are close to the standard zeolite as can be seen in figure 5.

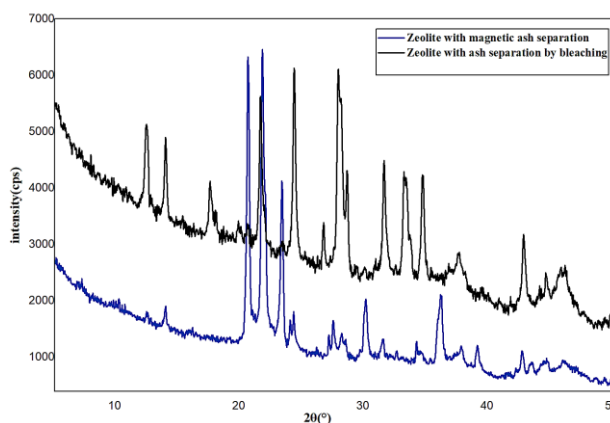


Figure 5. XRD Diffraction Pattern of Zeolite X

The bleached zeolite exhibits sharper diffraction peaks and a higher degree of crystallinity (73.39%) than the magnetically separated zeolite (35.04%). The high crystallinity indicates that the bleaching process is more effective in producing a silica source that supports optimal aluminosilicate framework formation. A higher crystallinity value suggests that a larger proportion of silica and alumina species successfully participated in crystal growth during the hydrothermal process. The removal of metal impurities by acid bleaching likely minimized interference during nucleation and crystal development, thereby promoting the formation of a more ordered zeolite X framework. Conversely, the low crystallinity in the magnetically separated zeolite is thought to be due to the presence of crystalline silica that has not yet fully reacted during synthesis. Residual impurities may also have hindered crystal growth, resulting in the

formation of partially amorphous phases. These results align with FTIR characterization, which shows a more pronounced double-ring band (D6R) in the bleached zeolite. Thus, bleaching pre-treatment produces better quality zeolite X than magnetic separation.

Scanning Electron Microscope

The SEM characterization results of zeolite X synthesized from rice husk ash prepared through bleaching shown in Figure 6. The bleached zeolite exhibits a crystalline morphology with polygonal to semi-octahedral shapes, a characteristic of zeolite X (Rizal et al., 2022). The crystals appear more defined, although interparticle agglomeration still occurs. Furthermore, interparticle cavities and a relatively rough surface are observed, potentially increasing surface area and facilitating gas diffusion to the active sites of the catalyst.

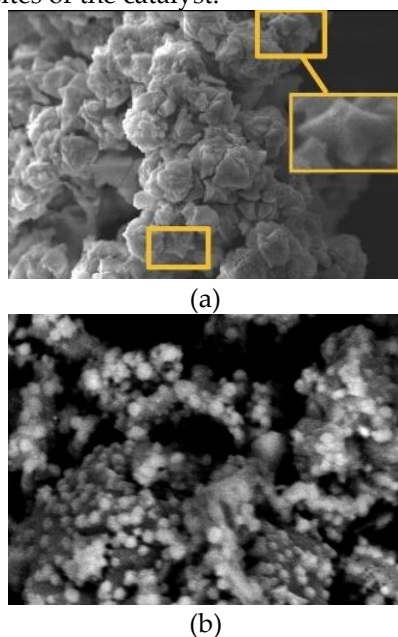


Figure 6. (a) SEM Zeolite X Synthesis Results from Separation Ash by Bleaching, (b) SEM Zeolite X Synthesis Results from Magnetic Separation Ash

In contrast, Figure 6 (b) shows that the magnetically separated zeolite is dominated by aggregated granular particles with poorly defined crystal shapes. In some areas, chunks of silica are still visible that have not fully reacted with the alumina, indicating that the formation of the aluminosilicate framework has not yet occurred optimally (Pei et al., 2022). The presence of this unreacted silica phase aligns with the XRD results, which indicate lower crystallinity compared to the bleached zeolite. The well-defined crystal morphology of the bleached zeolite is expected to provide a larger accessible

surface area and a more uniform pore system, facilitating the diffusion of gas molecules to active adsorption sites. In contrast, particle agglomeration and incomplete crystal formation in the magnetically separated zeolite may limit gas transport and reduce adsorption efficiency.

Fabrication of 7-Hole Catalytic Converter

Solid pulp waste consisting of biosludge, grits, and dregs was first ground and sieved until it passed a 100-mesh sieve to obtain a uniform particle size. Finer particle size improves the homogeneity of the mixture and increases the contact area between particles, thus supporting the formation of a better material structure. In this study, grits and dregs were used as one type of waste because they have relatively similar physical and chemical characteristics, thus simplifying the processing process without reducing the quality of the resulting material. Next, the solid pulp waste was mixed with the synthesized zeolite X at a weight ratio of 4:5 to obtain a homogeneous mixture.

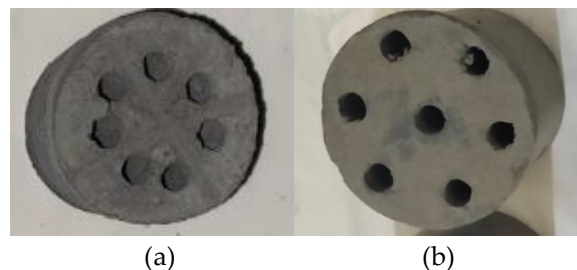


Figure 7. 7-hole Catalytic Converter (a) from Magnetic Separation Ash, (b) from Bleaching Separation Ash

Homogeneity of the mixture is very important to ensure an even distribution of components so that the resulting material properties and catalytic activity are more consistent. The mixture was then molded into a cylindrical monolith with seven gas flow channels (7-hole) and subsequently dried and heat treated to increase its mechanical strength. The catalytic converter product can be seen in the figure. The seven-channel design was chosen because it is able to produce a more even gas flow distribution and increase contact between the exhaust gas and the catalyst surface, thereby increasing the efficiency of adsorption and catalytic conversion (Jahro et al., 2026).

The Effect of Rice Husk Ash Pretreatment Method on the Performance of Catalytic Converter Based on Zeolite X and Pulp Waste

The catalytic converter based on zeolite X synthesized from bleached rice husk ash

exhibited removal efficiencies of 65.50%, 67.07%, and 77.55% for CO, HC, and CO₂, respectively. In comparison, the catalytic converter prepared from zeolite X synthesized using magnetic separation pretreatment achieved removal efficiencies of 51.61%, 69.95%, and 38.04%, respectively (Table 2 and Figure 8). These results indicate that the pretreatment method significantly influenced the catalytic performance of the resulting zeolite.

Table 2. Catalytic converter with pretreatment Different zeolites in terms of adsorption capacity

Catalytic converter with pretreatment different zeolites	Gas Absorption Capacity		
	CO (%)	HC (ppm)	CO ₂ (%)
Bleaching	65.50	67.07	77.55
Magnetic	51.61	69.95	38.04

These differences are closely related to the physicochemical properties of the synthesized zeolites. Characterization results showed that the bleached zeolite possessed higher crystallinity, a more ordered zeolite X framework, and a better-developed crystal morphology. These characteristics provide a larger number of accessible active sites and facilitate the diffusion of exhaust gas molecules through the zeolite pores. Consequently, the interaction between pollutants and catalytic active sites becomes more effective, leading to improved adsorption and catalytic conversion performance.

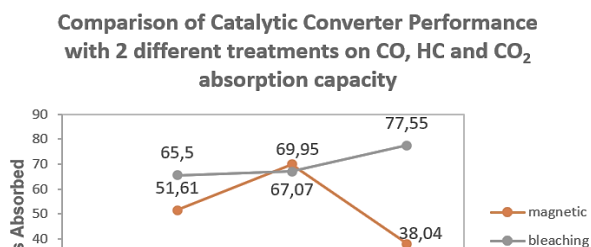


Figure 8. Catalytic Converter with Pretreatment Different Zeolites In Terms of Adsorption Capacity CO, HC and CO₂

The reduction in CO and HC emissions indicates that the zeolite X-based catalytic converter is capable of improving the exhaust gas oxidation process. Carbon monoxide is oxidized to carbon dioxide through the reaction: $2x\text{CO}_{(g)} + \text{O}_{2(g)} \rightarrow 2x\text{CO}_{2(g)}$. Meanwhile, hydrocarbons that are not completely burned are oxidized to CO₂ and H₂O through the reaction: $\text{C}_x\text{H}_{4x(g)} + 2x\text{O}_{2(g)} \rightarrow x\text{CO}_{2(g)} + 2x\text{H}_2\text{O}_{(g)}$ (Jahro *et al.*, 2024). In

addition, the microporous structure of zeolite X enables the adsorption of pollutant molecules within its pore channels, increasing the residence time of exhaust gases and promoting more effective oxidation reactions.

The higher removal efficiencies obtained by the catalytic converter prepared from bleached rice husk ash suggest that the pretreatment method improved the effectiveness of gas adsorption and catalytic conversion. During exhaust gas flow, pollutant molecules such as CO and HC are first adsorbed onto the zeolite surface and subsequently undergo oxidation reactions in the presence of oxygen. As a result, pollutant concentrations decrease while the conversion products are formed. This mechanism explains the higher reductions in CO and CO₂ emissions observed for the bleached-zeolite catalytic converter. The results demonstrate that the pretreatment method plays an important role in determining the catalytic performance of zeolite X for vehicle exhaust emission control.

Table 3. Catalytic converter with pretreatment different zeolites of increase in O₂ gas

Catalytic converter with pretreatment different zeolites	increase in O ₂ gas
Bleaching	14.40
Magnetic	26.03

In addition to reducing CO and HC emissions, catalytic converter performance was also evaluated based on changes in O₂ concentration in the exhaust gas. The test results showed that the catalytic converter based on magnetically separated zeolite produced an O₂ increase of 26.03%, whereas the catalytic converter based on bleached zeolite produced a lower O₂ increase of 14.40%, as shown in Figure 9.

Comparison of Catalytic Converter Performance with Bleaching Pretreatment on Increase in O₂ Emissions (%)

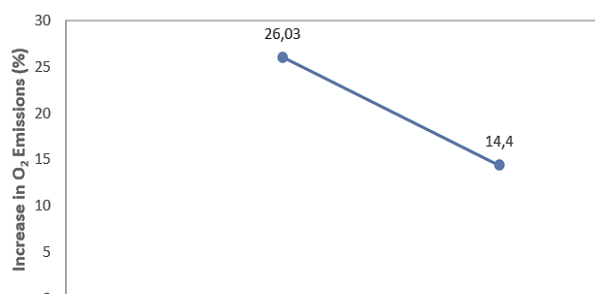


Figure 9. Catalytic Converter with Pretreatment Different Zeolites of Increase in O₂ Gas

The difference in O₂ concentration indicates that the pretreatment method influenced the exhaust gas composition after passing through the catalytic converter. Although the catalytic converter based on magnetically separated zeolite exhibited a higher increase in O₂ concentration, this does not necessarily reflect superior catalytic performance. During catalytic oxidation, oxygen is consumed to convert CO and unburned hydrocarbons into less harmful products such as CO₂ and H₂O. Therefore, the lower O₂ concentration observed in the exhaust gas of the bleached-zeolite catalytic converter suggests that oxygen was utilized more effectively in oxidation reactions. This interpretation is consistent with the higher reductions in CO and HC emissions achieved by the bleached-zeolite catalytic converter, indicating more efficient exhaust gas conversion. Overall, the results demonstrate that the bleaching pretreatment contributed to a more effective catalytic converter performance in reducing vehicle exhaust emissions.

CONCLUSION

Both bleaching and magnetic separation pretreatments successfully produced rice husk ash with high silica content suitable for zeolite X synthesis. However, bleaching pretreatment yielded zeolite X with superior physicochemical characteristics, including higher crystallinity, improved crystal morphology, and a more favorable Si/Al ratio. When applied in a 7-hole catalytic converter, the bleached zeolite exhibited higher CO, HC, and CO₂ removal efficiencies of **65.50, 67.07 and 77.55%, respectively**, than the zeolite obtained from magnetic separation. These findings demonstrate that bleaching pretreatment is more effective in producing high-quality zeolite X and enhancing catalytic converter performance. Furthermore, the study highlights the potential of rice husk ash-derived zeolite X as a sustainable catalyst material for reducing vehicle exhaust emissions while promoting the value-added utilization of agricultural waste.

RECOMMENDATION

Future research should focus on optimizing bleaching variables, including acid concentration, soaking duration, and temperature, together with hydrothermal synthesis parameters to further improve the properties of zeolite X. Performance evaluation under varying engine speeds, loads, and operating periods is also recommended. In

addition, durability and stability assessments are required to determine the long-term effectiveness and reusability of the catalyst material. Such work would strengthen the understanding of the practical application of rice husk ash-derived zeolite X for exhaust emission mitigation.

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