

Transformation of Sugarcane Bagasse Ash Assisted by Polyethylene Glycol into Hierarchical ZSM-5

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Abstract

Recently, the conversion of agricultural waste into valuable materials offers a promising pathway toward sustainable materials production. Concurrently, zeolite ZSM-5, a prominent zeolite framework, has long been employed as a highly effective catalyst for various reactions. Herein, the sugarcane bagasse ash (SCBA) was employed as a silica source to synthesize hierarchical ZSM-5 zeolite via a hydrothermal method assisted by polyethylene glycol (PEG). In this regard, the silica extracted from SCBA was used as the primary silica source, while PEG served as a mesopore-former to induce auxiliary mesoporosity, and commercial ZSM-5 acted as the crystallization seed. The result showed the formation of an MFI framework, which was confirmed through XRD and FTIR characterization. Moreover, the nitrogen adsorption-desorption analysis revealed a considerable improvement in textural properties. In this case, the surface area increased from 245 m²/g (without PEG) to 320 m²/g (PEG-assisted sample). The synergistic effect of silica from SCBA and PEG-induced porosity resulted in a more accessible pore network, which is highly advantageous for mass transport. Hence, this study may provide a sustainable and economical route for producing hierarchical ZSM-5 from biomass waste.

Keywords: Zeolite; ZSM-5; sugarcane bagasse ash; polyethylene glycol; sustainable.

Introduction

Zeolite ZSM-5 (Zeolite Socony Mobil-5) is a microporous aluminosilicate zeolite with an MFI framework structure and is widely used as a catalyst in various chemical processes, such as isomerization^[1], catalytic cracking^{[2],[3]}, and methanol-to-hydrocarbon (MTH) conversion^[4]. This is due to its high thermal stability, strong acidity, and uniform pore size distribution^{[5]-[7]}. However, the conventional ZSM-5 zeolite possesses predominantly microporous, which significantly hinders the diffusion of bulky molecules into the active sites. As a result, recent studies have increasingly focused on the development of hierarchical zeolite.

Hierarchical zeolite integrates micro-, meso-, and/or macropores to improve the diffusion and active-site accessibility^{[8]-[10]}.

Generally, zeolite synthesis relies on synthetic silica such as tetraethyl orthosilicate (TEOS), Ludox, or other commercial sodium silicate. In fact, the use of chemical precursors not only increases production costs but also raises environmental concerns. Consequently, researchers have shifted their effort to natural or biomass-derived silica sources as more economical and environmentally friendly alternatives^{[11]-[13]}. Among these wastes, sugarcane bagasse ash (SCBA), a solid waste generated from the combustion of sugarcane

residues in the sugar and bioethanol industries, has emerged as a promising candidate. SCBA typically contains 60–80% amorphous silica depending on combustion conditions, making it an attractive precursor for zeolite synthesis [14],[15]. Indonesia, as one of the largest sugarcane producers in Southeast Asia, produces significant amounts of bagasse waste annually [16]. In regions such as Berastagi, North Sumatra, bagasse residue from local milling operations remains underutilized and is often discarded directly into the environment [16]. With appropriate chemical treatment, involving acid leaching for purification and alkaline extraction, the ash produced from burning bagasse can serve as a local silica source for zeolite catalyst production [15].

Processing SCBA into usable silica generally involves an alkaline–acid extraction route [14]. In this method, NaOH is used to dissolve silica into sodium silicate. Subsequently the resulted mixing then precipitated using acids such as HNO₃ to form silica hydrogel [15],[17]. Moreover, variations in molar ratios, temperature, and extraction time can influence the resulting silica structure, which in turn affects the properties of the synthesized zeolite [14],[15].

Several works showed that hierarchical zeolite, including ZSM-5, frequently employed polyethylene glycol (PEG) as a soft templating agent to generate additional mesopores within the zeolite framework [18],[19]. PEG utilized as a mesopore-forming agent that decomposes during calcination process, leaving the mesoporous voids that enhance surface area and facilitate molecular diffusion [18],[20]. Although previous studies have investigated hierarchical ZSM-5 using sugarcane bagasse-derived silica and PEG-assisted mesostructured ZSM-5 separately, their combined application provides an opportunity to develop a sustainable approach for preparing hierarchical zeolites [14],[18],[21]. Herein, we report the synthesis of hierarchical ZSM-5 using silica extracted from sugarcane bagasse ash, commercial ZSM-5 as seeds, and PEG as a mesopore-forming agent. The novelty of this study lies in integrating a waste-derived silica source, ZSM-5 seeding, and PEG-assisted

mesostructuring within a single synthesis approach, followed by a direct comparison between PEG-free and PEG-assisted samples. The resulting PEG-free and PEG-assisted ZSM-5 samples were compared in terms of their structural and textural properties, including the MFI framework formation, BET surface area, external surface area, total pore volume, and micropore volume. Ultimately, this study demonstrates a viable and sustainable route for transforming agricultural waste into hierarchical ZSM-5 with tailored textural characteristics.

Experimental

Instruments

The instruments used in this work are glassware, grinder, mortar, hotplate, autoclave, oven, furnace, Fourier-transform Infrared spectrometer (FTIR, Thermo Fisher Scientific), X-ray Diffraction (XRD, Bruker D8 Advance with radiation of Cu K α), and N₂ adsorption-desorption analyzer (Quantachrome Autosorb IQ) operated at 77 K.

Materials

The materials used in this work were sugarcane bagasse from local farmers in Berastagi, North Sumatra, sodium hydroxide (NaOH, analytical grade, Merck), nitric acid (HNO₃, 65%, Merck), polyethylene glycol (PEG-4000, Merck), sodium aluminate (NaAlO₂, Merck), distilled water (H₂O), and commercial ZSM-5 as seed crystals. All chemicals were used without further purification.

Method

Silica Extraction from Sugarcane Bagasse Ash

The methodology of silica extraction was adapted from Rilyanti et al [14]. The sugarcane bagasse was soaked in 2.5% HNO₃ and heated at 80 °C for 1 h to remove organic impurities. After washing and drying at 100 °C, the sample was calcined at 600 °C for 1 h to obtain sugarcane bagasse ash (SCBA). The SCBA was then extracted using 2 M NaOH at 80 °C for 1 h and left at room temperature for 24 h. The resulting

filtrate was added with 10% HNO_3 until pH 7 to form a hydrogel, which was subsequently incubated at room temperature for 24 h and washed with deionized water to remove residual salts. The resulting solid was dried at 80 °C for 12 h.

Synthesis of mesoporous ZSM-5 Zeolite

The extracted silica was mixed with the aluminum source, PEG, and commercial ZSM-5 seed crystals. The molar ratio of components used in the synthesis was $\text{SiO}_2 : \text{Al}_2\text{O}_3 : \text{NaOH} : \text{H}_2\text{O} : \text{PEG} = 1 : 0.05 : 0.11 : 12 : 0.01$, with ZSM-5 seeds added at 15 wt % of the total silica mass. Hydrothermal crystallization was performed at 170 °C for 48 h. The solid product then washed with distilled water, filtered, and dried overnight (12 h) at 80 °C. Subsequently, the resulting product was calcined at 550 °C for 6 h to remove PEG. For comparison, ZSM-5 zeolite without PEG was carried out with the same method without PEG addition. The samples then coded with ZSP, ZS, ZC for ZSM-5 with PEG, ZSM-5 synthesis without PEG, and ZSM-5 commercial, respectively.

Results and Discussion

The IR spectrum recorded in absorbance mode, as depicted in Figure 1a, shows characteristic absorption bands at 1085 cm^{-1} which correspond to Si–O–Si stretching vibrations [22]. The peak in wavenumber of 968 and 790 cm^{-1} were attributed

to Si–O asymmetric stretching vibrations. Moreover, the absorption bands at 3443 and 1631 cm^{-1} corresponding to the OH vibration of Si–OH groups. These results indicate the presence of Si–O–Si bonds in the extracted material, supporting the formation of silica-containing material from SCBA [14]. The XRD pattern (Figure 1b) exhibits a weak amorphous hump around $2\theta = 22^\circ$, indicating the predominantly amorphous nature of the extracted silica [23],[24]. This result indicates that the extracted material can be used as a silica source for subsequent zeolite synthesis. This result is consistent with the findings of Keawkumay et al., who reported that acid–alkali treatment of sugarcane bagasse ash effectively removes organic groups and enhances the intensity of the Si–O–Si band [15].

The FTIR spectra of all samples (ZC, ZS, and ZSP) display the principal vibrational modes associated with the aluminosilicate framework (Figure 2a). The broad band in the region of 1080 cm^{-1} corresponds to the asymmetric stretching of Si–O–Si, which reflects the presence of interconnected silica tetrahedra forming the primary network structure of ZSM-5 [22],[25]. The absorption around 790 cm^{-1} is attributed to the symmetric stretching of tetrahedral linkages (Si–O–Si / Si–O–Al) [26],[27]. The band at 550 cm^{-1} represents the characteristic double five-membered ring vibration, commonly associated with the MFI framework [28].

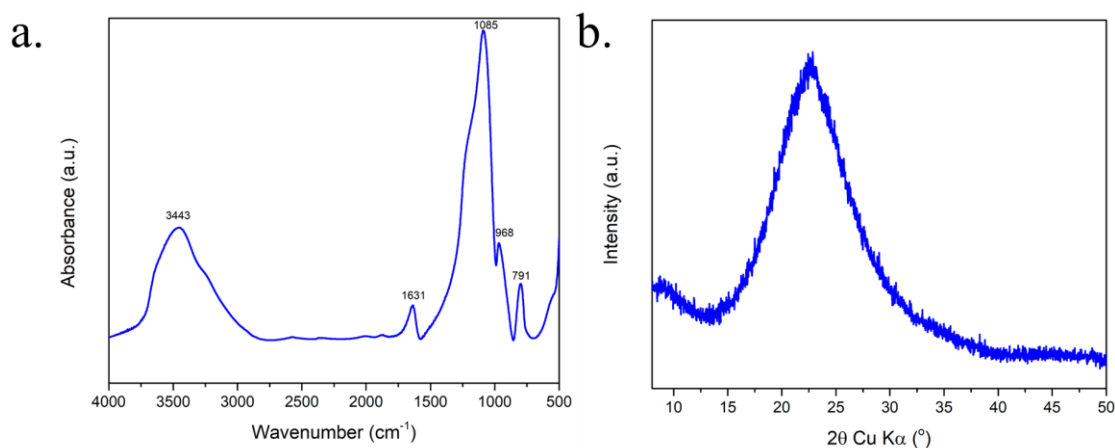


Figure 1. a) FTIR spectrum and b) X-ray diffraction pattern of extracted silica from SCBA.

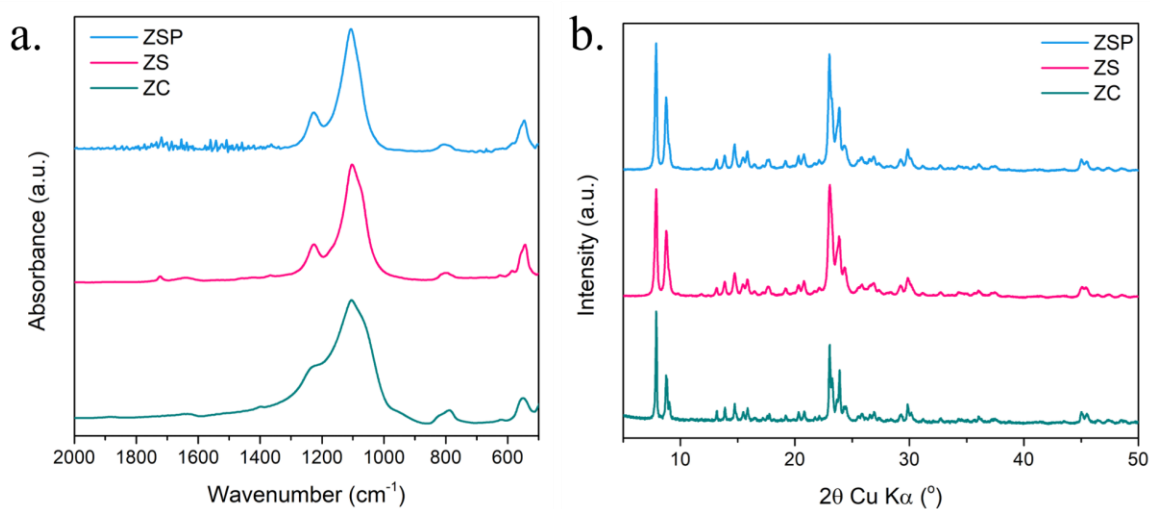


Figure 2. a) FTIR spectra and b) X-ray diffraction patterns of ZC, ZS, and ZSP samples.

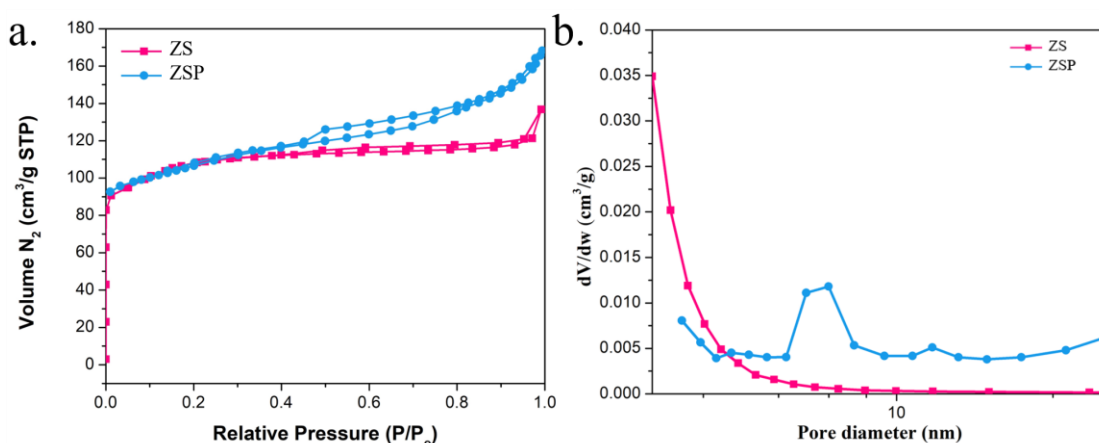


Figure 3. a) N₂ adsorption-desorption isotherm and b) BJH pore size distribution of ZS and ZSP samples.

Meanwhile, the feature around 450 cm⁻¹ is associated with T–O bending vibrations, further confirming the presence of a tetrahedral aluminosilicate lattice. All vibrational peaks clearly verify that the fundamental structural units and connectivity required for the formation of ZSM-5 are preserved in all samples.

In agreement with the FTIR results, the XRD patterns exhibit the characteristic diffraction reflections of ZSM-5 zeolite within the regions of $2\theta \approx 7\text{--}9^\circ$ and $22\text{--}25^\circ$, confirming the presence of the MFI topology across all the samples (Figure 2b) [11],[29]. While minor variations in peak intensity and band broadening are observed, these differences are attributed to intrinsic effects of precursor composition and synthesis conditions, but do not compromise structural

formation. Furthermore, these results verify that silica derived from sugarcane bagasse ash is a suitable precursor for producing ZSM-5. In addition, the PEG incorporation does not hinder the crystallization of the MFI framework. To quantitatively verify the crystallinity preservation upon PEG modification, the relative crystallinity was evaluated based on the peak area integration method in the $2\theta = 22\text{--}25^\circ$ range according to ASTM D5756. Taking the ZS sample as the baseline reference (100% relative crystallinity, integrated area = 105736.29), the relative crystallinity of the PEG-assisted sample (ZSP) was determined to be 87.88% (integrated area = 92917.99).

Table 1. The textural properties of ZSM-5 synthesized

Sample	S_{BET} (m^2/g) ^a	S_{ext} (m^2/g) ^b	V_{total} (cm^3/g) ^b	V_{micro} (cm^3/g)
ZS	245	89	0.210	0.088
ZSP	320	142	0.280	0.096

^adetermined using BET method^bdetermined using t-Plot method

This minor reduction indicates the formation of mesopores induced by the PEG, which slightly lowers the bulk crystalline volume density without causing structural collapse or phase transformation. Overall, the high retention of relative crystallinity quantitatively confirms that mesoporosity is successfully introduced while maintaining the structural integrity of the MFI framework.

The nitrogen adsorption–desorption result reveals distinct porosity for ZS and ZSP. The ZS sample exhibits a type I isotherm, characteristic of predominantly microporous materials [30]. In contrast, ZSP presents a Type IV isotherm with pronounced uptake at intermediate to high relative pressures and a hysteresis loop, indicating the presence of mesopores [31]. In agreement with these observations, the BJH pore-size distribution analysis confirms the development of secondary mesoporosity in ZSP, displaying a distinct mesopore population centered around 5–6 nm [32]. Conversely, ZS does not show significant mesopore distribution in the BJH range, consistent with its predominantly microporous nature as determined by the *t*-plot method. These textural differences suggest that PEG incorporation contributes to the development of additional mesoporous characteristics while preserving the intrinsic microporous MFI framework [18],[33]. The resulting hierarchical textural characteristics may facilitate mass transport and improve accessibility to the internal pore system, although direct evaluation of molecular transport was not performed in this study [20],[32].

Table 1 exhibits the textural parameters of ZS and ZSP samples. The ZS sample possesses a BET surface area of 245 m^2/g , with a relatively low external surface area (89 m^2/g) and a

micropore volume of 0.088 cm^3/g , consistent with its Type I isotherm and predominantly microporous character. In comparison, the PEG-assisted sample (ZSP) shows a higher BET surface area of 320 m^2/g and an increased external surface area of 142 m^2/g , alongside a larger total pore volume (0.28 cm^3/g). Although the micropore volume of ZSP (0.096 cm^3/g) remains comparable to ZS, the substantial increase in external surface area and total pore volume indicates the successful development of secondary mesopores [33]. These enhancements may be associated with the templating action of PEG during crystallization, which promotes the formation of additional mesopores without compromising the intrinsic microporous MFI structure [18]. The BJH pore size distribution further indicates the presence of pores within the mesopore range. Further morphological investigation, particularly using TEM, would be beneficial for clarifying the nature and origin of these additional pores, including whether they arise from intracrystalline mesoporosity or interparticle/ intercrystalline voids.

For comparison, the textural properties of the present ZSM-5 samples were evaluated against related systems reported in the literature. In a previous study using sugarcane bagasse ash-derived silica, the template-assisted ZSM-5 exhibited a BET surface area of 94.15 m^2/g , an external surface area of 13.34 m^2/g , and a total pore volume of 0.059 cm^3/g , while the corresponding non-templated sample showed values of 197.19 m^2/g , 15.46 m^2/g , and 0.115 cm^3/g , respectively [14]. In comparison, both ZS and ZSP in the present study exhibited higher external surface areas and total pore volumes. For PEG-assisted ZSM-5, Nanda et al. reported a BET surface area of 400 m^2/g and an external surface area of 198 m^2/g for the PEG-4000-

assisted sample [18]. Although the textural parameters of ZSP ($S_{\text{BET}} = 320 \text{ m}^2/\text{g}$; $S_{\text{ext}} = 142 \text{ m}^2/\text{g}$) are lower than those reported by Nanda et al., they remain substantially higher than those of ZS ($S_{\text{BET}} = 245 \text{ m}^2/\text{g}$; $S_{\text{ext}} = 89 \text{ m}^2/\text{g}$). This comparison suggests that the textural development achieved in the present study is consistent with the pore-structuring effects reported for PEG-assisted ZSM-5, while the incorporation of SCBA-derived silica and ZSM-5 seeding provides a distinct synthesis approach.

Based on the characterization results, a plausible mechanism for the crystallization and mesostructuring behavior during the synthesis of hierarchical ZSM-5 from SCBA-derived silica using PEG and seed assistance can be formulated. Initially, the amorphous silica extracted from Berastagi sugarcane bagasse ash dissolves into silicate species, which then interact with the added sodium aluminate precursor within the alkaline hydrothermal medium, alongside polyethylene glycol (PEG) molecules and commercial ZSM-5 seeds. As thermal energy is applied, structural rearrangement through polycondensation takes place. In this sense, the dispersed commercial seeds act as preferred nucleation sites to accelerate crystal growth kinetics and preserve the MFI framework [22],[34].

Furthermore, the mechanism underlying the formation of mesopores through PEG intervention can be proposed as follows. This phenomenon begins with interactions between the hydroxyl groups of the PEG chains and the surface silanol groups as well as aluminum species present in the zeolite precursors. Consequently, the flexible PEG molecules can coat the growing crystal faces [35]. Upon calcination, removal of the organic species may contribute to the development of additional pore volume in the final zeolite product. The combination of preserved microporosity and newly formed mesopores confirms the hierarchical nature of ZSP, consistent with its Type IV adsorption profile. Such hierarchical features are widely reported in the literature to potentially reduce intracrystalline diffusion

resistance and facilitate accessibility to active sites [32],[36]. To be noted, direct evaluations of molecular transport and catalytic performance were not conducted in this study and remain subjects for future investigation.

Compared with previous studies that investigated sugarcane bagasse-derived silica and PEG-assisted mesostructured ZSM-5 separately, the present study integrates these approaches with commercial ZSM-5 seeding in a single synthesis system. The direct comparison between ZS and ZSP demonstrates that PEG addition increases the external surface area from 89 to 142 m^2/g and the total pore volume from 0.21 cm^3/g to 0.28 cm^3/g , while maintaining a comparable micropore volume. These results demonstrate the development of hierarchical textural characteristics in ZSM-5 synthesized from sugarcane bagasse ash-derived silica using a seed-assisted and PEG-assisted approach. Thus, the present study extends the previous approaches by combining a waste-derived silica source, ZSM-5 seeding, and PEG-assisted mesostructuring within one synthesis strategy.

Conclusions

Silica extracted from sugarcane bagasse ash was successfully utilized as a silica source for ZSM-5 synthesis. Both ZS and ZSP samples successfully crystallized into the MFI framework, demonstrating that SCBA-derived silica can serve as a potential alternative silica source for ZSM-5 synthesis. Textural analysis showed that ZS possessed a BET surface area of 245 m^2/g , while the PEG-assisted ZSP achieved a substantially higher value of 320 m^2/g . The external surface area and total pore volume also increased from 89 to 142 m^2/g and 0.210 to 0.28 cm^3/g , respectively, indicating the development of additional mesoporous characteristic in ZSP. The results suggest that PEG acts as an effective soft template to generate mesopores without compromising the microporous MFI framework. Ultimately, the combination of SCBA as natural silica resource with polymer templating offers a practical approach to synthesizing ZSM-5 zeolites with hierarchical textural characteristics.

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Declaration of Generative AI and AI-assisted Technologies

The authors declare that no generative AI or AI-assisted technologies were used in the preparation of this manuscript.

Author Contributions

Conceptualization, S.M.; methodology, S.M. and S.; validation, S.M. and S.; formal analysis, T.M.N.; writing—original draft, S.M. and T.M.N.; writing—review and editing, S.M., S. and T.M.N.; funding acquisition, S.M.

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Declaration of Conflicts of Interest

The authors declare no conflict of interest.

References

1. Liu, W., Zhang, X., Yu, Q., Li, J., Wang, Y., Yu, W., Yang, Z., *et al.*, Unconventional seed-assisted strategy for Al-rich hierarchical ZSM-48 zeolite. *J. Colloid Interface Sci.*, **653(PB)**: 1715–1724 (2024).
2. Zang, Y., Wang, J., Gu, J., Qu, J. & Gao, F., Mesopore-free synthesis of hierarchical HZSM-5 for LDPE catalytic cracking. *CrystEngComm*, **22(21)**: 3598–3607 (2020).
3. Stanton, A. R., Iisa, K., Mukarakate, C. & Nimlos, M. R., Role of Biopolymers in the Deactivation of ZSM-5 during Catalytic Fast Pyrolysis of Biomass. *ACS Sustain. Chem. Eng.*, **6(8)**: 10030–10038 (2018).
4. Ticali, P., Salusso, D., Ahmad, R., Ahobasam, C., Ramirez, A., Shterk, G., Lomachenko, K. A., *et al.*, CO₂hydrogenation to methanol and hydrocarbons over bifunctional Zn-doped ZrO₂/zeolite catalysts. *Catal. Sci. Technol.*, **11(4)**: 1249–1268 (2021).
5. Hájek, M., Kocík, J., Smoláková, L., Kutálek, P. & Čapek, L., Preparation of methyl ester by heterogeneous catalysed esterification and transesterification. *Chem. Eng. Trans.*, **42**: 79–84 (2014).
6. Cueto, J., Korobka, V., Faba, L., Díaz, E. & Ordóñez, S., Aldol Condensation of Biomass-Derived Levulinic Acid and Furfural over Acid Zeolites. *ACS Sustain. Chem. Eng.*, **8(11)**: 4371–4383 (2020).
7. Makertihartha, I. G. B. N., Kadja, G. T. M., Gunawan, M. L., Mukti, R. R. & Subagio., Exceptional aromatic distribution in the conversion of palm-oil to biohydrocarbon using zeolite-based catalyst. *J. Eng. Technol. Sci.*, **52(4)**: 584–597 (2020).
8. Xu, X., Zhang, Y., Li, X., Xia, X., Jiang, H. & Toghan, A., Comparative study on the catalytic behaviors of zeolites with different diffusion limitation in ethane aromatization. *Microporous Mesoporous Mater.*, **315**: (2021).
9. Li, W., Wang, H., Wu, X., Betancourt, L. E., Tu, C., Liao, M., Cui, X., *et al.*, Ni/hierarchical ZSM-5 zeolites as promising systems for phenolic bio-oil upgrading: Guaiacol hydrodeoxygenation. *Fuel*, **274(January)**: 117859 (2020).
10. Hartmann, M., Thommes, M. & Schwieger, W., Hierarchically-Ordered Zeolites: A Critical Assessment. *Adv. Mater. Interfaces*, 2001841 (2021). doi:10.1002/admi.202001841

11. Aulia, D., Maghfirah, A. & Kadja, G. T. M., Green synthesis of hierarchical ZSM-5 using cellulose nanocrystal-mesoporegen at low temperature for catalytic cracking of palm oil into aromatic-rich gasoline. *Results Eng.*, **24(10)**: 102954 (2024).
12. Madhu, J., Santhanam, A., Natarajan, M. & Velauthapillai, D., CO₂ adsorption performance of template free zeolite A and X synthesized from rice husk ash as silicon source. *RSC Adv.*, **12(36)**: 23221–23239 (2022).
13. Flores, C. G., Schneider, H., Dornelles, J. S., Gomes, L. B., Marcilio, N. R. & Melo, P. J., Synthesis of potassium zeolite from rice husk ash as a silicon source. *Clean. Eng. Technol.*, **4(September 2020)**: 100201 (2021).
14. Rilyanti, M., Ningrum, A. D. W., Ilim, I., Suharso, S., Mulyono, M., Ayoub, M. & Simanjuntak, W., Green Synthesis of Hierarchical H-ZSM-5 from Sugarcane Bagasse Silica and Application as Catalyst for Conversion of Cellulose into Glucose. *J. Multidiscip. Appl. Nat. Sci.*, **5(1)**: 305–319 (2025).
15. Keawkumay, C., Krukkratoke, P., Youngjan, S., Osakoo, N., Deekamwong, K., Khemthong, P., Phanthasri, J., *et al.*, Extraction of silica from sugarcane bagasse ash and its utilization in zeolite 4A synthesis for CO₂ adsorption. *RSC Adv.*, **14(27)**: 19472–19482 (2024).
16. Javadian, A., Chan, X. Y., Saeidi, N., Hebel, D. E. & Schultmann, F., Valorizing Southeast Asian agricultural residues into high-performance mycelium-based biocomposites. *Sci. Rep.*, **16(1)**: 25292 (2026).
17. Sarker, A., Rabbi, A. S., Nadi, N. A., Rahman, A. K. M. L., Momin, A. A., Ahmed, K. S. & Simol, H. A., Structural and transport properties of newly synthesized ZSM-5 sourcing silica from coconut shell ash. *Results Chem.*, **11**: 101810 (2024).
18. Nanda, A. S. F., Maghfirah, A., Khalil, M., Rasrendra, C. B., Fahma, F. & Kadja, G. T. M., Mesoporous zeolite ZSM-5 directed by polyethylene glycol (PEG) at low temperature for producing high aromatic green gasoline from palm oil. *J. Porous Mater.*, 1–11 (2025). doi:10.1007/S10934-025-01826-6/FIGURES/7
19. Tao, H., Yang, H., Liu, X., Ren, J., Wang, Y. & Lu, G., Highly stable hierarchical ZSM-5 zeolite with intra- and inter-crystalline porous structures. *Chem. Eng. J.*, **225**: 686–694 (2013).
20. Mardiana, S., Kusnadi, A., Arcana, I. M., Ismunandar. & Kadja, G. T. M., Realizing mesoporous *MRE zeolites using polyethylene glycol and their catalytic evaluation in palm oil and polyethylene cracking. *Results Chem.*, **15**: 102244 (2025).
21. Gao, S., Ma, A., Yang, Z., Ge, S., Zhang, Z. & Wu, Z., Direct synthesis of low-silica ZSM-48 zeolite via seed-assisted hydrothermal synthesis with 1,6-hexanediamine as template. *Microporous Mesoporous Mater.*, **382**: 113369 (2025).
22. Kadja, G. T. M., Azhari, N. J., Mukti, R. R. & Khalil, M., A Mechanistic Investigation of Sustainable Solvent-Free, Seed-Directed Synthesis of ZSM-5 Zeolites in the Absence of an Organic Structure-Directing Agent. *ACS Omega*, **6(1)**: 925–933 (2021).
23. Snider, J. L., Streibel, V., Hubert, M. A., Choksi, T. S., Valle, E., Upham, D. C., Schumann, J., *et al.*, Revealing the Synergy between Oxide and Alloy Phases on the Performance of Bimetallic In-Pd Catalysts for CO₂ Hydrogenation to Methanol. *ACS Catal.*, **9(4)**: 3399–3412 (2019).
24. Chindaprasirt, P. & Rattanasak, U., Eco-production of silica from sugarcane bagasse ash for use as a photochromic pigment filler. *Sci. Rep.*, **10(1)**: 1–8 (2020).
25. Gamliel, D. P., Cho, H. J., Fan, W. & Valla, J. A., On the effectiveness of tailored mesoporous MFI zeolites for biomass catalytic fast pyrolysis. *Appl. Catal. A Gen.*,

- 522: 109–119 (2016).
26. Neumann, G. T. & Hicks, J. C., Novel hierarchical cerium-incorporated MFI zeolite catalysts for the catalytic fast pyrolysis of lignocellulosic biomass. *ACS Catal.*, **2**(4): 642–646 (2012).
27. Pan, M., Zheng, J., Liu, Y., Ning, W., Tian, H. & Li, R., Construction and practical application of a novel zeolite catalyst for hierarchically cracking of heavy oil. *J. Catal.*, **369**: 72–85 (2019).
28. Desmurs, L., Cammarano, C., Sachse, A., Gimello, O., Gaillard, T., Barberat, S., Blanquer, S., *et al.*, ZSM-5 monolithic microreactors with hierarchical porosity: Maximizing selective production of para-xylene. *Microporous Mesoporous Mater.*, **377**: 113201 (2024).
29. Alaba, P. A., Sani, Y. M., Mohammed, I. Y., Abakr, Y. A. & Daud, W. M. A. W., Synthesis and application of hierarchical mesoporous HZSM-for biodiesel production from shea butter. *J. Taiwan Inst. Chem. Eng.*, **59**: 405–412 (2016).
30. Qiao, K., Zhou, F., Han, Z., Fu, J., Ma, H. & Wu, G., Synthesis and physicochemical characterization of hierarchical ZSM-5: Effect of organosilanes on the catalyst properties and performance in the catalytic fast pyrolysis of biomass. *Microporous Mesoporous Mater.*, **274**: 190–197 (2019).
31. Azhari, N. J., Mardiana, S. & Kadja, G. T. M., ZSM-48 zeolites with controllable mesopore formation: synthesis, characterization, and catalytic performance. *Chem. Eng. J. Adv.*, **16**(July): 100533 (2023).
32. Khan, W., Jia, X., Wu, Z., Choi, J. & Yip, A. C. K., Incorporating hierarchy into conventional zeolites for catalytic biomass conversions: A review. *Catalysts*, **9**(2): (2019).
33. Mardiana, S., Arcana, I. M., Ismunandar. & Kadja, G. T. M., Tailoring MFI@RFE hybrid zeolites for enhanced polyethylene cracking performance. *Particuology*, **113**: 113–122 (2026).
34. Ma, D., Li, X., Liang, J., Wang, Z. & Yang, W., Distilling seed-assisted zeolite synthesis conditions by machine learning. *Microporous Mesoporous Mater.*, **339**(April): 112029 (2022).
35. Karimi, H., Towfighi, J. & Akhgar, S., Synthesis of hierarchical SAPO-34 zeolites with tuned mesopore structure for methanol to olefins (MTO) reaction using polyethylene glycol as a soft template. *J. Sol-Gel Sci. Technol.*, **100**(2): 286–298 (2021).
36. Wang, W., Luo, Z., Li, S., Xue, S. & Sun, H., Novel micro-mesoporous composite zsm-5 catalyst for aromatics production by catalytic fast pyrolysis of lignin residues. *Catalysts*, **10**(4): (2020).