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Application of 3Å Synthetic Zeolite as an Adsorbent to Reduce the Hygroscopicity of B40 Biodiesel

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Abstract: This study investigates the effectiveness of synthetic 3Å zeolite and silica in reducing water content in B40 biodiesel, a high-FAME blend prone to moisture absorption. Adsorption tests were performed using varying adsorbent masses (1.5–7.5 g) and contact durations (60–180 minutes), with water content measured via Karl Fischer titration. Both materials significantly reduced moisture levels, with the highest reduction observed using 7.5 g of silica after 180 minutes. Multiple linear regression analysis confirmed that adsorbent mass and contact time had statistically significant effects ($p < 0.001$), while adsorbent type did not ($p = 0.088$), indicating that performance differences were not consistent across all conditions. These results refine the understanding of adsorbent behavior in biodiesel drying and support more informed selection based on operational priorities such as adsorption speed or reusability. This research contributes to the optimization of non-thermal moisture control strategies in biodiesel purification and highlights the need for future studies on adsorbent regeneration and scale-up feasibility.

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Introduction

Biodiesel has received growing attention as a renewable alternative to fossil fuels due to its potential to reduce greenhouse gas emissions (Ai et al., 2024). Among available blends, B40—comprising 40% fatty acid methyl esters (FAME) and 60% diesel—has gained traction for commercial-scale applications. However, high-FAME blends like B40 are intrinsically hygroscopic, meaning they readily absorb moisture from the environment. This absorbed water negatively affects fuel stability, increases microbial contamination risk, and accelerates corrosion in storage and distribution systems.

In industrial contexts such as the oil and gas sector, the presence of water in fuels is particularly detrimental. Even low moisture levels (≥200 ppm) can accelerate corrosion in tanks and pipelines (Santos & Barbosa, 2012), promote microbial contamination (Christensen & McCormick, 2023), and result in scale formation and emulsions that impair flow assurance and reservoir integrity (Jewo & Obaro, 2023). As a result, controlling water content in biodiesel is not merely a matter of fuel quality—it is a critical operational requirement. Thermal drying, a conventional moisture removal technique, is energy-intensive and difficult to scale efficiently (Fregolente et al., 2015). Solid adsorbents offer a promising alternative due to their lower energy demand and operational simplicity. Among them, synthetic zeolite 3Å and silica are widely used desiccants in industrial processes, but limited comparative data exist on their effectiveness in biodiesel systems—particularly B40—under practical operating conditions.

Zeolite 3Å is a microporous aluminosilicate (molecular sieve) whose framework has exchangeable cations and ~3.0 Å pores (Sowa et al., 2023). These features make it extremely hydrophilic: water molecules are strongly adsorbed into the tiny pores, coordinating with framework cations. The adsorption performance of these materials depends on their pore structure and water-binding mechanisms. Zeolite 3Å is a microporous material (~3.0 Å pores) with strong affinity for water, making it effective at low humidity but prone to quick saturation due to limited pore volume (Acha et al., 2023). In contrast, silica is amorphous $SiO_2 \cdot nH_2O$ with a network of silanol (Si–OH) groups and larger pores. In contrast, silica has a mesoporous structure (2–50 nm) with a high surface area and numerous silanol (Si–OH) groups that facilitate multilayer water adsorption, especially under high humidity (Hazrat et al., 2021).

These structural differences suggest that while zeolite may provide strong selectivity and durability, silica could offer higher overall capacity and faster water uptake.

Adsorbent pore size plays a crucial role in moisture removal performance. Microporous materials like zeolite 3Å (pore size ~3.0 Å) offer strong water affinity due to confinement effects and the presence of ionic sites, making them highly effective at low humidity levels (Lin et al., 2015). However, such narrow pores can become diffusion-limited, slowing down uptake at higher humidity. In contrast, mesoporous materials like silica (pore size 2–50 nm) offer larger pore volume and faster molecular transport, enabling higher overall uptake under humid conditions. Mesoporous silica (8–10 nm) absorbed up to three times more water than microporous variants (Xu et al., 2025) and (Polish et al., 2020) found that mesopores facilitate multilayer water adsorption. Thus, while zeolite 3Å is advantageous for selective drying at moderate humidity, silica may offer greater capacity and throughput for biodiesel dehydration in real-world environments (Zhang et al., 2023).

Despite this theoretical understanding, few experimental studies have quantitatively compared the two adsorbents in biodiesel drying. In particular, there remains a lack of statistically validated data on how adsorbent type, contact time, and dosage influence water content in B40. This study addresses that gap by systematically evaluating and comparing the performance of synthetic zeolite 3Å and silica in reducing the water content of B40 biodiesel. By quantifying water reduction efficiency and analyzing the kinetics under various conditions, the findings aim to inform practical adsorbent selection for biodiesel purification systems.

Research Method

Material and Preparation

This study was designed to evaluate the adsorption efficiency of synthetic 3Å zeolite and silica in reducing water content in B40 biodiesel under controlled laboratory conditions. A full factorial 5×3 design was employed, involving two independent variables: (i) adsorbent mass (1.5 g, 3.0 g, 4.5 g, 6.0 g, 7.5 g), and (ii) contact time (60, 120, and 180 minutes). Each adsorbent mass was applied to 500 mL of B40 biodiesel in sealed 600 mL glass vessels. The tests were conducted at ambient temperature (25 ± 1 °C) and relative humidity below 55%. The study began with adsorbent preparation through oven-drying at 105 °C for 3 hours, followed by application in a 5×3 factorial design involving varying adsorbent masses (1.5–7.5 g) and contact times (60–180 min) (Figure 1). Each treatment was applied to 500 mL of B40 biodiesel in sealed vessels under ambient conditions. Water content was measured before and after treatment using Karl Fischer titration. Data were then processed to calculate water reduction efficiency and adsorption capacity, followed by multiple linear regression analysis to evaluate the effects of adsorbent mass, contact time, and adsorbent type on moisture removal performance.

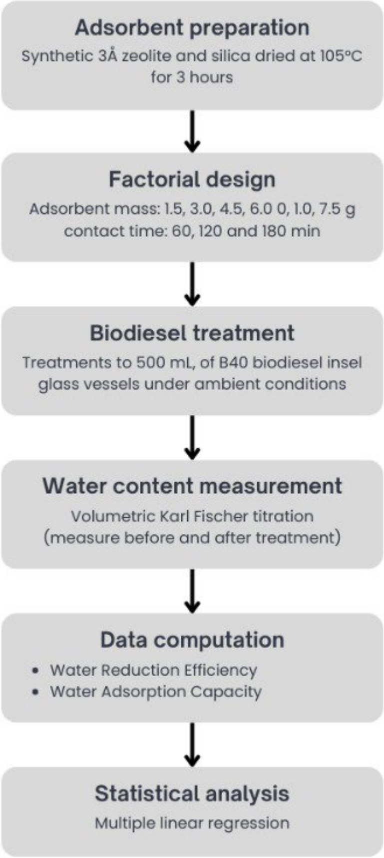

Figure 1 Flowchart of the Experimental Procedure for Evaluating Water Adsorption Efficiency of Zeolite 3Å and Silica Gel in B40 Biodiesel.

For each treatment condition, triplicate runs (n = 3) were performed using freshly homogenized biodiesel and regenerated adsorbents. Prior to use, zeolite and silica were oven-dried at 105 °C for 3 hours and stored in airtight desiccators. Manual stirring was applied for 30 seconds every 15 minutes (~1 Hz) using a glass rod and metronome for consistency. These adsorbent doses and durations were selected based on references from previous adsorption studies, which indicated that increased dosage and prolonged contact improve dehydration performance until reaching saturation points (Chungcharoen et al., 2025). The primary adsorbent used was synthetic zeolite 3Å (molecular sieve 3A). 3Å zeolite has a pore diameter of approximately 3 angstroms, enabling it to selectively adsorb water molecules (~2.8 Å in diameter) and reject larger molecules (Pérez-Botella et al., 2022). These properties make 3Å zeolite effective as a desiccant to reduce the water content of fuel without significantly absorbing its constituent hydrocarbons (Ni et al., 2022).

For comparison, silica adsorbent was also tested under similar conditions to assess its water absorption effectiveness. Silica is a commonly used commercial adsorbent for drying products; this material can absorb approximately 10–20% of its own weight in water vapor (Wang et al., 2014). However, silica's performance can be affected by external factors (e.g., temperature and humidity), thus limiting its effectiveness in reducing the water content of biodiesel (Maseko et al., 2025). This comparison is expected to demonstrate the more selective performance of 3Å zeolite.

The equipment used in the study included a 500 mL measuring cylinder to prepare the sample volume, a digital scale to measure the adsorbent mass, a stopwatch to set the contact time, and a Karl Fischer titrator to measure the water content of the biodiesel. The volumetric Karl Fischer titration method was used because it is the most widely used standard technique for determining water content in biodiesel and similar fuels (Sumartono et al., 2024). A Karl Fischer titration apparatus (e.g., Metrohm Titrando or equivalent) was used to measure the initial water content of the B40 sample and the water content after adsorbent treatment.

Before use, adsorbents were oven-dried at 105 °C for 3 hours and stored in airtight containers. Each experiment was conducted in a sealed 600 mL glass vessel at a room temperature of 25 ± 1 °C and relative humidity below 55%. Manual stirring was performed every 15 minutes for 30 seconds using a glass rod, paced at ~1 Hz with the aid of a metronome to maintain consistency and minimize operator variability. After the specified contact time, the adsorbent was separated from the biodiesel via vacuum filtration. Each condition was repeated in triplicate using fresh adsorbent and biodiesel from the same homogenized batch. In total, 30 experimental runs were conducted, consisting of 15 unique combinations of adsorbent mass and contact time for each adsorbent type (zeolite 3Å and silica), each repeated in triplicate to ensure reproducibility and statistical validity. The water content before and after treatment was measured using volumetric Karl Fischer titration, which had been calibrated daily for accuracy.

Data Processing and Statistical Analysis

A Karl Fischer volumetric titration system (Metrohm 870 KF Titrino Plus) was used to measure water content in ppm (mg/kg). This method complies with ASTM D6304 and EN ISO 12937, ensuring high sensitivity and international standardization. Titration was carried out on untreated samples and again after adsorbent treatment. Each measurement was performed in duplicate or triplicate to ensure precision. The main supporting tools included: 500 mL measuring cylinders (for sample preparation), analytical balance (±0.01 g precision), vacuum filtration system, stopwatch and metronome for stirring intervals.

To quantify the adsorptive performance of each treatment, the following parameters were calculated, Water Reduction Efficiency (%), as shown in Equation (1).

$$\text{Efficiency} = \left(\frac{C_0 - C_t}{C_0}\right) \times 100 \tag{1}$$

Where: C_0= initial water content (ppm), C_t= final water content after treatment (ppm), Water Adsorption Capacity (mg H_2O/g adsorbent), as shown in Equation (2).

$$q = \frac{(C_0 - C_t) \times V}{m} \tag{2}$$

Where: V= volume of biodiesel (L), m= mass of adsorbent (g), q= adsorption capacity in mg H_2O/g adsorbent. All water content values were reported as mean ± standard deviation (SD). Prior to statistical modeling, Grubbs' test was used to identify and remove any outliers ($\alpha = 0.05$). A multiple linear regression model was used to analyze the relationship between water content (dependent variable) and three independent predictors:, adsorbent mass (continuous, in g), contact time (continuous, in minutes), adsorbent type (categorical: zeolite or silica). The regression formula is expressed as shown in Equation (3).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon \tag{3}$$

Where: Y: final water content (ppm), X_1: adsorbent mass, X_2: contact time, X_3: adsorbent type (binary: 0 = zeolite, 1 = silica), ε: error term. T-tests were also conducted to compare mean performance between zeolite and silica treatments. All analyses were carried out using IBM SPSS v26 and Microsoft Excel. All water content results were recorded in ppm and processed using descriptive statistics, including mean and standard deviation, to summarize the central tendency and variability of each treatment group. To evaluate the effect of adsorbent mass, contact time, and adsorbent type on the reduction of water content, a multiple linear regression analysis was conducted. The regression model included three predictors: adsorbent mass (g), contact time (minutes), and adsorbent type (categorical: zeolite or silica). This model was used to determine the combined and individual influence of the independent variables on the dependent variable (water content in ppm).

Result and Discussion

The experimental tests were conducted over 180 minutes with water content measurements recorded at 60-minute intervals, using various adsorbent masses ranging from 1.5 g to 7.5 g per 500 mL of B40 biodiesel. Each test condition was replicated three times (n = 3) to ensure reliability, and all reported values represent mean results. The standard deviations for each condition ranged between ±2.3 and ±6.8 ppm, indicating acceptable reproducibility across all treatments. This replication effort strengthens the validity of the findings and ensures that the observed trends are statistically consistent.

As shown in Figure 2 and Table 1, increasing either the mass of zeolite or the duration of contact time consistently led to lower water content in the biodiesel. For instance, at 60 minutes, water content declined from 425.80 mg/kg (control, no adsorbent) to 370.38 mg/kg when 7.5 g of zeolite was used. The same pattern is observed across the 120- and 180-minute intervals, where higher dosages led to progressively lower moisture levels. At 180 minutes and 7.5 g zeolite, the final water content reached 295.04 mg/kg, which corresponds to an approximate reduction of 30.74% compared to the control condition at the same duration (452.75 mg/kg).

Table 1 Effect of Mass and Duration of Zeolite Testing on Water Content (B40)

Duration (minutes)	Without Zeolit	Zeolit 1,5 g	Zeolit 3,0 g	Zeolit 4,5 g	Zeolit 6,0 g	Zeolit 7,5 g
60	425,799	415,625	384,907	381,533	374,111	370,380
120	439,272	404,58	372,249	349,996	336,68	332,711
180	452,745	393,535	359,591	318,460	299,249	295,043

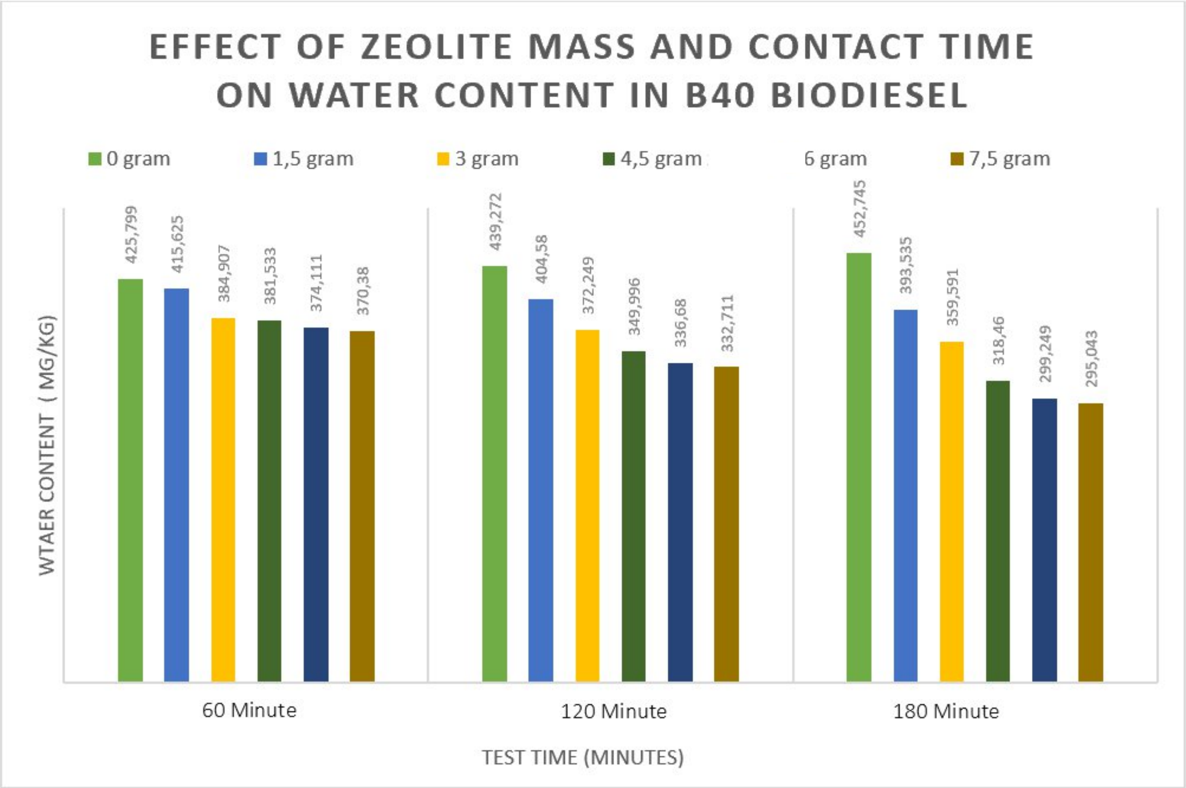

Figure 2 The Effect of Zeolite on the Water Content of B40 Biodiesel

Figure 2 suggests a pattern of diminishing returns—larger zeolite masses continued to improve performance, but the rate of improvement decreased after 6.0 g. For example, increasing zeolite from 1.5 g to 3.0 g (at 180 min) resulted in a reduction from 393.54 mg/kg to 359.59 mg/kg (33.95 ppm difference), while increasing from 6.0 g to 7.5 g led to a smaller improvement from 299.25 mg/kg to 295.04 mg/kg (only 4.21 ppm difference). This trend indicates that zeolite adsorption begins to approach saturation beyond 6.0 g under the given test conditions.

In terms of time, the biodiesel samples without adsorbent showed a steady increase in water content over time, which is expected due to biodiesel's hygroscopic nature. However, in the presence of zeolite, prolonged contact time significantly improved drying performance. For example, with 3.0 g of zeolite, water content decreased from 384.91 mg/kg at 60 minutes to 359.59 mg/kg at 180 minutes—a 25.32 ppm improvement. At the highest mass of 7.5 g, the reduction was even more substantial, from 370.38 mg/kg to 295.04 mg/kg over the same interval, confirming the importance of contact duration in achieving maximum adsorption.

Scientifically, this behavior aligns with known adsorption principles, that the availability of more active sites (through higher adsorbent mass) and longer interaction times allow more water molecules to diffuse into and bind within the zeolite’s microporous structure. However, once most binding sites are occupied, additional adsorbent or time produces only marginal gains. This supports the concept of a saturation point in solid-liquid adsorption systems and is consistent with previous studies highlighting pore-capacity limitations in molecular sieves such as zeolite 3Å. The adsorption capacity of zeolite 3Å reaches saturation rapidly, with maximum water uptake ranging between 0.22–0.24 g H_2O per gram of zeolite (Acha et al., 2023). Their analysis across multiple molecular sieves revealed that nearly all microporous sites were occupied within minutes of exposure, leading to diminishing improvements even with prolonged contact time or increased adsorbent dosage. This trend was attributed to the limited internal pore volume inherent to 3Å zeolite, which imposes a natural ceiling on adsorption capacity once saturation is approached. Similarly, evidence through thermogravimetric and isotherm analyses on LTA-type zeolites, including 3Å, reporting a consistent Langmuir-type saturation behavior (Zhang et al., 2023). Their results showed that water molecules rapidly occupied available micropores up to a maximum capacity of approximately 20–22 wt%, beyond which no further adsorption was observed.

In addition to zeolite, silica was also evaluated as an adsorbent to compare its efficiency in reducing water content in B40 biodiesel. Figure 3 and Table 2 illustrate the changes in water content across varying masses of silica (1.5–7.5 g) and contact times (60, 120, and 180 minutes). Similar to zeolite, silica demonstrated a consistent downward trend in moisture levels as both adsorbent mass and contact duration increased. However, the extent of reduction achieved by it was noticeably more substantial. At 60 minutes, the addition of 7.5 g silica reduced the water content from 402.8 mg/kg (control) to 374.4 mg/kg, a modest decrease of 28.4 ppm. By contrast, at 120 minutes, the same dose brought the moisture content down to 343.25 mg/kg—a stronger effect indicating the positive impact of contact time. The most significant reduction occurred at 180 minutes with 7.5 g of silica, which achieved a final water content of just 237.0 mg/kg, compared to 442.6 mg/kg in the control group. This represents a total decrease of over 205 ppm or approximately 46.3%, the highest among all tested configurations in this study. As illustrated in Figure 2, the bars indicate a clear trend, that the higher the mass of silica and the longer the exposure time, the lower the residual water content in biodiesel. Moreover, unlike zeolite which displayed diminishing returns at higher masses and durations, silica showed sustained adsorption potential even at the highest load (7.5 g) and longest duration (180 minutes). The reduction from 343.2 mg/kg at 120 minutes to 237.0 mg/kg at 180 minutes using 7.5 g adsorbent reflects an ongoing adsorption gradient, suggesting that silica did not yet reach full saturation under these conditions.

Table 2 Effect of Mass and Duration of Silica Testing on Water Content (B40)

Duration (minutes)	Without adsorbent (0 g)	Silica 1,5 g	Silica 3,0 g	Silica 4,5 g	Silica 6,0 g	Silica 7,5 g
60	402.8	392.6	387.9	385.5	378.3	374.4
120	407.5	381.3	380.1	360.9	347.8	343.2
180	442.6	338.3	319.3	281.5	260.8	237

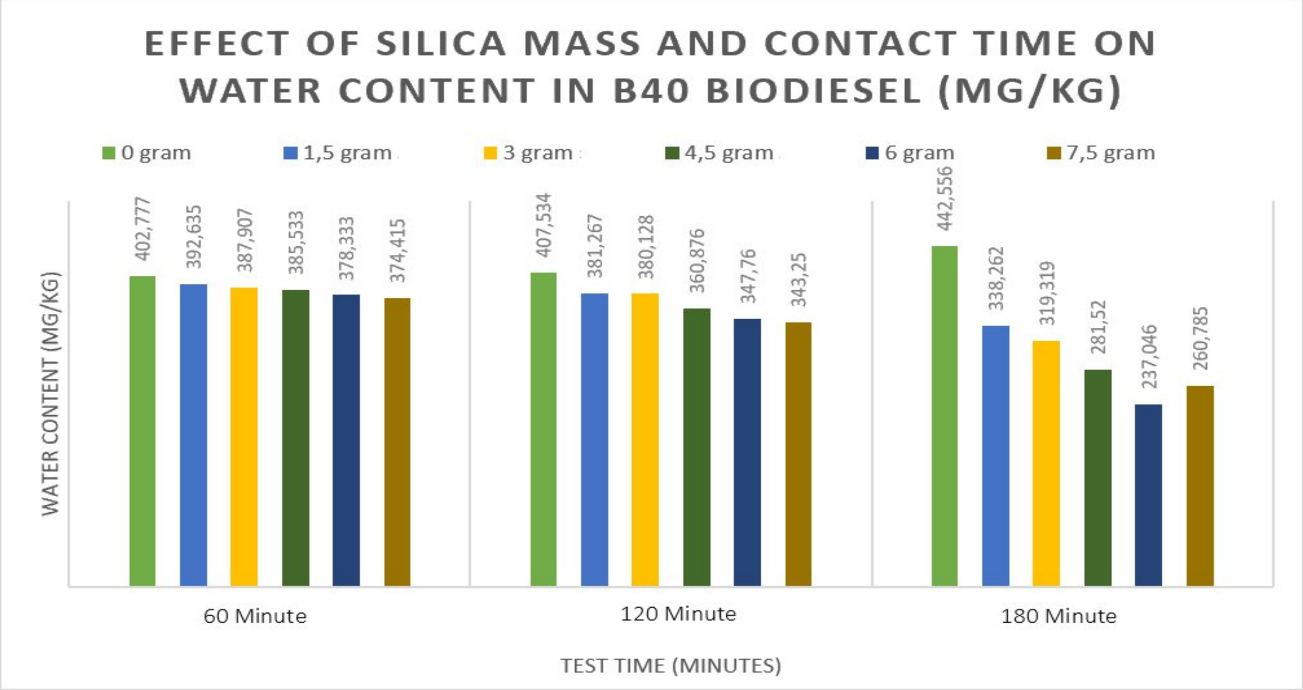

Figure 3 The Effect of Silica on the Water Content of B40 Biodiesel

These findings align with the known behavior of mesoporous adsorbents. Silica contains larger pore diameters (typically 2–50 nm) and a high surface area enriched with silanol (Si–OH) groups that promote multilayer water adsorption (Hazrat et al., 2021). This structural advantage allows it to accommodate a greater volume of water molecules and maintain diffusion efficiency even at higher humidities and extended times. In contrast to the pore saturation observed in zeolite, silica's performance indicates a broader working range and higher water-loading capacity, making it particularly effective in high-humidity environments or prolonged exposure scenarios.

Both adsorbents demonstrate the expected inverse relationship: increasing adsorbent mass and contact time leads to progressively lower water content in biodiesel. However, the degree and consistency of this reduction vary significantly between the two materials. In the zeolite trials (Table 1 and Figure 1), the most significant water content reduction occurred between 60 and 180 minutes. For instance, using 6.0 g of zeolite, the water content dropped from 374.11 mg/kg to 299.25 mg/kg—a 20% absolute reduction. Notably, the gains became marginal at higher dosages, with only a ~4 mg/kg improvement from 6.0 g to 7.5 g at 180 minutes (299.25 → 295.04 mg/kg). This plateau effect aligns with zeolite's microporous structure, which offers strong initial adsorption due to high water affinity, but saturates quickly due to limited pore volume (Sowa et al., 2023). Silica showed a more linear and consistent reduction in water content across both time and mass. At 180 minutes and 6.0 g mass, silica reduced water content from 442.56 mg/kg to 260.8 mg/kg—a greater reduction than zeolite under equivalent conditions. Furthermore, unlike zeolite, silica maintained a strong gradient of moisture removal between 120 and 180 minutes, showing no signs of early saturation. The water content dropped by more than 100 mg/kg in this interval for most mass values (e.g., at 6.0 g: 347.8 → 260.8 mg/kg), indicating sustained adsorption capacity. This can be attributed to the mesoporous nature of silica (pore size 2–50 nm), which allows for multilayer adsorption and faster mass transport of water molecules (Xu et al., 2025). Thus, silica performs better in high-humidity or prolonged-contact scenarios due to its higher accessible surface area and slower saturation rate.

The performance trend reflects fundamental differences in pore structure. Zeolite, a microporous material with ~3 Å pore size, adsorbs water quickly at low concentrations but reaches saturation early due to its limited internal volume. In contrast, silica has a mesoporous structure (2–50 nm) that supports multilayer water adsorption and allows for continued moisture uptake over extended durations. This structural advantage explains why silica maintained strong adsorption gradients even between 120 and 180 minutes, while zeolite's efficiency gains diminished significantly in the same interval. Thus, while both materials effectively reduce water content in B40 biodiesel, silica offers higher removal capacity and is better suited for long-duration or high-humidity applications, whereas zeolite may be preferable for selective adsorption under controlled or shorter exposure scenarios. While both adsorbents effectively reduce moisture in B40 biodiesel, silica demonstrates superior water removal performance under prolonged contact time or high-humidity conditions. This advantage is attributed to its mesoporous structure and high surface area, which facilitate multilayer adsorption and capillary condensation. Silica exhibited faster adsorption kinetics and higher moisture capacity than zeolite during atmospheric water capture tests, particularly under elevated humidity (Rafat et al., 2025). Silica significantly improved biodiesel purification by effectively removing water, methanol, and free glycerol during the dry-washing process, resulting in product quality that complied with international fuel standards (Jariah et al., 2021). These findings support the strategic use of silica in biodiesel drying systems requiring higher capacity and extended operation, while zeolite remains suitable for selective adsorption in more controlled or short-duration applications.

These comparative trends are further validated in Table 3, which presents the percentage reduction in water content achieved by each adsorbent over time. At a contact duration of 180 minutes, silica consistently demonstrated higher efficiency across all mass levels. For instance, at 7.5 grams, silica achieved a 41.07% reduction in water content, while zeolite reached only 34.83%. Similarly, at 6.0 grams, silica removed 43.44% of the water, whereas zeolite managed 33.90%. This performance gap remains visible at lower masses: even at 3.0 grams, silica's 27.85% removal clearly surpasses zeolite's 20.57%.

The data in Table 3 also illustrate silica's increasing efficiency over time with minimal signs of saturation. In contrast, zeolite's efficiency gains taper off as mass and contact time increase, supporting the hypothesis of early pore saturation. For example, between 120 and 180 minutes, zeolite's removal efficiency improved by only 0.9–3.4% across mass variations, while silica showed a more substantial jump of 4–9%, particularly at higher doses. This suggests that silica maintains a more favorable adsorption gradient over extended durations due to its mesoporous structure and multilayer adsorption capability.

Table 3 Effect of Mass and Duration of Zeolite Testing on Water Content (B40)

Time	60 minutes		120 minutes		180 minute	
Mass	**Zeolit**	**Silika**	**Zeolit**	**Silika**	**Zeolit**	**Silika**
1,5 gram	2,387 %	2,518 %	7,897 %	6,440 %	13,070 %	23,566 %
3,0 gram	9,603 %	3,691 %	15,257 %	6,724 %	20,570 %	27,846 %
4,5 gram	10,395 %	4,281 %	20,323 %	11,448 %	29,660 %	36,262 %
6,0 gram	12,139 %	6,068 %	23,355 %	14,667	33,903 %	43,437 %
7,5 gram	13,015%	7,041 %	24,258 %	15,773 %	34,832 %	41,072 %

This reversal in performance trend over time supports the known differences in adsorption dynamics between microporous and mesoporous materials. Zeolite's small pore size (~3.0 Å) offers strong initial binding but leads to rapid saturation, limiting its capacity to remove additional moisture beyond the first phase of adsorption. Silica, with its larger mesopores (2–50 nm), supports multilayer adsorption and sustained moisture uptake across longer durations. The data in Table 3 clearly reflect this: silica's performance continues to improve over time and mass, while zeolite reaches a plateau after 120 minutes, especially at 6.0 g and above.

Taken together, Table 3 confirms that while zeolite is effective for quick and moderate moisture reduction, silica offers superior long-term performance and higher adsorption capacity. These insights suggest that silica is more suitable for applications where extended drying time is feasible and high water removal is required, whereas zeolite may be preferable in scenarios that demand rapid but moderate dehydration within shorter timeframes. Table 4 presents the results of the multiple linear regression analysis, which quantitatively examines how contact time, adsorbent mass, and adsorbent type influence the water content in B40 biodiesel. The regression equation based on unstandardized coefficients is given in Equation (4).

$$\textbf{Water Content (ppm)} = \textbf{494.173} - \textbf{0.469} \times \textbf{Contact Time} - \textbf{13.190} \times \textbf{Mass} - \textbf{15.809} \times \textbf{Adsorbent Type}. \qquad (4)$$

Each of these predictors contributes differently to water reduction performance. First, contact time shows a negative and statistically significant effect on water content, with an unstandardized coefficient of −0.469 (p = 0.000). This indicates that for every additional minute of contact between the adsorbent and biodiesel, the water content decreases by approximately 0.469 ppm, assuming other variables remain constant. The standardized coefficient (β = −0.471) and t-value (−5.113) confirm the strength and consistency of this effect, highlighting that longer exposure enhances molecular interaction and water adsorption. Second, adsorbent mass has the most substantial influence in the model, with an unstandardized coefficient of −13.190 and a highly significant p-value (p = 0.000). This means that for every 1-gram increase in adsorbent mass, the water content decreases by an average of 13.19 ppm. Its standardized coefficient (β = −0.693) represents the largest effect size among all predictors, which aligns with adsorption theory: more adsorbent mass provides more active binding sites for water molecules, enhancing dehydration efficiency. Finally, adsorbent type, treated as a categorical variable (zeolite = 0, silica = 1), has a negative coefficient of −15.809, suggesting that silica reduced water content by approximately 15.8 ppm more than zeolite on average. However, this effect is not statistically significant (p = 0.088). The lack of significance may be due to several factors: (1) the relatively small sample size (n = 3 per treatment group), which limits statistical power; (2) overlapping confidence intervals between silica and zeolite results, indicating high within-group variability; and (3) the interaction effect between adsorbent mass and type was not modeled, which may have masked type-specific trends under varying doses. Despite silica showing better mean performance, the statistical model suggests that this advantage is not consistently strong across all conditions. The model itself is robust, as demonstrated by Tolerance and VIF values of 1.000 for all predictors, indicating no multicollinearity between variables.

Table 4 Coefficients of Multiple Linear Regression Analysis on the Effect of Contact Time, Adsorbent Mass, and Adsorbent Type on Water Content (ppm).

Model		Unstandardized	Coefficients	Standardized Coefficients	t	Sig.	Correlation			Collinearity Statistics	
		B	Std. Error	Beta			Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	494.173	19.155		25.799	.000					
	Contact Time (min)	−.469	.092	−.471	−5.113	.000	−.471	−.671	−.471	1.000	1.000
	Mass (g)	−13.190	1.755	−.693	−7.514	.000	−.693	−.799	−.693	1.000	1.000
	Adsorbent Type	−15.809	8.994	−.162	−1.758	.088	−.162	−.297	−.162	1.000	1.000

In addition to regression, a two-sample independent t-test was conducted to compare the mean water content achieved by zeolite and silica across all trials (Table 5). The group statistics show that the mean water content for the zeolite group was 372.58 ppm, while for silica it was 356.77 ppm. Although silica demonstrated a lower average, the Levene's Test indicated equal variance ($p = 0.577$), and the resulting t-test showed no significant difference ($t = 0.957$, $df = 34$, $p = 0.345$). The 95% confidence interval of the difference (−17.75 to 49.37 ppm) includes zero, reinforcing the conclusion that, statistically, there was no significant difference in average water removal between the two adsorbents across the dataset. This suggests that silica outperformed zeolite in reducing water content under the test conditions. Despite this, the standard error of the mean remains relatively close between the two groups (10.72 ppm for zeolite vs. 12.56 ppm for silica), implying that both sets of trials provide reasonably stable estimates of average performance.

Table 5 Descriptive Statistics of Water Content (ppm) for Zeolite and Silica Adsorbents (t-test)

Adsorbent Type	N	Mean (ppm)	Std. Deviation	Std. Error Mean
Zeolite	18	372.58144	45.462334	10.715787
Silica	18	356.77200	53.298727	12.562630

The first step in interpreting the table is to examine the Levene's Test for Equality of Variances, which shows a significance value (p = 0.577) (Table 6). Since this p-value is greater than 0.05, we can conclude that the variances between the two groups are homogeneous, and thus, the correct row to interpret is the one labeled "Equal variances assumed." The t-test results show a t-value of 0.957 with a two-tailed significance (p-value) of 0.345. Because the p-value is greater than 0.05, we conclude that there is no statistically significant difference in the mean water content between zeolite and silica. Although the descriptive statistics (Table 5) indicate that silica had a lower average water content (356.77 ppm) compared to zeolite (372.58 ppm), the mean difference of 15.81 ppm is not statistically significant. This is further confirmed by the 95% Confidence Interval for the mean difference, which ranges from –17.75 to 49.37 and crosses zero, indicating that the observed difference could be due to random variation rather than a true effect of adsorbent type. This finding suggests that while silica appears to offer slightly better average performance, both adsorbents performed comparably in statistical terms. Therefore, the choice of adsorbent in practical applications may depend more on other factors such as cost, availability, or reusability rather than on performance differences alone.

Table 6 Independent Samples t-Test Results Comparing Water Content (ppm) Between Zeolite and Silica Adsorbents

		Levene's Test for Equality of Variances		**t-test for Equality of Means**						
		F	**Sig.**	**t**	**df**	**Sig. (2 - tailed)**	**Mean Difference**	**Std. Error Difference**	**95% Confidence Interval of the Difference**	
									Lower	**Upper**
Water Content (ppm)	Equal variances assumed	.317	.577	.957	34	.345	15.809444	16.512049	-17.747.077	49.365966
	Equal variances not assumed			.957	33.175	.345	15.809444	16.512049	-17.777.836	49.396725

To further validate and quantify the relationship between experimental variables and water content reduction, linear regression models were constructed for both adsorbent types. These models aimed to assess the degree to which changes in adsorbent mass and contact time individually influenced the final water content in B40 biodiesel. Figures 3 and 4 illustrate the regression trends for mass versus water content and contact time versus water content, respectively, comparing the performance of zeolite 3Å and silica.

Figure 3 illustrates the linear relationship between adsorbent mass and the resulting water content in B40 biodiesel for both zeolite and silica. The regression model for zeolite is expressed as $Y = 465.734 - 14.452x$with a coefficient of determination $R^2 = 0.832$, while the model for silica is $Y = 475.184 - 11.927x$with $R^2 = 0.685$. These negative slopes indicate that increasing the adsorbent mass leads to a reduction in water content for both adsorbents. However, zeolite exhibits a steeper slope than silica, meaning that for each additional gram of adsorbent, zeolite removes more water than silica under the tested conditions. Moreover, the higher R^2 value for zeolite suggests that the linear model explains a greater proportion of the variance in water content, signifying stronger predictability. The distribution of data points also reinforces this interpretation: zeolite's points are more tightly clustered around the regression line, indicating more consistent performance, whereas silica shows greater scatter, suggesting higher variability and potentially more sensitivity to external factors like humidity. This behavior is scientifically consistent with the structural differences between the two materials—zeolite's microporous framework facilitates uniform water capture, while silica's mesoporous network allows for broader but more variable multilayer adsorption.

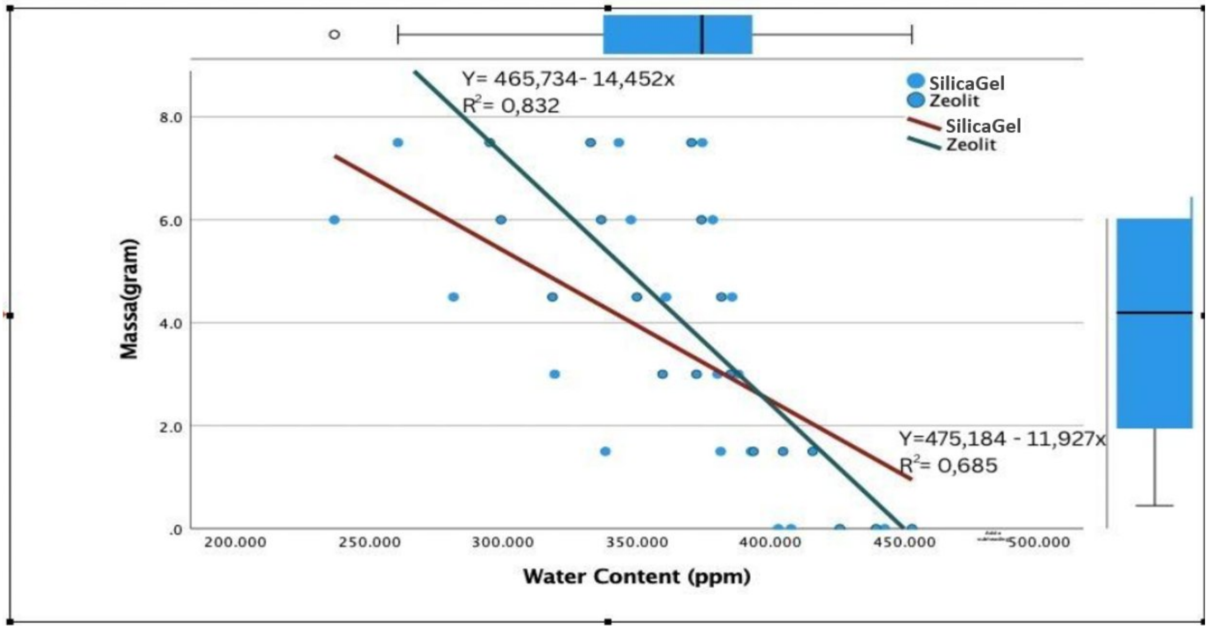

Figure 3 Linear Regression Model of Mass versus Water Content Between Zeolite and Silica

Similarly, Figure 4 presents the linear regression models between contact time and water content. The model for zeolite is $Y = 465.734 - 10.325x$with $R^2 = 0.832$, while that for silica is $Y = 475.184 - 0.614x$with $R^2 = 0.685$. These results demonstrate that zeolite achieves a significantly steeper decline in water content per unit of time, with each additional minute reducing moisture by approximately 10.325 ppm. In contrast, silica's slope of –0.614 indicates a much slower adsorption rate over time. The R^2values again highlight zeolite's superior predictability and linearity in performance, as its adsorption process closely follows the regression line. Silica's more scattered data suggests a plateauing effect, where adsorption slows over longer durations, possibly due to surface saturation or limited diffusion into deeper pores. Zeolite's strong linear response with contact time can be attributed to its fast porefilling kinetics and high affinity for water molecules, making it more responsive to incremental time increases. Overall, these regression models confirm that while both adsorbents effectively reduce water content in B40, zeolite demonstrates a more linear, time-efficient, and mass-dependent adsorption profile.

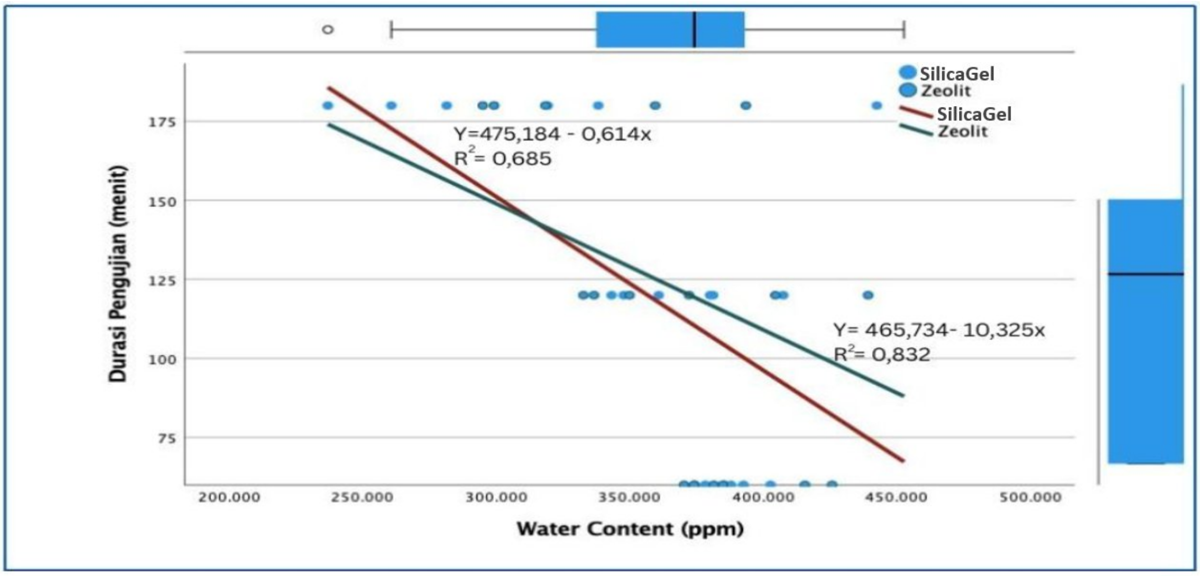

Figure 4 Linear Regression Model of Duration on Water Content Between Zeolite and Silica

Conclusions

This study has demonstrated the potential of both 3Å synthetic zeolite and silica as effective adsorbents for reducing water content in B40 biodiesel. Experimental results confirmed that increasing adsorbent mass and contact time significantly enhanced water removal performance. While silica consistently achieved greater water reduction across all tested conditions, the multiple regression analysis revealed that the adsorbent type was not statistically significant ($p = 0.088$), indicating that its superior performance may vary depending on operational conditions. The practical implications of these findings suggest that silica may be better suited for applications requiring high-capacity moisture removal over extended durations, whereas 3Å zeolite could be advantageous in systems prioritizing selectivity, reusability, or shorter contact periods. These insights provide a basis for more informed adsorbent selection in biodiesel dehydration processes.

Nevertheless, this study is subject to limitations. The experiments were conducted under controlled laboratory conditions, which may not fully replicate field scenarios where variables such as fluctuating temperature, humidity, or biodiesel composition could influence performance. Additionally, the study did not explore adsorbent regeneration cycles or long-term stability, which are crucial for assessing economic feasibility in industrial applications. Future research should explore hybrid adsorbent systems, evaluate the long-term regeneration and reuse performance of both materials, and validate findings under real-world biodiesel storage and transportation environments. Expanding the scope to include cost-benefit analyses and environmental impact assessments would also support the development of more sustainable biodiesel purification strategies.

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References

Acha, E., Agirre, I., & Barrio, V. L. (2023). *Development of High Temperature Water Sorbents Based on Lanthanum Oxide and Coke*.

Ai, W., Cho, H. M., & Mahmud, I. (2024). *The Impact of Various Factors on Long-Term Storage of Biodiesel and Its Prevention : A Review*. 1–16.

Christensen, E. D., & McCormick, R. L. (2023). Water contamination impacts on biodiesel antioxidants and storage stability. *Energy & Fuels*, *37*(7), 5179–5188.

Chungcharoen, T., Limmun, W., Srisang, S., Phetpan, K., Ruttanadech, N., Youryon, P., Kongtragoul, P., & Srisang, N. (2025). Enhanced biodiesel purification using coffee husk bioadsorbents: The role of pyrolysis temperature, KOH activation, and adsorption efficiency. *Renewable Energy*, *244*, 122700. https://doi.org/https://doi.org/10.1016/j.renene.2025.122700

Fregolente, P., Maciel, W., & Oliveira, L. (2015). Removal of water content from biodiesel and diesel fuel using hydrogel adsorbents. *Brazilian Journal of Chemical Engineering*, *32*, 895–901. https://doi.org/10.1590/0104-6632.20150324s20140142

Hazrat, M. A., Rasul, M. G., Khan, M. M. K., Mofijur, M., Ahmed, S. F., Ong, H. C., Vo, D.-V. N., & Show, P. L. (2021). Techniques to improve the stability of biodiesel: a review. *Environmental Chemistry Letters*, *19*(3), 2209–2236.

Jariah, N. F., Hassan, M. A., Taufiq-Yap, Y. H., & Roslan, A. M. (2021). Technological Advancement for Efficiency Enhancement of Biodiesel and Residual Glycerol Refining: A Mini Review. In *Processes* (Vol. 9, Issue 7, p. 1198).

https://doi.org/10.3390/pr9071198

Jewo, A. O., & Obaro, O. L. (2023). *Bacteriological and Physicochemical Assessment of Treated Petroleum Effluent Obtained from Some Petrochemical Industries in Warri , Nigeria Using Activated Rice Husk. April*, 14–24. https://doi.org/10.12691/env-11-1-3

Lin, R., Ladshaw, A., Nan, Y., Liu, J., Yiacoumi, S., Tsouris, C., DePaoli, D. W., & Tavlarides, L. L. (2015). Isotherms for water adsorption on molecular sieve 3A: influence of cation composition. *Industrial & Engineering Chemistry Research*, *54*(42), 10442–10448.

Maseko, N. N., Enke, D., Owolawi, P. A., Iwarere, S. A., Oluwafemi, O. S., & Pocock, J. (2025). Usage of Silica Xerogel from African Sugarcane Leaves as a Catalyst in Biodiesel Production through Transesterification. *ACS Omega*.

Ni, P., Zhang, Z., Xu, H., Wang, X., & Xia, Q. (2022). Diffusion and hygroscopicity of particles from diesel and biodiesel combustion in an environmental chamber. *Energy Reports*, *8*, 8271–8281.

Pérez-Botella, E., Valencia, S., & Rey, F. (2022). Zeolites in adsorption processes: State of the art and future prospects. *Chemical Reviews*, *122*(24), 17647–17695.

Polish, V., Tarasenko, S., Antypov, I., & Kozak, N. (2020). *Investigation of the Efficiency of Wet Biodiesel Purification. 02006*.

Rafat, M., Chandrasekaran, G., Shrivastava, S., Farsad, A., Ananpattarachai, J., Qiu, A., Sinha, S., Westerhoff, P., & Phelan, P. (2025). *Assessment of Beaded , Powdered and Coated Desiccants for Atmospheric Water Harvesting in Arid Environments*.

Santos, D. Q., & Barbosa, T. G. G. (2012). Biodiesel: production, characterization, metallic corrosion and analytical methods for contaminants. *Biodiesel: Feedstocks, Production and Applications*, 129.

Sowa, M., Sztekler, K., & Mlonka-m, A. (2023). *An Overview of Developments In Silica Matrix Composite Sorbents for Adsorption Chillers with Desalination Function*.

Sumartono, H., Al Huda, M., Tk, B. F., Widodo, A., Dzulfiqar, F., Suryana, N., Muhamed, A., Isa, I. M., Bakar, S. A., & Nuryadi, R. (2024). Improved low concentration water content detection in biodiesel utilizing phase-shift-based capacitive method. *IEEE Sensors Journal*, *24*(24), 41981–41988.

Wang, D., Zhang, J., Tian, X., Liu, D., & Sumathy, K. (2014). Progress in silica–water adsorption refrigeration technology. *Renewable and Sustainable Energy Reviews*, *30*, 85–104.

Xu, Y., Peng, P., Wang, H., Xiong, H., Xu, Z., Chen, X., Li, Y., Zheng, A., Wei, Y., & Yan, Z. (2025). Revealing the Crucial Roles of Pore Interconnectivity between Zeolitic and Nonzeolitic Components in Enhancing Diffusion and Catalytic Efficiency of Industrial

Zeolite-Based Catalysts. *Journal of the American Chemical Society*.

Zhang, S., Fu, J., Xing, G., Zhu, W., & Ben, T. (2023). *Recent advances in porous adsorbent assisted atmospheric water harvesting: a review of adsorbent materials*.