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Comparison of Moisture Sorption Isotherm Models and Desorption Kinetics of Silica-Impregnated Biochar Composite Desiccant

Hadiantono Hadiantono^a, Moh Djaeni^{a*}, and Setia Budi Sasongko^a

^aDepartment of Chemical Engineering, Faculty of Engineering, Diponegoro University. Jl. Prof. H. Soedarto SH, Semarang 50275, Central Java, Indonesia

* Corresponding author: E-mail: moh.djaeni@live.undip.ac.id

ABSTRACT

This study investigates the moisture sorption behavior and regeneration performance of a composite based on biomass-derived activated carbon (biochar) impregnated with silica (Na2SiO3) named AC/Si as desiccant. The composite was characterized by SEM and nitrogen adsorption analysis to evaluate structural changes after impregnation. Water vapor adsorption isotherms were fitted to five models (BET, Halsey, Henderson, Oswin, and Smith), with the Halsey model exhibiting the highest accuracy. The AC/Si composite exhibited a maximum water vapor adsorption capacity of 0.3 g/g at 27 °C and 97% RH. The saturated composite was subsequently used for desorption kinetics evaluation at 313–333 K, applying pseudo-first-order (PFO) and pseudo-second-order (PSO) models, with the PSO model providing a superior fit as evidenced by high R2 and low RMSE. The Arrhenius equation was employed to determine the activation energy (Ea) of the composite's desorption process, resulting in an Ea of 40.23 kJ/mol, which suggests efficient regeneration under moderate heating. These findings support the potential of AC/Si composites as energy-efficient, reusable desiccants for general-purpose moisture control.

ARTICLE INFO

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1. INTRODUCTION

Controlling humidity is critical in industries such as food, pharmaceuticals, electronics, and sensitive goods storage, where excess moisture accelerates degradation, reduces product quality, and increases microbial spoilage risks [1,2]. This has driven extensive research into developing desiccants that effectively adsorb water vapor under diverse environmental conditions [1]. Among these, biochar, an activated carbon (AC) which is a porous, carbon-rich material produced from biomass pyrolysis such as wood, rice husks, or coconut shells, offers excellent adsorption properties [3,4]. Its performance can be further enhanced through chemical modification, particularly silica impregnation using sodium silicate (Na₂SiO₃), which increases surface hydrophilicity and water vapor uptake [5,6], enabling the development of high-efficiency biocharbased composite desiccants for moisture-sensitive environments.

Biochar-based desiccants have attracted attention as sustainable alternatives for humidity control, but their adsorption efficiency and regeneration performance often lag behind commercial desiccants such as silica gel and zeolites. For instance, while superporous gels offer superior moisture uptake compared to many traditional materials [7], structural and compositional factors remain critical in determining adsorption behavior, as highlighted in rotary desiccant studies by [8]. Moreover, biochar's long-term performance is affected by environmental exposure; [9] reported that aging alters its adsorption-desorption characteristics, thereby affecting reliability in repeated applications. These limitations are compounded by the lack of consistent modeling frameworks for predicting sorption behavior. [10] emphasized the need for employing multiple isotherm models tailored to specific desiccant types to

better characterize adsorption mechanisms under varying conditions. Hence, to realize biochar's full potential, systematic evaluation of isotherm models and kinetic parameters is essential for optimizing design and performance in humidity control systems.

Adsorption isotherms are fundamental to understanding water vapor uptake on porous adsorbents. These curves, which describe the relationship between equilibrium water activity and adsorbed moisture content, are critical for both theoretical modeling and practical applications [11,12]. Factors such as surface heterogeneity, pore structure, and thermodynamic conditions all influence adsorption behavior. Thus, accurate isotherm modeling not only predicts equilibrium performance but also provides insights into the adsorption mechanisms, enabling the rational design of desiccant systems.

The variety of available isotherm models including BET, Halsey, Henderson, Oswin, and Smith reflects the complexity of moisture adsorption phenomena. Each model is based on distinct assumptions regarding monolayer or multilayer adsorption and the uniformity of surface properties [12]. As a result, evaluating these models against experimental data is essential, particularly for composite materials where the interaction between biochar's intrinsic porosity and the enhanced surface characteristics from silica addition must be properly captured.

While previous studies have advanced the characterization of biochar and its derivatives, limited research exists comparing the predictive performance of multiple moisture sorption isotherm models on silicaimpregnated biochar composites [11]. A direct comparative analysis is needed to determine which model most accurately describes the observed adsorption behavior. In the present study, desorption kinetics are evaluated under low-temperature conditions and modeled using pseudo first-order (PFO) and pseudo second-order (PSO) kinetic frameworks. The desorption rate constants obtained at various temperatures are further analyzed using the Arrhenius equation to determine the activation energy (Ea) of desorption. This evaluation provides critical insight into whether the desorption mechanism is physically or chemically controlled and informs the energy requirements necessary for effective adsorbent regeneration [13,14].

Accordingly, the objective of this study is to compare the performance of several moisture sorption isotherm models in representing the adsorption behavior of silicaimpregnated biochar composite desiccants. This comparison is based on rigorous statistical criterion, including root mean square error (RMSE), along with theoretical interpretation of each model's underlying assumptions [15]. In addition, the study assesses the desorption kinetics of the material to provide a comprehensive understanding of its regeneration potential. By combining experimental validation with model-based insights, this work aims to support the development of sustainable and high-efficiency desiccant materials for humidity control applications.

2. MATERIAL AND METHOD

Activated carbon (AC) derived from mangrove wood was sourced from East Jakarta, Indonesia. The activation process involved the use of sodium silicate (Na2SiO3, 47.17% water content, technical grade, ROFA Laboratorium Centre Ltd. Co.), hydrochloric acid (HCl, 32% concentration, technical grade, ROFA Laboratorium Centre Ltd. Co.), and distilled water. Sodium hydroxide (NaOH) solutions, prepared from solid NaOH purchased from ROFA Laboratorium Centre Ltd. Co., were employed as the controlling agents for water activity (a_w) during the adsorption isotherm experiments.

A total of 5 g of dried AC, sieved to particle sizes between 20 and 25 mesh, was impregnated with 100 mL of a 20 wt% Na₂SiO₃ solution (20 g of Na₂SiO₃ solid per 100 g of total solution). The mixture was stirred briefly using a magnetic stirrer and subsequently aged at room temperature for 60 hours. The sodium silicate-impregnated activated carbon (AC/Si) was thoroughly rinsed with distilled water and 5% v/v HCl until the pH of the wash solution reached neutrality. The final product was then dried at 393 K overnight.

Morphological characterization of the activated carbon was carried out using a scanning electron microscope (SEM, FEI, Inspect-S50). The pore size distribution (PSD) was evaluated by nitrogen (N₂) adsorption-desorption isotherm measurements at 77 K using a Micromeritics Tristar II Plus 3020 system. The PSD data were analyzed based on the Barrett-Joyner-Halenda (BJH) method.

The adsorption capacity of the composite desiccant was evaluated by placing 3 g of the composite into a sealed glass jar containing NaOH solutions of varying concentrations (0, 1.5, 4, 6, 9, 12, 16, and 20 molal) to regulate the relative humidity (RH) environment. RH was monitored using an RH meter with an integrated sensor placed inside the jar, positioned above the solution surface. RH readings were recorded periodically over time, and the average RH value during the adsorption period was used for analysis (Figure 1). Regeneration analysis was conducted thermally in an oven at low temperatures, specifically at 313, 323, and 333 K, using AC/Si with 0.3 g/g water content. The mass of the adsorbent was recorded every 15 minutes until a constant weight was achieved. Moisture sorption isotherms were analyzed using the BET, Oswin, Smith, Halsey, and Henderson models, while the desorption kinetics were modeled using PFO and PSO equations (Table 1).

The quality of the model fitting was assessed based on the root mean square error (RMSE) (Eq. 1) [15].

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(q_{exp} - q_{cal} \right)^2}$$
(1)

Furthermore, the temperature dependence of the desorption rate constants obtained from the kinetic modeling was analyzed using the Arrhenius equation (Eq. 2) to determine the activation energy (Ea) associated with the desorption process [13].

$$k = A \times e^{\frac{-Ea}{RT}}$$
or linearized as :
(2)

$$\ln k = \ln A - \frac{Ea}{RT}$$



Figure 1 Experimental setup of moisture sorption isotherm

Table 1 Moisture sorption isotherm models and kinetic models used in prese	nt study	y
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(3)

Model	Non-linear form	Linear form		
Moisture sorption isotherm equation				
BET	$q_e = \frac{q_b B a_w}{[(1 - a_w)(1 - a_w + B a_w)]}$	$\frac{a_{w}}{q_{e}(1 - a_{w})} = \frac{1}{q_{b}B} + \frac{(B - 1)}{q_{b}B}a_{w}$		
Oswin	$q_{e} = K_{Os} \left[\frac{a_{w}}{(1 - a_{w})} \right]^{n_{Os}}$	$\ln q_{e} = \ln K_{0s} + n_{0s} \ln \left(\frac{a_{w}}{(1 - a_{w})} \right)$		
Smith	$q_e = A_{Sm} + \ln(1 - a_w)^{B_{Sm}}$	$q_e = A_{Sm} + B_{Sm} \ln(1 - a_w)$		
Halsey	$q_e = e^{\frac{(\ln K_H - \ln a_w)}{n_H}}$	$\ln q_{e} = \frac{1}{n_{H}} \ln K_{H} - \frac{1}{n_{H}} \ln a_{w}$		
Henderson	$q_{e} = \left[\frac{-ln(1 - a_{w})}{K_{He}}\right]^{\frac{1}{n_{He}}}$	$\ln q_{e} = \frac{1}{n_{He}} \ln \left(-\ln(1 - a_{w}) \right) - \frac{1}{n_{He}} \ln K_{He}$		
Kinetic model equation				
Pseudo-first-	$\frac{\mathrm{d}\mathbf{q}_{\mathrm{t}}}{\mathrm{d}\mathbf{r}} = \mathbf{k}_{\mathrm{t}}(\mathbf{q}_{\mathrm{t}} - \mathbf{q}_{\mathrm{t}})$	$\ln(q_e - q_t) = -k_1t + \ln q_e$		
order	$dt = \frac{1}{1} \left(\frac{1}{4e} - \frac{1}{4t} \right)$			
Pseudo-second-	$\frac{\mathrm{d}q_{\mathrm{t}}}{\mathrm{d}q_{\mathrm{t}}} = k_{\mathrm{c}}(q_{\mathrm{c}} - q_{\mathrm{c}})^{2}$	$\frac{t}{t} = \frac{1}{t} + \frac{t}{t}$		
order	dt "200e ut	$q_t k_2 q_e^2 q_e^2$		

3. RESULTS AND DISCUSSIONS

Figure 2 presents the morphological comparison between AC and AC/Si. As shown in Figure 2(a), the AC surface exhibits an irregular morphology characterized by a complex network of pores and channels, primarily formed as a result of volatile compound release during the carbonization process. Some of these pores appear partially blocked by residual matter such as tar deposit (Figure 2(b)), a phenomenon similarly observed in previous studies [16].

Following Na_2SiO_3 impregnation for 60 hours, substantial structural changes are observed, resulting in a more developed and uniformly distributed pore system (Figure 2(c-d)). The chemical activation mechanism with Na_2SiO_3 is consistent with the reaction from Eq. 4 [6] :

$$Na_2SiO_3 + 2H_2O \rightleftharpoons H_2SiO_3 + 2NaOH$$
(4)

The NaOH produced during this reaction infiltrates the carbon matrix, enhancing porosity by widening existing

pores and creating new channels [6]. In addition, NaOH promotes the removal of hemicellulose and lignin, thereby facilitating further pore development [17]. This is further supported by the observation that the impregnated samples exhibited a strongly alkaline pH (~12), which persisted during the washing process and required repeated rinsing to achieve neutrality. However, it should be noted that in the present study, no direct chemical characterization was conducted to confirm the presence or specific role of NaOH on the AC/Si surface. As such, the proposed mechanism is inferred based on established findings reported in prior literature. Additionally, some pores may become obstructed by deposited silica gel as a result of the impregnation process [6,18].

Figure 3 presents the nitrogen adsorption-desorption PSD curves of AC and AC/Si. For AC, the PSD curve (Figure 3(a)) shows a dominant mesopore peak at a pore diameter of approximately 19.2 nm with a corresponding dV/dr value of 5.04×10^{-5} cm³/g.nm. Minor contributions from macropores (d > 50 nm) are also observed, with a maximum dV/dr of 4.42×10^{-5} cm³/g.nm at 50.25 nm. In contrast, the AC/Si sample exhibits a notable broadening and rightward shift in the PSD curve, as shown in Figure 3(b). The most prominent peak shifts to a larger pore diameter of ~25.4 nm with an increased dV/dr value of 6.95 \times 10⁻⁵ cm³/g.nm, while the overall curve demonstrates enhanced intensity in both the upper mesoporous (20 - 50)nm) and macroporous (d > 50 nm) ranges. Notably, additional peaks are observed at 40.2 nm and 50.9 nm with higher dV/dr values than those of AC, indicating significant development of wider mesopores and early macropores. Moreover, desorption data confirm this trend, with AC/Si showing a pronounced increase in dV/dr in the pore diameter range of 14 - 28 nm (from 5.17×10^{-5} cm³/g.nm in AC to 7.86×10^{-5} cm³/g.nm in AC/Si). These shifts suggest an effective pore widening mechanism induced by the chemical activation with Na₂SiO₃, likely through in situ NaOH generation and partial silica deposition. The increase in meso- and macroporosity is crucial for water vapor adsorption performance, as these larger pores serve as primary transport pathways that facilitate the diffusion of vapor molecules into the finer pores within the carbon structure [19,20].

The characterization of the water vapor adsorption behavior of AC/Si was evaluated through the fitting of experimental data to several moisture sorption isotherm models. The model that best captures the adsorption mechanism was selected not only based on its statistical performance but also its theoretical relevance to the physicochemical characteristics of the composite material. The experimental adsorption isotherm of AC/Si is presented in Figure 4(a), showing the relationship between a_w and q_e . Figure 4(b) compares the experimental data with the predicted curves generated using parameters derived from the linear fitting of various isotherm models (Table 2). All model parameters were obtained via linear regression using the respective linearized forms of each isotherm model, and the resulting constants were subsequently substituted into their original nonlinear equations to construct the theoretical isotherms. This approach ensures that the visual comparison in Figure 4(b) is firmly supported by the quantitative fitting results presented in Table 2. The combined presentation of graphical comparisons and statistical metrics (R² and RMSE) strengthens the overall evaluation of model performance. Among the tested models, the Halsey model showed the best agreement with the experimental data, as indicated by the highest R² value (0.9771) and the lowest RMSE (0.0170). This strong statistical performance is evident in the close alignment between the predicted and experimental curves, particularly at higher aw levels where multilayer adsorption is predominant.



Figure 2 SEM images of (a–b) AC and (c–d) AC/Si

The Halsey model is well-suited for explaining multilayer adsorption mechanisms, where water vapor molecules not only adsorb onto the surface of activated carbon (monolayer adsorption) but also form successive layers atop the initial layer. This phenomenon becomes more dominant at high aw levels, where vapor concentration is sufficient to support multilayer development. The model additionally accounts for the variation in adsorption energies across layers, reflecting the heterogeneous nature of the adsorbent surface [21]. This theoretical basis aligns with the physicochemical features of AC/Si, which exhibits surface heterogeneity due to the presence of both hydrophilic and hydrophobic regions arising from silica distribution. The silica introduced during Na2SiO3 activation contributes silanol (Si-OH) groups that increase hydrophilicity and provide high-energy binding sites, especially at low a_w. This fosters strong water-surface interactions in the initial layer, followed by multilayer growth via water-water interactions as a_w increases [22,23].

In the Halsey model, the n_H parameter describes the degree of surface heterogeneity: $n_H < 1$ typically indicates a highly heterogeneous surface, whereas $n_H > 1$ reflects a more homogeneous adsorption environment [23]. In this study, the obtained n_H value of -0.3451 suggests significant variability in adsorption energies across the composite surface. However, it should be noted that a negative n_H value alone does not unequivocally confirm multilayer adsorption behavior, as negative values can also arise from fitting artifacts or deviations from ideal model assumptions [22].

Nonetheless, the observed value supports the existence of a wide distribution of active sites, which is consistent with the porous and chemically heterogeneous nature of AC/Si. The increase in meso- and macropore volume, as shown in the PSD analysis, further supports the potential for multilayer adsorption by providing sufficient space for water cluster growth. Additionally, the hydrophilic surface functional groups act as nucleation centers that facilitate successive water layer formation. The variation in surface energy is likely attributed to the presence of functional groups introduced through silica impregnation, which enhances the surface hydrophilicity and creates a variety of adsorption sites. At lower aw, water molecules strongly interact with hydrophilic groups on the carbon surface, forming primary adsorption layers. As a_w increases, subsequent water molecules primarily associate with already adsorbed molecules, leading to multilayer growth and a decrease in adsorption energy per molecule [22,23]. The high R^2 value and low RMSE observed in this study strongly support the applicability of the Halsey model, indicating that multilayer adsorption and surface heterogeneity are likely dominant mechanisms. Furthermore, the K_H value of 1.4808 indicates a high affinity of the AC/Si composite towards water vapor, likely due to enhanced hydrogen bonding facilitated by surface silanol groups introduced during silica impregnation [6,22].



Figure 3 Pore distribution of (a) AC and (b) AC/Si



Figure 4 Moisture sorption isotherm curve at 27 °C, (a) equilibrium water vapor uptake of AC/Si and (b) the models comparison

Recent investigations have reaffirmed the effectiveness of the Halsey model in describing multilayer adsorption at elevated aw, indicating a possible clusterbased mechanism within the composite's porous framework. As aw increases, stronger intermolecular interactions promote the formation of discrete water clusters, which subsequently serve as nuclei for further water uptake. Beyond the strong agreement between the experimental data and the Halsey model, indirect evidence from the PSD analysis further supports this interpretation. The AC/Si composite exhibits a considerable proportion of mesopores and macropores, which are known to provide the spatial configuration necessary for water cluster formation and growth at higher aw. These larger pore structures facilitate capillary condensation and enable successive water layer accumulation beyond monolayer coverage, particularly under humid conditions. Although this study did not employ spectroscopic techniques to directly confirm cluster formation, the observed pore architecture, combined with the multilayer fitting behavior, strongly suggests that cluster-based adsorption occurs within the porous framework of the AC/Si composite. This hypothesis is further supported by previous findings that uniform pore structures enhance adsorption kinetics and capacity through efficient and reproducible pore filling [19]. Additionally, surface functional group modifications have been shown to stabilize adsorption sites, promote cluster nucleation, and accelerate multilayer adsorption processes [24].

Although the Halsey model achieved the best statistical fit, as evidenced by the highest R² value, other models such as Henderson and Oswin also provided reasonable fits, albeit with slightly lower accuracy. Nonetheless, the ability of the Halsey model to integrate the effects of multilayer adsorption and surface heterogeneity renders it the most suitable model for describing the adsorption behavior of AC/Si [11]. In contrast, models such as BET are limited to monolayer assumptions, while Henderson and Oswin are semi-empirical and do not explicitly account for the energy gradient or multilayer interactions typical of hydrophilic porous adsorbents [12]. Therefore, the superior fitting performance of the Halsey model, combined with its theoretical capacity to describe multilayer adsorption phenomena and surface heterogeneity, establishes it as the most appropriate model for representing the water vapor adsorption behavior of the AC/Si composite. Overall, the superior fitting performance of the Halsey model, combined with its theoretical capacity to describe multilayer adsorption phenomena and surface heterogeneity, establishes it as the most appropriate model for representing the water vapor adsorption behavior of the silica-impregnated biochar composite. The statistical outcomes and theoretical considerations collectively support the conclusion that multilayer adsorption mechanisms dominate the sorption behavior of AC/Si, particularly at higher a_w levels.

Understanding desorption behavior is essential for evaluating the reusability and energy efficiency of the adsorbent, particularly in applications involving repeated humidity control cycles. Figure 5 presents the experimental desorption curves over time, while Figure 6 shows the corresponding kinetic model fittings. As summarized in Table 3, the PSO model demonstrates superior agreement with the experimental data, as indicated by its consistently higher R² values and lower RMSE compared to the PFO model. This suggests that the desorption process is governed not only by diffusion but also by surface-related phenomena, such as the activity and accessibility of functional groups [25,26]. This statistical finding is further corroborated by visual inspection of Figures 5 and Figure 6. In Figure 5, the desorption curves exhibit an initially steep release of water vapor followed by a gradual plateau, a trend that the PSO model in Figure 6(b) captures accurately across all temperatures. In contrast, the PFO model tends to underestimate the initial desorption rate and fails to reproduce the curve's bending behavior (Figure 6(a)). The PSO model's reliance on the squared concentration difference allows it to more realistically represent surfacecontrolled desorption kinetics. Hence, the visual

consistency between the experimental and modeled curves strongly reinforces the statistical evidence supporting the PSO model's applicability.

Table 2 Parameters of linear moisture sorption isothermmodals at $27 \, {}^{\circ}C$

models at 27°C					
Model	Parameter	Value	R ²	RMSE	
BET	В	0.5878	0.1162	0.8066	
	q_b	0.0814			
Oswin	n _{Os}	0.8656	0.8929	0.1170	
	K _{Os}	0.0306			
Smith	A_{Sm}	-0.0205	0.9424	0.0277	
	B_{Sm}	-0.1054			
Halsey	n _H	-0.3451	0.9771	0.0170	
	K_{H}	1.4808			
Henderson	n _{He}	0.6211	0.9635	0.0588	
	K _{He}	5.6677			



different temperatures

The observed temperature-dependent increase in the desorption rate constant (k_2) further substantiates that higher thermal energy facilitates the disruption of intermolecular interactions between adsorbed water molecules and the adsorbent surface, thereby accelerating the desorption process. This trend aligns with findings that elevated temperatures enhance desorption kinetics by providing sufficient energy to overcome physical and chemical binding forces at active sites [27].

The effective regeneration performance of the composite can be attributed not only to the favorable kinetics described by the PSO model but also to the enhanced thermal properties introduced through silica impregnation. As reported by [18], the incorporation of silica improves the thermal conductivity of activated carbon composites, enabling more rapid and uniform heat transfer during the regeneration process. Thermal diffusivity governed by the material's specific heat capacity, density, and thermal conductivity also plays a critical role in desorption efficiency. This is evident from the observed

differences in desorption rates at 313, 323, and 333 K, where higher temperatures facilitate faster desorption by enhancing thermal diffusion throughout the material. Enhanced thermal diffusivity promotes а more homogeneous temperature distribution the across composite, leading to more efficient moisture release even under relatively low regeneration temperatures. Moreover, uniform heat distribution minimizes localized thermal gradients, which is essential for the accurate determination of Ea using the Arrhenius approach [14].

The Arrhenius equation fitting of k_2 in Figure 7 resulting linear equation as follow:

$$\ln k_2 = -4838.41 \left(\frac{1}{T}\right) + 15.981 \tag{5}$$

Table 4 summarizes the kinetic parameters obtained from the Arrhenius equation fitting. The Ea value of approximately 40 kJ/mol is classified as moderate, suggesting a favorable energy profile for regeneration processes. In desorption kinetics, a moderate Ea indicates that the energy barrier is substantial enough to stabilize adsorption but low enough to allow efficient regeneration under moderate heating conditions. This is consistent with studies showing that combining silica gel and carbon-based materials, reveal that tailored pore structures and optimized composite architectures yield desorption kinetics with similar activation energy values, leading to reduced overall energy consumption [28]. When compared to benchmark materials reported by [29], such as struvite-based sorbents (41.6 kJ/mol), biochar (47.9 kJ/mol), and MOF sorbents (as low as 0.09 kJ/mol) for ammonia gas desorption, the AC/Si composite demonstrates comparable or lower energy requirements than biochar while maintaining favorable regeneration characteristics. Unlike MOF-based sorbents that desorb minimal amounts due to strong chemisorption, the Ea of AC/Si suggests a balanced interaction strength that supports sufficient water retention during adsorption while enabling effective release during desorption. This positions the AC/Si composite within an energetically efficient range for water vapor desorption applications, particularly for cyclic humidity control systems.



Figure 6 Comparison between (a) PFO and (b) PSO kinetic model of AC/Si

This temperature-dependent behavior of the desorption rate constant (k₂) reflects the fundamental principle of thermally activated processes, in which an increase in temperature enhances the molecular mobility and reduces the residence time of water molecules on the surface. As thermal energy increases, adsorbed molecules gain sufficient energy to overcome both physisorption and weak chemisorption forces, resulting in higher desorption rates. Additionally, the porous architecture and surface chemistry of the AC/Si composite play a critical role in modulating desorption. Materials with interconnected mesoporous and macroporous structures offer lower diffusion resistance, facilitating more rapid escape of water molecules once thermal excitation is provided. The presence of hydrophilic functional groups on the silica surface may also contribute by forming weaker hydrogen bonds with water molecules, making them more responsive

to temperature changes [22,23]. When benchmarked against alternative regeneration methods, such as supercritical CO₂ drying for spent desiccants, the energy demands associated with the AC/Si composite remain competitive [30]. Notably, conventional activated carbon regeneration processes often require substantially higher thermal energy stronger adsorbate-adsorbent interactions, due to underscoring the advantage of the composite system developed in this study. Overall, the systematic increase in desorption rate constants with rising temperature highlights the pivotal influence of thermal energy. Enhanced heat transfer and surface activation collectively improve desorption performance, thereby supporting the long-term reusability and energy efficiency of AC/Si composite [25,31].

Model	Temp. (K)	Parameter	Value	R ²	RMSE
PFO	313	$k_1 (min^{-1})$	0.0562	0.9561	0.1355
		q _e cal (g/g)	0.1676		
	323	k_1 (min ⁻¹)	0.0926	0.9713	0.0855
		q _e cal (g/g)	0.2179		
	333	k_1 (min ⁻¹)	0.0865	0.9383	0.0857
		q _e cal (g/g)	0.2207		
PSO	313	$k_2(g/g/min)$	1.6294	0.9987	0.0096
		q _e cal (g/g)	0.3038		
	323	$k_2(g/g/min)$	2.9238	0.9985	0.0069
		q _e cal (g/g)	0.3023		
	333	$k_2(g/g/min)$	4.1140	0.9973	0.0066
		q _e cal (g/g)	0.2946		

Table 3 Parameters of linear PFO and PSO model desorption curve fitting



Figure 7 The plot of ln k against 1/T for desorption kinetic

4. CONCLUSION

This study demonstrated that silica-impregnated biochar composites exhibit excellent potential as efficient and reusable desiccant materials for humidity control applications. SEM analysis revealed that silica impregnation modified the surface morphology of activated carbon, promoting the development of more uniform and accessible pore structures. PSD analysis showed an increase in pore size distribution after impregnation, facilitating easier water vapor diffusion into the internal structure and enhancing the overall adsorption capacity. Among the moisture sorption isotherm models evaluated, the Halsey model provided the best fit to experimental data, with a value of 0.9771 and an RMSE of 0.0170, indicating multilayer adsorption behavior facilitated by a heterogeneous surface structure. Desorption kinetics analysis revealed that the PSO model best described the

experimental desorption behavior, achieving high R² values and low RMSE, confirming that both surface reactions and diffusion phenomena govern the regeneration process. The activation energy for desorption, determined as 40.23 kJ/mol from Arrhenius analysis, suggests that effective regeneration can be achieved with moderate thermal input, supporting energy-efficient operation. This Ea value is slightly lower than that of conventional biochar (47.9 kJ/mol) and comparable to other desorbents such as struvite-based materials (41.6 kJ/mol), indicating that AC/Si offers a favorable energy profile for practical desorption applications. The analysis shows that silica impregnation contributed to faster and more uniform moisture release, minimizing temperature gradients during desorption. These results collectively highlight the potential of silica-modified biochar composites for sustainable, lowenergy, and rapid-cycle humidity management systems.

 Table 4 Summary of Arrhenius parameters obtained from desorption kinetics modeling

Model	Slope (-Ea/R)	Intercept (ln A)	R ²	Ea (kJ/mol)	A (min ⁻¹)
PSO	-4838.41	15.981	0.9825	40.2265	8.72×10^{6}

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Competing interests

The authors declare that they have no competing interest.

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