JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(1), 186–195
https://doi.org/10.12911/22998993/195573
ISSN 2299–8993, License CC-BY 4.0

Received: 2024.10.28
Accepted: 2024.11.15
Published: 2024.12.01

The harnessing of natural zeolite for adsorption of methylene blue active substances from carwash wastewater: A kinetic and isotherm study

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ABSTRACT

The removal of surfactants from wastewater is critically important, particularly in Jordan, which is the third-most water-scarce country in the world. Jordan is rich in natural zeolite, a highly absorbent material, making it ideal for removing liquid-solid contaminants like surfactants from wastewater. This study investigates the adsorption capacity of zeolite to remove methylene blue active substances (MBAS) from carwash wastewater (CWW) using batch-sorption experiments. Various parameters, including zeolite dosage, contact time, and temperature, were tested to evaluate their impact on the sorption process. he results demonstrate that natural zeolite achieved a maximum removal efficiency of 93.02%, with optimal performance at pH 6.8. Dosages of 0.1, 0.5, and 1.0 grams were tested, revealing that increased zeolite dosage, longer contact times, higher temperatures, and lower initial concentrations enhanced removal efficiency. The best removal efficiency for SDBS-MBAS was achieved within a 30-minute mixing time. At a dosage of 1 gram, the adsorption coefficient rose from 6.3% to 23.5% as temperature increased from 25 °C to 45 °C, indicating an endothermic process. The adsorption was found to be endothermic, spontaneous, and irreversible. Additionally, adsorption isotherm models, including Langmuir, Freundlich, and Pseudo-second-order, were applied to analyze the adsorption behavior. The Langmuir model provided the best fit, while the Freundlich model showed the highest error values. Error analysis confirmed the validity of the Pseudo-second-order and Langmuir models for describing the adsorption kinetics.

Keywords: adsorbent weight, methylene blue active substances, Freundlich isotherm, pseudo-model, Langmuir model, contact time, zeolite, synthesized zeolite.

INTRODUCTION

Sodium dodecyl benzene sulfonate (SDBS), a type of MBAS, is a common pollutant in wastewater due to its widespread use in carwash operations. MBAS compounds are extensively used as surfactants in carwash water, and they can pose significant risks to human health, animals, and plants if they enter irrigation systems (Rice et al., 2017; Bdour et al., 2015). For instance, even low concentrations of SDBS can be toxic to humans, while larger quantities discharged into water bodies can lead to eutrophication and harmful effects on aquatic life (Hashim and Zayadi, 2016). Consequently, many local environmental protection agencies, such as those in Jordan, mandate reducing MBAS levels in reclaimed domestic wastewater to below 25 mg/L (JS 893/2021) (JSMO, 2021).

A variety of methods have been examined for MBAS removal from wastewater. Collivignarelli et al. (2019) evaluated the removal of non-ionic and anionic MBAS from laundry wastewater using a thermophilic aerobic membrane reactor and

nanofiltration with activated carbon, achieving up to 76% removal efficiency, although the cost was high. Similarly, Bering et al. (2018) used a two-stage moving bed bioreactor filled with Kalends K5 for treating laundry wastewater, resulting in 85–96% removal of anionic and non-ionic surfactants.

Natural zeolite, known for its large specific surface area, has limited adsorption capacity but is still effective in adsorbing heavy metals from industrial wastewater, pharmaceuticals, and SDBS from detergent processes (Hamed et al., 2024; Taffarel and Rubio, 2010). Studies like Shi et al. (2018) have highlighted the potential of natural materials as useful adsorbents for removing cations from wastewater. Recently, efforts have focused on modifying zeolite surfaces to improve their adsorption capacity for pollutants (de Magalhães et al., 2022; Hailu et al., 2017). Modifications can significantly alter zeolite's surface chemistry and pore structure, thereby enhancing its effectiveness in pollutant removal (Mahmoodi and Saffar-Dastgerdi, 2019; Xie et al., 2013). For example, Solińskaet and Bajda (2022) examined the sorption efficiency of unwashed cationic surfactant-modified natural zeolite (Cp) for removing inorganic compounds (NH^{4+}, SO_4^{2-}, NO^{3-}, Fe, Mn, Zn, and Ni) from wet flue gas desulphurization wastewater. Castañeda and Medina (2017) also demonstrated the use of surfactants in enhancing metal affinity, facilitating the removal of diverse organic and inorganic pollutants from water.

Regeneration of zeolite is essential for maintaining its adsorption efficiency over multiple cycles. Common methods include thermal, chemical, and biological regeneration (Daligaux et al., 2021). Thermal regeneration involves heating the zeolite to desorb contaminants, but excessive heat can degrade its structure. Chemical regeneration uses solvents or acids to facilitate desorption but may alter the zeolite's characteristics (Chang, 1995). Biological methods leverage microorganisms to metabolize organic adsorbates, offering a sustainable alternative (Abromaitis et al., 2016). While regeneration can reduce adsorption capacity over time due to incomplete desorption and structural changes, optimized protocols can help retain significant adsorption efficiency, enhancing the long-term viability of zeolite in wastewater treatment applications. However, given that zeolite is abundant in Jordan, the need for regeneration may be economically unfeasible. The natural availability of zeolite allows for its effective utilization in wastewater treatment processes without costly regeneration, ensuring that significant adsorption efficiency can be maintained in various applications (Abdallat et al., 2024).

In Jordan, natural clay is commonly used for surfactant removal from wastewater (Abdallat et al., 2024). Abdel-Rahem et al. (2019) studied the adsorption of single surfactants onto a 3% weight per volume of Jordanian natural clay, showing strong adsorption tendencies that reveal the complex interactions of synergistic surfactants with the adsorption process. Other studies have focused on modified zeolites and clays to remove heavy metals from water and wastewater, showing promising results for surfactant removal. However, further research is needed to better understand the interactions between sorbents and surfactants to optimize wastewater treatment performance (Popaliya and Mishra, 2023; Mahmoodi et al., 2019; Palmer and Hatley, 2018; Shi et al., 2018).

Additionally, predicting the mechanisms of zeolite adsorption systems through modeling experimental data is essential. To enhance understanding of the physicochemical kinetics involved in zeolite applications for surfactant removal in wastewater, this study examines the efficiency of zeolite in removing MBAS from carwash wastewater and investigates the role of adsorption isotherms. Specifically, it explores the use of Langmuir, Freundlich, and Pseudo-second-order isotherms. These adsorption models provide critical insights into key operational variables, such as adsorption capacity (mg/g) and adsorption mechanism, which are essential for developing efficient wastewater treatment systems. The outcomes of this study may contribute to addressing Jordan's water scarcity by facilitating the reuse of treated water for car washing and agricultural purposes (DOS, 2022).

MATERIALS AND METHODS

This study examined wastewater from five carwash stations in Amman, Jordan: Total Station, Alozi, Almanaseer, Alhajawi, and Alwataneh. Five samples were collected from each station, and the concentration of the active compound SDBS–MBAS was analyzed in both raw and treated carwash water at the Water Authority of Jordan laboratories using ASTM D2330-02 standards (Rice et al., 2017). The average inlet concentration for the five samples was calculated. To begin treatment, the raw samples underwent a pre-treatment process starting with sedimentation, followed by

filtration. Water was directed through a rectangular basin with dimensions of 60×20×20 cm³ at a controlled, slow velocity and left undisturbed for 24 hours to allow particulates to settle. Subsequently, the water was sent to a flotation and aeration tank to separate oil from water. The next stage involved sand filtration through a tank with the same dimensions as the settling basin, filled with Swieleh sand as the filtration medium. Specifications for this medium include a gravel particle diameter of 1.5 mm, sand particle diameter of 0.05 mm, specific gravity of 2.65, and bed porosity of 0.82. A batch equilibrium technique was employed to study the adsorption isotherms of MBAS on synthesized zeolite used as an adsorbent. Different concentrations of zeolite (0.1 g, 0.5 g, and 1.0 g) were tested at varying temperatures (25°C, 35 °C, and 45 °C) and a pH of 6.8, which is commonly used in relevant research. The mixture was agitated at different time intervals (5, 30, 60, and 120 minutes), then filtered, and the residual SDBS-MBAS concentration in the treated samples was measured using the same standard method.

This research applied adsorption equations and isotherms to assess the adsorption efficiency of zeolite for removing SDBS-MBAS from car-wash wastewater. To this end, three primary adsorption models and kinetics were employed.

Adsorption performance indicators

Performance indicators, including uptake efficiency, uptake capacity, and distribution coefficient, were determined following methods described by Chang and Franses (1995).

Uptake efficiency (E)

$$E = \frac{C_o - C_e}{C_o} \times 100\% \quad (1)$$

where: C_o is the initial concentration of SDBS (mg/L), C_e is the residual concentration of SDBS ion in the solution after equilibrium (mg/L).

Uptake capacity (q_e)

$$q_e = \frac{(C_o - C_e) \times V}{m} \times 100\% \quad (2)$$

where: q_e is the amount of SDBS uptake by synthesized natural zeolite (mg SDBS/g of natural zeolite), V is the volume of the solution (L) and m is the natural zeolite dose (g), m is the weight of zeolite dose (g).

Partition coefficient, K_d (L/g)

$$K_d = \frac{(C_o - C_e) \times V}{C_O \times m} \times 100\% \quad (3)$$

Adsorption isotherms and kinetics

The batch-sorption experiment results were used to evaluate the applicability of six isotherm models to describe the adsorption process. These models include four Langmuir models, the Freundlich model, and the pseudo-second-order model. The equations for these models, adapted from Razavi et al. (2020), are as follows:

$$C_e \text{ versus } \frac{C_e}{q_e} \text{ First order langmuir} \quad (4)$$

$$\frac{1}{q_e} \text{versus } \frac{1}{C_e} \text{ Second order langmuir} \quad (5)$$

$$\frac{q_e}{C_e} \text{ versus } q_e \text{ Third order langmuir} \quad (6)$$

$$q_e \text{versus } \frac{q_e}{C_e} \text{ Fourth order langmuir} \quad (7)$$

$$\log q_e \text{ versus Freunldich model} \quad (8)$$

$$t \text{ versus } \frac{t}{q_e} \text{Pseudo second order} \quad (9)$$

where: t is the mixing time in batch adsorption experiment.

Thermodynamic study

Thermodynamic experiments were conducted at various temperatures (25, 35, and 45 °C) with a pH value of 6.8. The thermodynamic parameters, enthalpy (ΔH_o in kJ/mol) and entropy (ΔS_o in J/(K·mol)), were calculated using the following equations (Sultana et al., 2024):

$$Ln\ K_d = \frac{\Delta S_o}{R} - \frac{\Delta H_o}{RT} \quad (10)$$

where: T is the temperature in Kelvin, R is the gas constant, which is equal to 8.314 J/(mol.K), A plot of (ln K_d) versus (1/T) provides a slope of ($\Delta H_o/R$) and an intercept of ($\Delta S_o/R$), from which (ΔS_o) and ΔH_o can be determined. The change in Gibbs free energy ($\Delta G°$, kJ/mol) was calculated as follows:

$$\Delta G_O = \Delta H_O - T\Delta S_O \quad (11)$$

Error analysis

The coefficient of determination (R^2) is commonly used to assess the model's predictive capability with respect to the experimental data. However, (R^2) alone may not adequately reflect

the error within the isotherm model. To evaluate the model's fit to the experimental data, two additional indicators were employed: Mean square error (MSE) and Chi-square test (χ^2), as defined by Terdputtakun et al. (2017).

$$q_{e=\frac{q_{mK_L C_e}}{1+K_{LC_e}}} \quad (12)$$

$$MSE = \frac{1}{n}\Sigma_{n-1}^{n}(q_{exp} - q_{cal})^2 \quad (13)$$

$$\chi^2 = \frac{\Sigma_{n-1}^{n}(q_{exp}-q_{cal})^2}{q_{cal}} \quad (14)$$

where: q_{exp} and q_{cal} are the experimental and calculated uptake values, respectively (mg/g).

RESULTS AND DISCUSSIONS

Effects of mixing time, temperature, and zeolite dosage effects on uptake efficiency of MBAS (SDBS)

The uptake efficiency of the adsorbate (SDBS-MBAS) ion was investigated as a function of zeolite dosage of 0.1 g, 0.5 g, and 1 g, and by varying the mixing time in the range of 5–120 minutes. Figure 1 shows the adsorption uptake efficiency of SDBS ions ranging from 74% to 77% using both 0.1 g and 0.5 g of zeolite weight at all mixing time intervals. However, it increased to 86% using 1 g of zeolite and continued to increase with the mixing time, reaching 93% after 30 minutes, then increased slowly to be constant at 94% after 2 hours. Therefore, the optimum condition for adsorption is using 1 g of zeolite, a mixing time of 30 minutes, and a pH of 6.8. Taffarel and Rubio (2010) studied the influence of contact time on the removal of MBAS by modified natural zeolite in Brazil. They found that 30 minutes was required to achieve the maximum adsorption capacity of 30.7 mg SDBS g^{-1}.

Table 1 presents the uptake of SDBS by zeolite at various temperatures. The data reveals that the adsorption of SDBS on zeolite increases with temperature. Specifically, the uptake rises from 24.22 mg SDBS/g at 25 °C to 26.9 mg SDBS/g at 35 °C, and further to 30.5 mg SDBS/g at 45 °C. This trend suggests that higher temperatures enhance the adsorption capacity of zeolite for SDBS, likely due to increased molecular motion and interaction between SDBS molecules and the zeolite surface (Wu et al., 2020). Furthermore, Figure 2 illustrates the effect of temperature on the adsorption coefficient (K_d) for SDBS, showing an inverse relationship. At elevated temperatures, increased water vaporization forms micro-cavities, leading to a reduction in adsorption capacity. When the zeolite dose is 1g, the adsorption coefficient rises from 6.3% to 23.5% as (1/T) increases from 25 °C to 45 °C, indicating that the adsorption process is endothermic (Basu et al., 2018).

Zeolite adsorption thermodynamics, temperature effects, and process stability

MBAS adsorption onto natural zeolite was found to be temperature-dependent, with higher

Table 1. SDBS uptakes at different temperatures.

Temperature (C)	SDBS uptake using zeolite (mg SDBS/g)
25	24.22
35	26.9
45	30.5

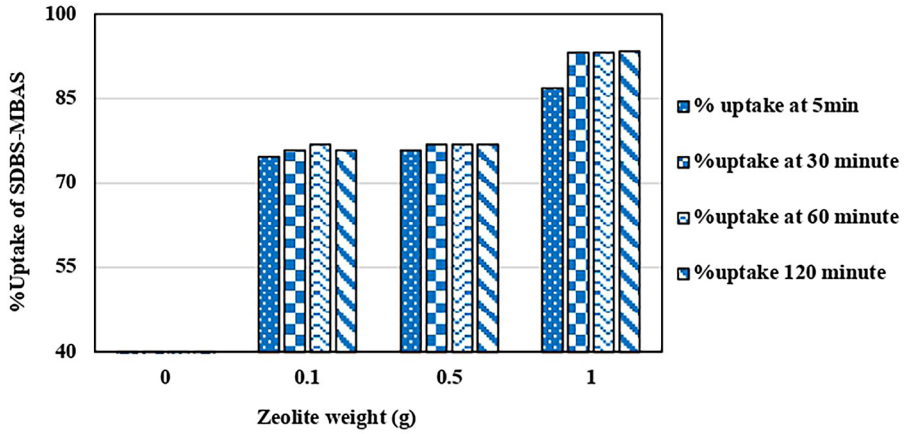

Figure 1. The uptake efficiency of SDBS-MBAS surfactant at (0.1, 0.5, 1.0) g of zeolite at different mixing time durations

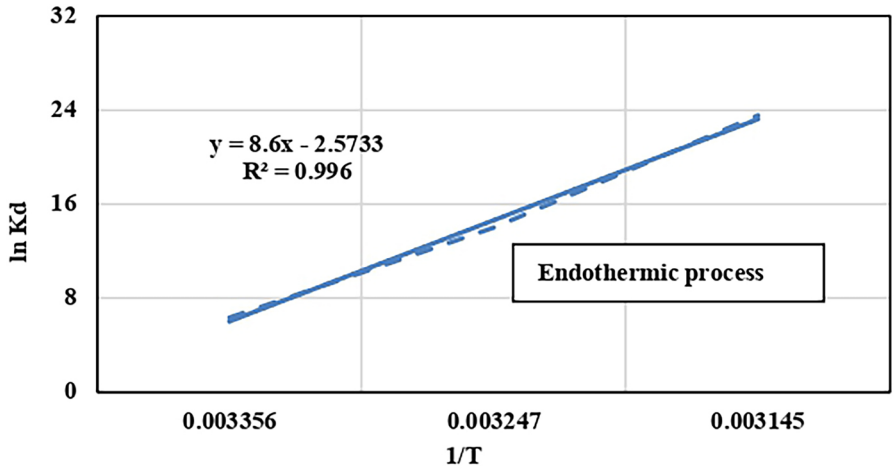

Figure 2. The relationship between the partition adsorption coefficient (K_d in L/g) of SBDS-MBAS at 1 g zeolite and pH=6.8 at different temperatures in Kelvin as (298, 308, and 318)

temperatures enhancing the adsorption capacity. As shown in Table 2, the adsorption uptake increased from 24.22 mg/g at 25 °C to 30.5 mg/g at 45 °C. This trend suggests that the adsorption process is endothermic, as higher temperatures provide the necessary energy to enhance the interaction between MBAS molecules and the active sites on the zeolite surface. The calculated adsorption equilibrium constants (Kd) further support this temperature dependence, showing an increase as the temperature rises. The positive relationship between temperature and Kd indicates that adsorption efficiency would decrease at lower temperatures, which could impact performance in colder environments. However, given the typical ambient temperatures in Jordan, this variability is not expected to significantly affect adsorption efficiency in most carwash wastewater treatment applications.

The endothermic nature of the adsorption process raises questions about its stability under variable temperature conditions. To understand the temperature effects, the thermodynamic parameters, including enthalpy (ΔH°) and entropy (ΔS°), were analyzed to provide further insights into the energetic feasibility and entropy-driven spontaneity of the process across various temperatures (Shi et al., 2023). The thermodynamics parameters were calculated from Figure 2, as the slope is equal to $\Delta H^o/R$, so the calculated enthalpy will be 8.6 multiplied by 8.314, which equals 71.5 kJ. This indicates that the process is endothermic. The entropy (ΔS^o) will be -2.5 multiplied by 8.314, which equals to -20.8 kJ. These values suggest a highly endothermic process with a positive entropy change, indicating that adsorption likely increases system disorder and is energetically favorable at higher temperatures.

In operational settings, ambient temperatures may not always be within the optimal range, particularly during colder seasons. Although zeolite's adsorption efficiency appears to benefit from moderate temperature increases, extreme temperature fluctuations could influence process stability. To address these potential challenges, operators might consider strategies such as pre-heating wastewater during colder months to maintain a stable adsorption rate, though this could introduce additional operational costs. Alternatively, selecting zeolite modifications or exploring mixed-sorbent systems may provide greater temperature resilience.

Table 2 demonstrates the MBAS-SDBS concentration at various mixing times using three different natural zeolite dosages. At a 0.1 g zeolite dose, the concentration starts at 4.8 mg/l for a 5-minute mixing time and gradually decreases to 4.0 mg/l after 2 hours. This trend indicates a steady decline in MBAS-SDBS concentration with increasing mixing time, suggesting that even a small amount of zeolite can effectively reduce concentration over time. For a 0.5 g dose, the initial concentration is 4.6 mg/l at 5 minutes, showing a slower reduction to 4.2 mg/l after 2 hours. This suggests that while a moderate increase in zeolite dose can still reduce MBAS-SDBS levels, the efficiency of reduction per unit time diminishes slightly compared to the 0.1 g dose. The most significant decrease

Table 2. MBAS-SDBS concentration with three natural zeolite dosages and five mixing times

Zeolite dose	Mixing time				
	5 min	30 min	50 min	1 hour	2 hour
0.1 g	4.8 mg/l	4.6 mg//	4.4 mg/l	4.1 mg/l	4.00 mg//
0.5 g	4.6 mg/l	4.5 mg//	4.3 mg/l	4.2 mg/l	4.20 mg//
1.0 g	2.5 mg/l	2.0 mg//	1.7 mg/l	1.3 mg/l	1.25 mg//

was observed with a 1.0 g zeolite dose, where the concentration drops from 2.5 mg/l at 5 minutes to 1.25 mg/l at 2 hours. This substantial reduction indicates a higher zeolite dosage's pronounced effectiveness in lowering MBAS-SDBS concentration. Generally, the batch-sorption results demonstrate that increasing both zeolite dosage and mixing time enhances the reduction of MBAS-SDBS concentration, with the highest dosage providing the most efficient reduction.

Then, further analysis was performed for the uptake efficiency percentages of MBAS (SDBS) by natural zeolite at a pH value of 6.8 and a mixing time of 30 minutes. As shown in Figure 3, the maximum uptake efficiency of zeolite was 93%. This result indicates that the geolimerization process successfully produced additional pores, thereby enhancing the zeolite's capacity for SDBS uptake. This effect is particularly evident at higher concentrations due to the increased availability of pores. At low concentrations, the existing pores are sufficient to accommodate most of the ions. However, at higher concentrations, the pores become insufficient, necessitating additional pores. The uptake efficiency for a 0.1 g dose of zeolite reached 75.8%, and for a 0.5 g dose, it was 76.8%. Comparing these results with previous studies indicates a high uptake efficiency of zeolite for SDBS removal (Makarchuk and Dontsova, 2016).

Adsorption isotherms analysis

The batch-sorption experimental data is analyzed to develop the adsorption kinetic models. The purpose of this analysis was trying to understand the adsorption mechanisms of zeolite in terms of mass transfer coefficients, transfer rates, and adsorbent operational performance. The following analysis provides detailed information on adsorbent phase transformation, internal diffusion process, and adsorbate-adsorbent interactions.

The kinetic analysis results shown in Table 3 demonstrate a detailed evaluation of the adsorption behavior of MBAS over various mixing times using Langmuir and Freundlich isotherms, as well as different reaction orders. As mixing time increases from 5 to 120 minutes, the adsorbate concentration (Ce) steadily decreases, indicating efficient adsorption behavior. This is further supported by the reciprocal values (1/Ce), which show an increasing trend, suggesting that adsorption sites become more saturated over time, aligning well with the Langmuir isotherm model. The Freundlich isotherm analysis, proved by the decrease in Log Ce values, indicates an increase in adsorption capacity over time, representing a favorable adsorption process on heterogeneous surfaces. Meanwhile, the Log qe values remain relatively stable, underscoring the steady efficiency of the adsorbent material.

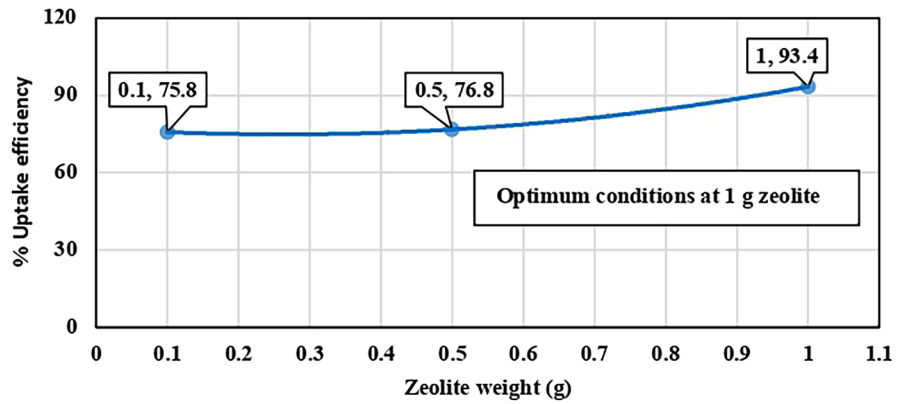

Figure 3. The uptake efficiency of SDBS-MBAS at (0.1, 0.5, 1.0) g at Ph = 6.8 and time 30 minute

Table 3. Kinetic parameters of batch-sorption models studied

Mixing time (min)	Langmuir isotherm								Freundlich isotherm		Pseudo 2nd order
	1st order		2nd order		3rd order		4th order				
	Ce	1/Ce	1/Ce	1/qe	qe/Ce	qe	qe	qe/Ce	Log *Ce*	Log qe	qe
5	2.5	0.4	0.4	1.21	0.33	0.83	0.825	0.33	0.40	-0.08	6.1
30	2	0.5	0.5	1.17	0.43	0.85	0.850	0.43	0.30	-0.07	23.5
60	1.3	0.77	0.77	1.13	0.69	0.89	0.885	0.69	0.11	-0.05	67.8
120	1.25	0.8	0.8	1.12	0.71	0.89	0.888	0.71	0.09	-0.052	135.2

The system's behavior aligns well with pseudo-second-order kinetics, as evidenced by the steady increase in qe/Ce values and the relatively stable 1/qe values over time. This pattern suggests that chemisorption processes may drive the adsorption, with the rate-limiting step involving the formation of chemical bonds between the adsorbate and adsorbent. Furthermore, the notable rise in qe values across all reaction orders (from 6.1 at 5 minutes to 135.2 at 120 minutes), indicates that higher-order kinetics might more accurately describe the system. This significant increase in adsorption capacity over extended mixing times highlights the strong affinity between SDBS-MBAS and the natural zeolite, affirming the efficacy of the adsorption process. The prolonged increase in adsorption capacity over time also suggests a robust interaction between the adsorbate and adsorbent, making the zeolite a viable option for practical applications where longer mixing times are feasible.

Table 4 presents the values of R^2, $q_{m,}$ and K_L values for the four Langmuir models, the Freundlich model, and the pseudo-second-order model. Based on the coefficients of determination R^2, the models are ranked as follows: Langmuir 1 > Langmuir 4 > Langmuir 2 > Langmuir 3. The q_m values increase with rising temperature, suggesting an endothermic adsorption process. Similarly, Taffarel and Rubio (2010) observed that in their study of SDBS adsorption on natural zeolite in Brazil, the equilibrium data showed the best fit with the Langmuir isotherm model, followed by the Freundlich model and, lastly, the Pseudo-second-order model.

The values of the Freundlich parameters n and K_L were derived from the intercept and slope of the linear plot for MBAS-SDBS adsorption onto zeolite at 25 °C and a pH of 6.8. These parameters, along with their correlation coefficients (R^2), are provided in Table 4. The correlation coefficient for the Freundlich model is 0.988 at pH 6.8 and 25 °C, as shown in Figure 4. Compared to the Langmuir models, the Freundlich model demonstrated a lower fit with the adsorption data, suggesting that homogeneous adsorption is more suitable for describing this process than heterogeneous adsorption. The n value of 0.02 indicates favorable adsorption of SDBS on the zeolite surface (Kołodyńska et al., 2017). The Freundlich adsorption constant was calculated as 6.167 at pH 6.8 and 25 °C. For the pseudo-second-order model, the values of K_L, q_m, and R^2 were determined using Excel Solver to minimize error, yielding an R^2 of 0.921 at pH 6.8 and 25 °C.

To assess model accuracy, two error metrics were employed: Mean Squared Error (MSE) and Chi-squared χ^2. As shown in Table 4, the Langmuir 3rd-order model had the lowest MSE and χ^2 values, indicating it provided the best fit among the evaluated models. This was followed by the Langmuir 2nd-order, then 1st-order, and finally the 4th-order models. In contrast, the Freundlich model exhibited the highest error values, making it the least accurate among the tested models. These findings support the suitability of the

Table 4. The values of determination coefficients R^2, adsorption isotherms of SDBS at temperature 25 °C

Langmuir Model 1st order					Langmuir Model 2nd order					Langmuir Model 3rd order				
R^2	q_m	K_L	MSE	χ^2	R^2	q_m	K_L	MSE	χ^2	R^2	q_m	K_L	MSE	χ^2
0.99	0.77	5.89	0.025	0	0.95	0.77	6.32	0.022	0	0.94	0.78	6.40	0.022	.00045
Langmuir model 4th order					Freundlich					Pseudo model 2nd order				
R^2	q_m	K_L	MSE	χ^2	R^2	q_m	K_L	MSE	χ^2	R^2	q_m	K_L	MSE	χ^2
0.96	9.36	1.09	0.034	2169	0.98	0.72	6.16	0.057	.0439	0.92	1.06	0.93	–	–

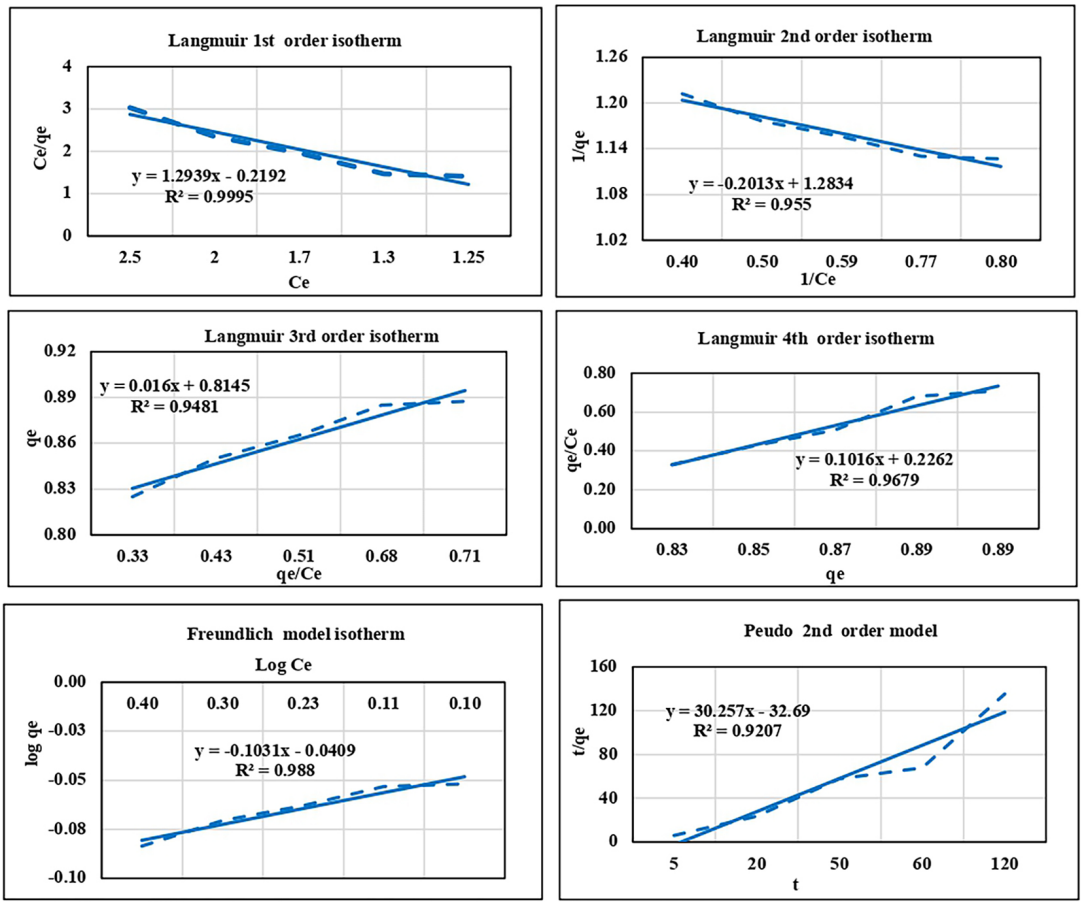

Figure 4. The adsorption isotherms of SDBS-MBAS with liner equations and coefficient of determination R^2

pseudo-second-order and Langmuir models for describing the adsorption process. Although both models have similar R^2 values, the notable differences in MSE and χ^2 emphasize that R^2 should primarily indicate trends, rather than evaluate precision. Equal R^2 values do not imply equivalent error levels, underscoring the importance of using multiple error metrics for a comprehensive evaluation of model performance.

CONCLUSIONS

This study evaluated the effectiveness of Jordanian natural zeolite for removing SDBS-MBAS from carwash wastewater (CWW), examining various parameters that could impact the adsorption process. Both isotherm and kinetic studies were conducted. Results indicated a maximum uptake efficiency of 93.02% for natural zeolite, with optimal adsorption observed at pH 6.8. Zeolite dosages of 0.1, 0.5, and 1.0 g provided optimal operational performance, and a feasible mixing time of 30 minutes was identified. The removal efficiency improved with higher zeolite dosages, longer contact times, increased temperatures, and lower initial concentrations. At a dosage of 1 g, the adsorption coefficient increased from 6.3% to 23.5% as the temperature rose from 25 to 45 °C, suggesting an endothermic process. The adsorption process was found to be endothermic, spontaneous, and irreversible.

Batch sorption results revealed that the adsorption mechanism of natural zeolite involves physicochemical interactions. The high surface area and porous structure of zeolite provide ample sites for SDBS-MBAS molecule adsorption. Additionally, the negative surface charge on the zeolite enhances electrostatic attraction for positively charged species, facilitating their uptake. The presence of exchangeable cations in the zeolite structure also enables ion exchange, further contributing to SDBS-MBAS adsorption.

The isotherm study showed the best fit with the Langmuir model, while the Freundlich model had the highest error values. Error analysis confirmed the suitability of the Pseudo-second-order and Langmuir models for describing the adsorption kinetics.

Acknowledgments

The authors would like to express their gratitude for the support extended to them throughout this research project by the colleagues and staff of Jordan University. This research was conducted in part using the resources of the university.

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