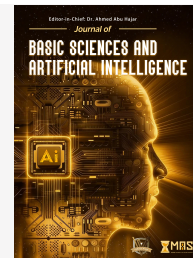




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RESEARCH ARTICLE

Preparation of Activated Carbon from Libyan Date Seed Biomass for Water Treatment Applications

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ABSTRACT

In line with the global trend towards using environmentally friendly materials from natural sources, this work presents the manufacture of activated carbon from three different Libyan date seeds, namely, Bekkari, Degla, and Halawi. The activation process involves chemical activation by phosphoric acid followed by thermal carbonization. The functional groups of the generated activated carbon samples were evaluated using Fourier Transform Infrared Spectroscopy (FTIR). Adsorption tests were carried out to determine their effectiveness in removing Allura Red dye from aqueous solutions. The FTIR findings indicated a high potential of date seeds as an efficient adsorbent. Batch adsorption testing revealed that all samples had good removal efficiency for Allura Red dye contaminants. The experimental results were fitted to Langmuir and Freundlich isotherm models, which confirmed that adsorption took place on heterogeneous surfaces via monolayer and multilayer processes. Overall, the findings indicate that activated carbon generated from Libyan date seeds is a potential, low-cost, and sustainable material for water filtration applications, particularly in areas with high agricultural waste.

KEYWORDS

Activated Carbon; Biomass; Date Seeds; Adsorption; Allura Red

1. INTRODUCTION

Activated carbon is a versatile material widely used in different applications such as water and wastewater treatment, gas purification, and catalysis due to its high surface area, well-developed porous structure, and diverse surface functional groups (Bennemla et al., 2024; Al-Rub et al., 2024). These properties are strongly influenced by both the nature of the precursor material and the activation method employed (Soudani et al., 2024; Muhari et al., 2025). The Activation of carbon can be achieved through two primary methods: physical activation and chemical activation. Physical activation involves an initial carbonization process under an inert atmosphere, followed by activation using oxidizing gases such as steam or carbon dioxide at elevated temperatures (Danish & Ahmad, 2018). In contrast, chemical activation involves the impregnation of the precursor with chemical activating agents such as phosphoric acid (H_3PO_4), zinc chloride ($ZnCl_2$), or potassium hydroxide (KOH) before thermal treatment. The impregnated material is then subjected to carbonization, during which both carbonization and activation occur simultaneously. This method is generally preferred due to its lower activation temperature, higher yield, and enhanced development of porous structure (Bennemla et al., 2024; Soudani et al., 2024).

Traditionally, activated carbon has been produced from non-renewable resources such as coal, lignite, and wood. However, environmental concerns and increasing production costs have driven the search for alternative, sustainable precursors. In recent years, agricultural residues have gained significant attention as low-cost and environmentally friendly raw materials for activated carbon production. These include coconut

shells, rice husks, fruit stones, and various lignocellulosic wastes (Muhari et al., 2025; Al-Rub et al., 2024).

Among these materials, date seeds have emerged as promising precursors for activated carbon production because of their high carbon content, low cost, and availability, particularly in date-producing regions of North Africa and the Middle East (Ahmed, 2016).

According to the Food and Agriculture Organization (FAO, 2023), global date production exceeds 8.5 million metric tons annually, with date seeds accounting for approximately 10% of the total fruit weight. Countries such as Libya, Egypt, Saudi Arabia, and Algeria are among the major producers, resulting in large quantities of date seed waste that remain underutilized (FAO, 2023). The lignocellulosic structure and mineral composition of date seeds make them suitable for the production of activated carbon with desirable adsorption properties. In recent years, increasing attention has been directed toward the development of sustainable adsorbent materials derived from agricultural waste, in line with the principles of green chemistry and circular economy. Biomass-derived activated carbon has demonstrated high efficiency in removing various contaminants from water, including dyes, heavy metals, and organic pollutants.

Activated carbon is widely recognized for its ability to remove a broad spectrum of contaminants due to its adsorption capacity and surface characteristics. It has been extensively applied in water purification systems to eliminate organic compounds, residual disinfectants, odors, and heavy metals. In addition, it is used in air filtration, gas purification, and industrial

processes due to its effectiveness and relatively low cost compared to alternative materials (Bennemla et al., 2024; Al-Rub et al., 2024). Despite these advantages, conventional production of activated carbon still relies heavily on non-renewable resources, raising environmental concerns such as deforestation and carbon emissions. Therefore, there is a growing need to develop sustainable, low-cost, and locally available precursors for activated carbon production (Muhari et al., 2025).

In this context, date seeds represent an abundant and underutilized biomass resource, particularly in Libya. Their availability, chemical composition, and structural properties make them a suitable candidate for producing activated carbon for water purification applications. Several studies have investigated the production of activated carbon from various agricultural wastes using chemical activation methods. For instance, Bennemla et al. (2024) reported the preparation of activated carbon from medlar seeds via chemical activation using H_3PO_4 . The study confirmed the successful development of a porous structure through various characterization techniques, including Scanning Electron Microscopy-Energy-Dispersive X-ray Spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), and nitrogen adsorption-desorption analysis. The optimal preparation conditions were identified as an activation temperature of 500 °C, an activation time of 60 min, and an impregnation ratio of 2:1. The resulting activated carbon exhibited a high specific surface area of 1845.32 m²/g, an average pore diameter of 2.88 nm, and a total pore volume of 0.896 cm³/g. Additionally, it showed excellent regeneration performance, maintaining 84.23% efficiency after five cycles.

Al-Rub et al. (2024) investigated the removal of pharmaceutical contaminants, specifically paracetamol, from aqueous solutions using activated carbon prepared from date pits via thermal and chemical activation with H_3PO_4 . The study evaluated the effect of several parameters, including contact time, pH, temperature, and impregnation ratio, and found that optimal conditions were achieved at a contact time of 150 min, pH 7.0, temperature of 25 °C, and an activation ratio of 1:1. The results showed a high removal efficiency of 92.9%, with a maximum adsorption capacity of 165 mg/g. The adsorption process was best described by a two-step Langmuir isotherm and pseudo-second-order kinetics, while thermodynamic analysis indicated that the process was exothermic and governed mainly by physisorption. Furthermore, the prepared activated carbon demonstrated good regeneration potential, with efficiencies of 60% using hot water and 68% using methanol.

Soudani et al. (2024) reported the preparation of activated carbon from date palm fibers using H_3PO_4 as a chemical activating agent for the removal of Cu^{2+} ions from aqueous solutions. The results demonstrated a high removal efficiency of 94.47% at an equilibrium time of 60 min. Kinetic studies showed that the adsorption process followed the pseudo-second-order model, with intra-particle diffusion occurring in multiple stages. Isotherm analysis indicated that the Langmuir model provided the best fit, with a maximum adsorption capacity of 48.59 mg/g, suggesting favorable monolayer adsorption. Thermodynamic parameters confirmed that the process was spontaneous and endothermic, involving both physical and chemical adsorption mechanisms.

Muhari et al. (2025) investigated the preparation of activated carbon from a mixture of coffee grounds and fly ash using H_3PO_4 activation for the treatment of laundry wastewater. The study focused on evaluating the effect of different mixing ratios and contact times on phosphate removal efficiency. The adsorbent was prepared through carbonization followed by chemical activation, and different composition ratios (1:4, 2:3, 1:1, 3:2, and 4:1) were tested. The findings demonstrated that combining agricultural waste with industrial by-products can enhance adsorption performance while providing a low-cost and sustainable solution for wastewater treatment.

In this work, three types of Libyan date seeds were collected. The seeds were used to prepare activated carbon. Chemical activation was employed to enhance the properties of activated carbon. The adsorption capacity of the prepared activated carbon was tested using the widely used dye Allura Red.

2. MATERIALS AND METHODS

2.1 Raw Materials

Three types of Libyan date seeds, namely Bekkari, Degla, and Halawi, were used as raw materials in this study. For convenience, the samples were designated throughout the manuscript as AC1 (Bekkari), AC2 (Degla), and AC3 (Halawi). Figure 1 shows the date seed used in this study. These date varieties were selected for their availability and potential differences in physical and chemical properties. H_3PO_4 (85 wt.%, supplied by HACH) was used as the chemical activating agent. Allura Red dye (E129, Sigma-Aldrich, Germany) was used as the model organic dye.

2.2 Preparation of Activated Carbon

The seeds were collected and thoroughly washed with distilled water to remove impurities and then oven-dried at 105°C to remove moisture. Then, the dried date seeds were ground using a mechanical grinder to obtain a uniform particle size. The ground samples were then chemically impregnated with H_3PO_4 at a concentration of 60%, with an impregnation ratio (acid to precursor) of 2:1. The mixture was left for 48 hours at room temperature to ensure proper penetration of the activating agent into the precursor structure to create a porous structure and improve the surface properties. After impregnation, the samples were subjected to carbonization in a muffle furnace at a temperature of 400°C for 1 hour under limited oxygen conditions, which allowed for the development of a porous carbon structure. Following carbonization, the samples were washed thoroughly with distilled water to remove residual acid and then dried for further use. Figure 2 shows the process of activation of carbon produced from date seeds.

The prepared activated carbon samples were characterized using FTIR to identify surface functional groups. FTIR analysis was performed at the Libyan Advanced Centre for Chemical Analysis in Tripoli.

2.3 Adsorption Experiments

The adsorption performance of the prepared activated carbon was evaluated using synthetic contaminated water containing Allura Red dye. Allura Red was chosen as the model organic pollutant because it is widely used in the food, cosmetics, pharmaceutical, and textile sectors. Despite its use, Allura Red is resistant to biodegradation and poses risks to both aquatic life and human health. Batch adsorption experiments were carried out under controlled laboratory conditions.

The adsorption tests were carried out with an initial dye concentration of 0.80 ppm, 0.5 grams of activated carbon, and a solution volume of 500 mL. The mixture was stirred thoroughly at room temperature to ensure complete dissolution and uniform distribution of the dye molecules. The prepared solution was used as synthetic wastewater to evaluate the adsorption performance of the activated carbon samples (AC1, AC2, and AC3). The interaction between the dye molecules and the adsorbent was investigated to determine the removal efficiency of each sample. While the initial concentration of the dye is known, the concentration during and at the end of the experiment was measured using a UV-Vis Spectrophotometer supplied by Thermo-USA. Removal efficiency was calculated following Equation (1).

$$\text{Removal efficiency (\%)} = \left(1 - \frac{C_t}{C_0}\right) * 100 \quad (1)$$

where C_t is the Allura Red concentration at time t , while C_0 is the initial Allura Red concentration.

The distribution coefficient (K_d) was calculated to evaluate the adsorption affinity of activated carbon toward Allura Red dye at different contact times. The K_d value represents the ratio between the amount of dye adsorbed onto the activated carbon and the remaining dye concentration in the aqueous solution at equilibrium.

The distribution coefficient was calculated using the following Equation (2):



Figure 1 Types of Date Seeds Used in This Study (AC1, AC2, and AC3)

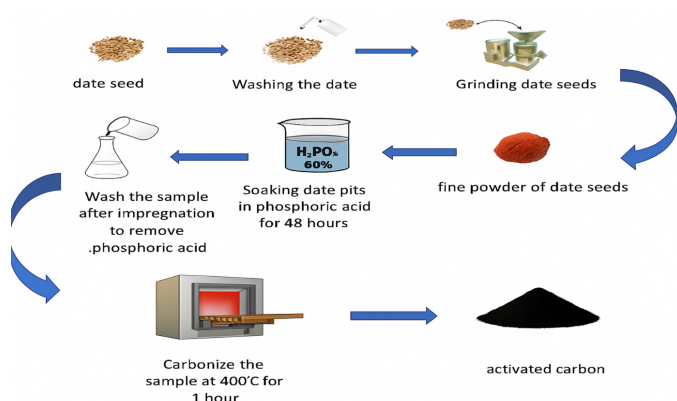


Figure 2 Preparation Process of Activated Carbon from Date Seeds

$$K_d = \left(\frac{C_0 - C_e}{C_e} \right) \times \left(\frac{V}{m} \right) \quad (2)$$

where:

- K_d is the distribution coefficient (mL/g).
- C_0 is the initial dye concentration in solution (mg/L).
- C_e is the dye concentration remaining in the solution after adsorption (mg/L).
- V is the volume of dye solution (mL).
- m is the mass of activated carbon used (g).

2.4 Adsorption Isotherm Models

The Langmuir model assumes that adsorption occurs on a homogeneous surface with a finite number of identical adsorption sites and involves the formation of a single molecular layer of adsorbate.

The linear form of the Langmuir equation was used (Equation (3)):

$$\frac{C_e}{Q_e} = \frac{1}{Q_{max}K_L} + \frac{C_e}{Q_{max}} \quad (3)$$

where:

- Q_{max} is the maximum adsorption capacity (mg/g).
- K_L is the Langmuir adsorption constant (L/mg).

- C_e/Q_e was plotted against C_e , and the values of Q_{max} and K_L were determined from the slope and intercept of the linear regression plot.

Another model, the Freundlich model, describes adsorption on heterogeneous surfaces with different adsorption energies and assumes multilayer adsorption.

The linear form of the Freundlich equation was applied (Equation (4)):

$$\log Q_e = \log K_F + \frac{1}{n} \log C_e \quad (4)$$

where:

- K_F is the Freundlich adsorption constant related to adsorption capacity.
- n is the adsorption intensity parameter.
- C_e and Q_e represent the equilibrium concentration and adsorption capacity, respectively.

A plot of $\log Q_e$ versus $\log C_e$ was used to determine the Freundlich constants (K_F and n) from the intercept and slope of the linear regression.

The suitability of both isotherm models was evaluated by comparing the correlation coefficient (R^2) values obtained from the linear fitting, where the model with the higher R^2 value was considered to provide a better description of the adsorption process.

3. RESULTS AND DISCUSSION

This section presents the experimental results of the characterization and adsorption performance of activated carbon derived from date seed samples.

3.1 FTIR Analysis of Activated Carbon Samples

FTIR spectroscopy was conducted to investigate the functional groups present on the surface of date seed samples before and after carbonization, providing insights into the chemical transformations occurring during the carbonization process. The analysis focused on the three date seed varieties (AC1, AC2, and AC3). Figures 3–8 present the FTIR spectra of the samples before and after carbonization.

Before carbonization, broad absorption bands were observed around $3300\text{--}3400\text{ cm}^{-1}$, corresponding to hydroxyl (–OH) stretching vibrations, likely due to moisture content or naturally occurring alcohols. After carbonization, these bands significantly diminished, indicating dehydration and the removal of hydroxyl-containing compounds as a result of thermal treatment.

Strong peaks at approximately $2920\text{--}2926\text{ cm}^{-1}$ and $2850\text{--}2855\text{ cm}^{-1}$,

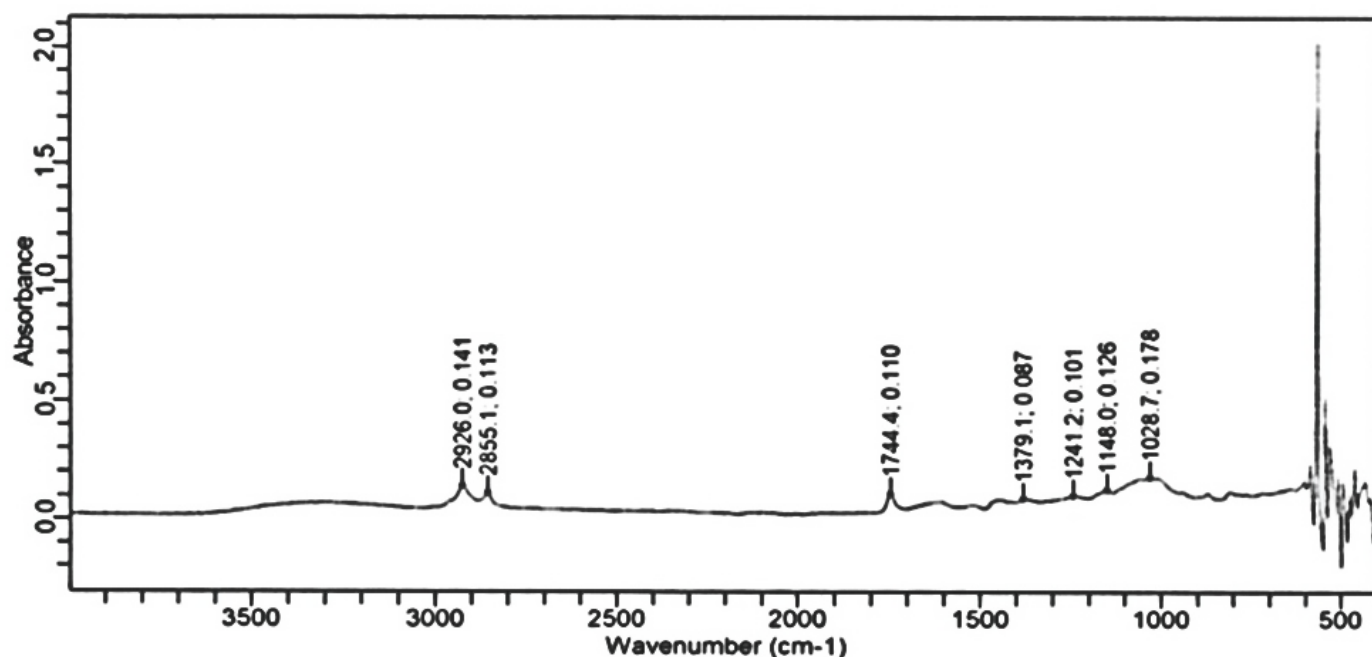


Figure 3 FTIR Spectrum of Date Seed Sample (AC1) before Carbonization

attributed to aliphatic C-H stretching vibrations of $-\text{CH}_2-$ and $-\text{CH}_3$ groups, were prominent before carbonization but were greatly reduced or absent after carbonization. This suggests the breakdown of aliphatic chains during carbonization.

Distinct peaks at around $1710\text{--}1744\text{ cm}^{-1}$, associated with C=O stretching vibrations from carbonyl groups such as carboxylic acids, esters, or ketones, were evident before carbonization and disappeared after carbonization. This indicates the removal of oxygenated functional groups due to thermal decomposition.

In the fingerprint region ($1500\text{--}1000\text{ cm}^{-1}$), the samples before carbonization displayed complex peaks related to C-O, C-C, and potentially C-N stretching, which were significantly reduced or lost after carbonization. This simplification highlights the substantial structural changes induced by carbonization.

After carbonization, new absorption bands emerged, particularly around $1595\text{--}1599\text{ cm}^{-1}$, suggesting the formation of aromatic C=C bonds indicative of the development of conjugated or graphitic carbon structures. Additionally, weak bands near 2359 cm^{-1} may correspond to adsorbed CO_2 on the carbon surfaces. Minor features, including a band at 1162 cm^{-1} and subtle peaks near 1699 cm^{-1} and 2907 cm^{-1} , may reflect residual or newly formed chemical structures following carbonization. Sharp peaks below 1000 cm^{-1} , observed in some carbonized samples, could be attributed to inorganic components or mineral residues that became more prominent after the removal of organic matter.

Overall, the FTIR analysis revealed consistent chemical transformations during carbonization, including the removal of hydroxyl and carbonyl groups, degradation of aliphatic chains, and the formation of aromatic or graphitized carbon structures. These changes confirm the successful carbonization of the date seed biomass and the evolution of its surface chemistry into a more carbon-rich and hydrophobic material.

FTIR analysis revealed consistent structural changes across all three date seed samples (AC1, AC2, and AC3) as a result of carbonization. The spectra of the raw samples displayed distinct absorption bands associated with hydroxyl ($-\text{OH}$), aliphatic C-H, and carbonyl (C=O) functional groups, indicating the presence of oxygen-rich organic matter. Following carbonization, these characteristic peaks were either significantly reduced or completely absent, signifying the effective decomposition and elimination of oxygenated functional groups and volatile compounds. In contrast, the emergence of weaker absorption bands in the range of $1595\text{--}1699\text{ cm}^{-1}$ in the carbonized samples points to the development of aromatic and

graphitic structures. Minor spectral differences among the samples—such as varying intensities near 2359 cm^{-1} —were observed but were not deemed substantial. Overall, the carbonization process induced similar chemical transformations in all three types of date seeds, yielding carbon-rich materials with lower surface functionality, which is advantageous for stability and subsequent adsorption performance. For a specific type of date, it can be observed that AC1 exhibits a simplified spectrum dominated by the primary aromatic C=C framework at $1595\text{--}1599\text{ cm}^{-1}$ and a weak band near 2359 cm^{-1} attributed to physisorbed atmospheric CO_2 on the newly formed pore channels. It lacks secondary heteroatom functional groups, pointing to a primarily non-polar, condensed carbon surface. For AC2, a distinct absorption band centered at 1162 cm^{-1} was observed. In H_3PO_4 activated carbons, this band is characteristic of P=O stretching, P-O-C aliphatic ester linkage stretching, or hydrogen-bonded $\text{P}=\text{O}\cdots\text{H}$ groups formed during chemical activation. This confirms the retention of residual phosphate complexes on the AC2 matrix, introducing localized acidic surface sites. AC3 displays the most chemically diverse surface functionality among the three adsorbents. Distinct Band near 2132 cm^{-1} : A key feature observed in AC3 (and noticeably absent in AC1 and AC2) is a distinct absorption band near 2132 cm^{-1} . In porous carbonaceous materials, bands in the $2100\text{--}2250\text{ cm}^{-1}$ region correspond to alkyne $\text{C}\equiv\text{C}$ stretching vibrations, ketene-like cumulated double bonds ($\text{C}=\text{C}=\text{O}$), or trapped carbon monoxide CO/ carbon dioxide CO_2 species within micro-cavities. The formation of these unsaturated moieties suggests that AC3 undergoes unique cross-linking and condensation pathways during acid thermal treatment.

3.2 The Effect of Prepared Activated Carbon on Adsorption of Allura Red Dye

The adsorption efficiency of activated carbon produced from date seeds was evaluated using Allura Red dye as the model contaminant. The experiments were carried out under batch conditions, employing an initial dye concentration of 0.80 ppm , an activated carbon dosage of 0.5 grams , and a total solution volume of 500 mL . Removal efficiency and the distribution coefficient (K_d) were monitored over time to determine the adsorption capacity and effectiveness of the synthesized materials. Table 1 presents the Removal Efficiency and Distribution Coefficient of AC1 at different contact times. Figure 9 revealed that the removal efficiency increased dramatically up to 6 minutes, then slowed down. In contrast, the K_d increment is more pronounced after 4 minutes in Figure 10.

For the AC2 sample, it is observed that 96.2% removal efficiency was achieved, as seen in Table 2. Figure 11 illustrates that the efficiency is

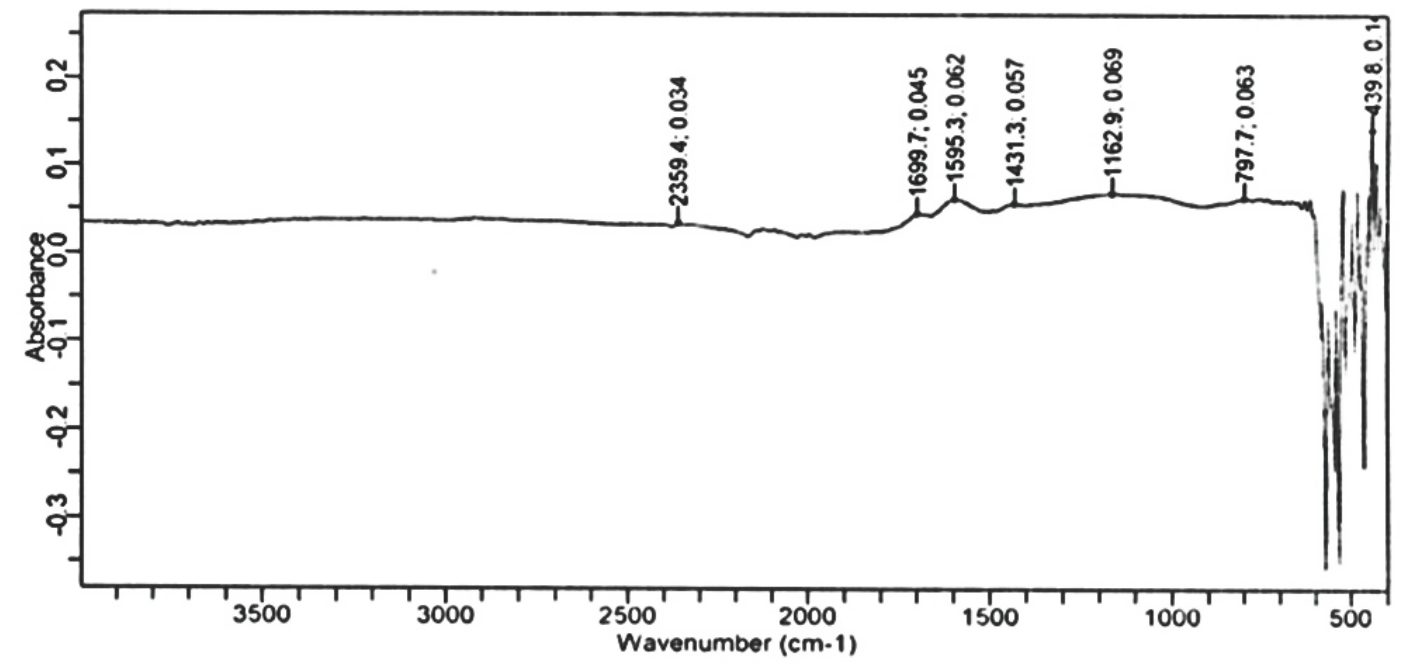


Figure 4 FTIR Spectrum of Date Seed Sample (AC1) after Carbonization

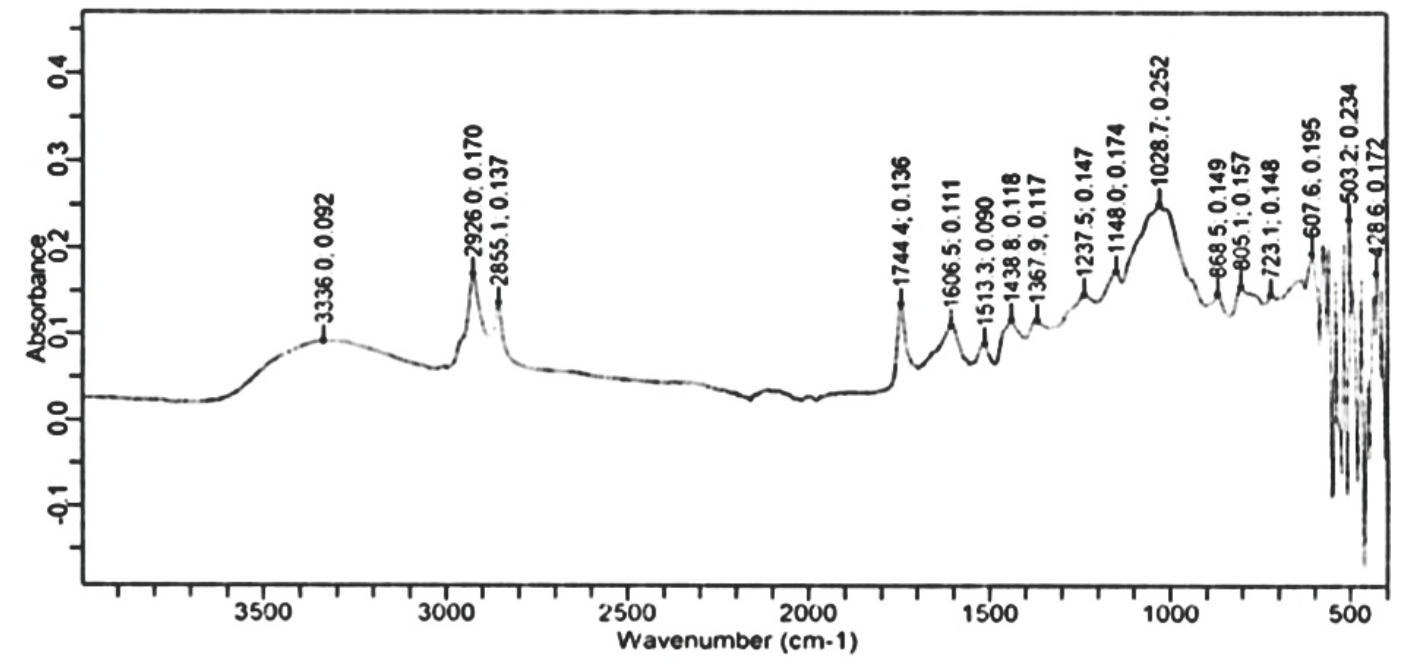


Figure 5 FTIR Spectrum of Date Seed Sample (AC2) before Carbonization

Table 1 Adsorption of Allura Red Dye by AC1 at Different Contact Times			
Time (min)	Concentration (ppm)	Removal efficiency (%)	Distribution coefficient (Kd) (mL/g)
0	0.80	0.0	0.0
2	0.71	11.7	132.4
4	0.48	40.3	673.9
6	0.17	79.2	3812.5
8	0.09	88.3	7555.6
10	0.05	93.5	14400.0

Table 2 Adsorption of Allura Red Dye by AC2 at Different Contact Times			
Time (min)	Concentration (ppm)	Removal efficiency (%)	Distribution coefficient (Kd) (mL/g)
0	0.80	0.0	0.0
2	0.64	20.1	252.0
4	0.49	39.2	645.8
6	0.33	58.9	1430.8
8	0.10	87.3	6900.0
10	0.03	96.2	25333.3

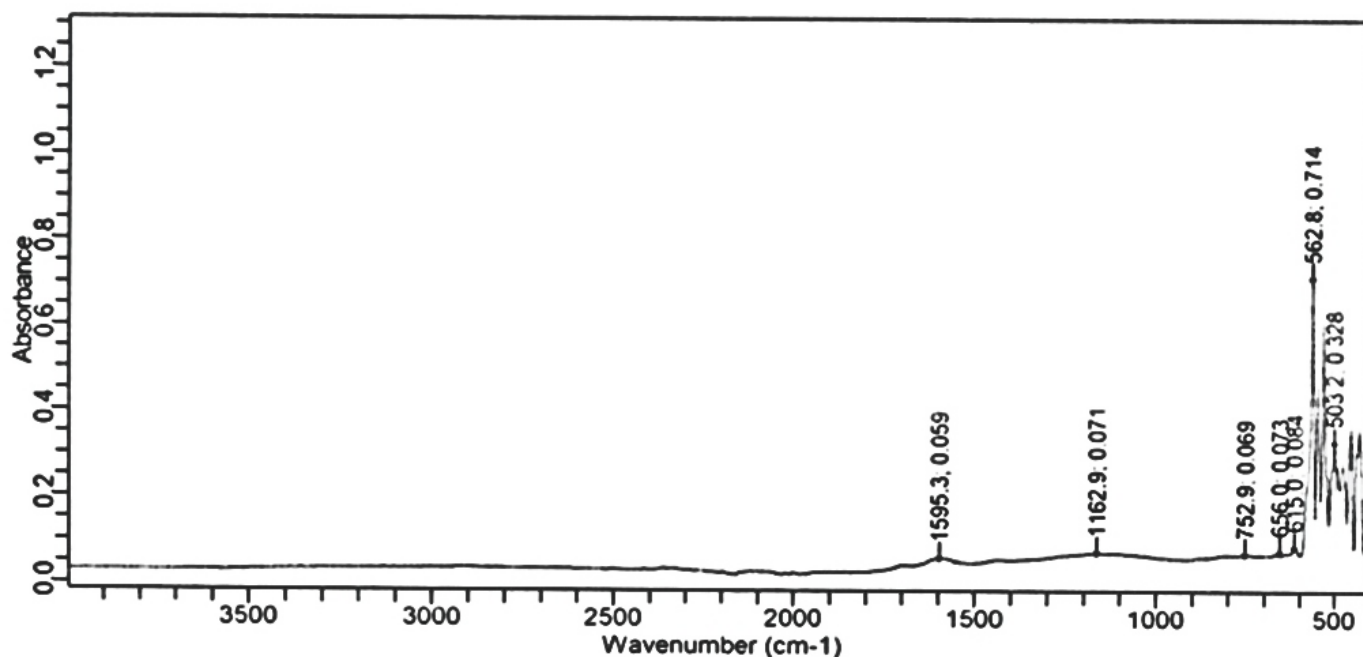


Figure 6 FTIR Spectrum of Date Seed Sample (AC2) after Carbonization

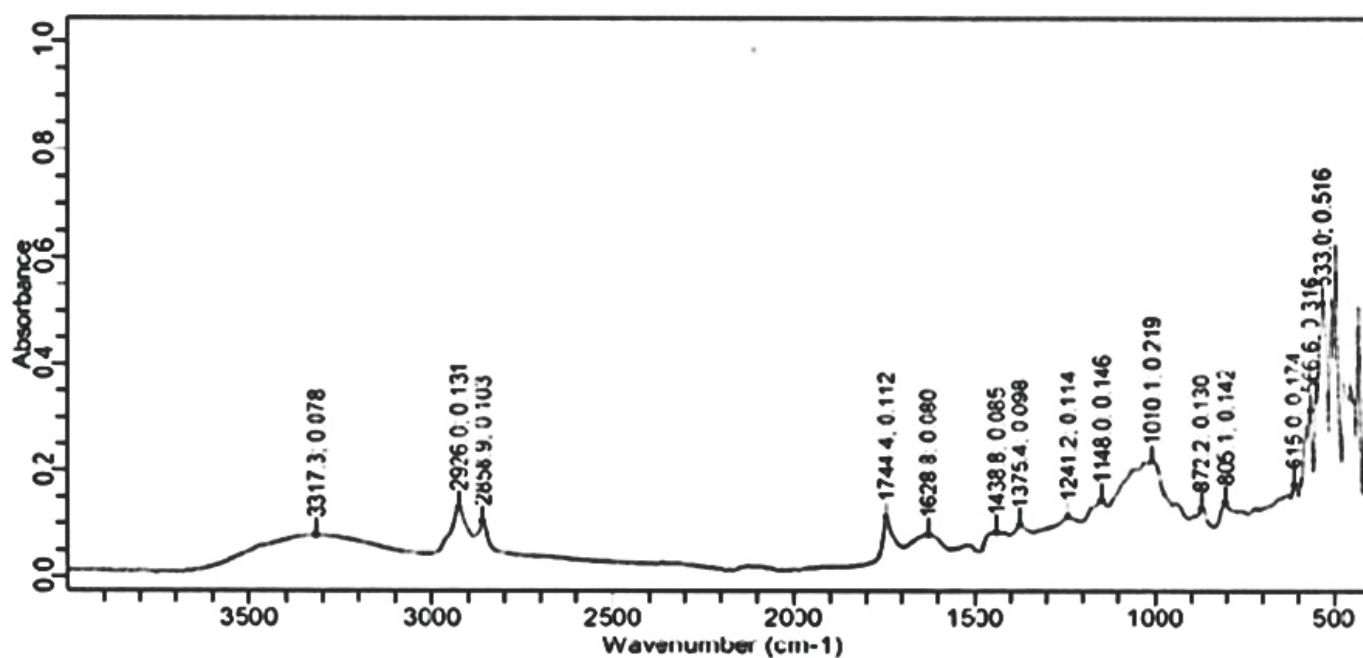


Figure 7 FTIR Spectrum of Date Seed Sample (AC3) before Carbonization

almost linear after 8 minutes. According to Figure 12, K_d increased more rapidly after 6 minutes.

The highest removal efficiency was reached by AC3, which is 96.3%, as shown in Table 3. This can be demonstrated by the effective functional groups and surface properties of this type of date seeds. Figure 13 and Figure 14 show the change in removal efficiency and K_d over time.

The adsorption results of Allura Red dye clearly show distinct differences in removal efficiencies and adsorption rates among the three activated carbon samples (AC1, AC2, and AC3). These variations are mainly influenced by differences in surface area, pore structure, and surface chemistry of each carbon material.

Sample AC3 exhibited the highest overall dye removal efficiency, achieving 96.3% removal within 10 minutes, followed closely by AC2 with 96.2% and

Table 3 Adsorption of Allura Red Dye by AC3 at Different Contact Times

Time (min)	Concentration (ppm)	Removal Efficiency (%)	Distribution Coefficient (K_d) (mL/g)
0	0.80	0.0	0.0
2	0.51	36.3	568.6
4	0.39	51.3	1051.3
6	0.21	73.8	2809.5
8	0.09	88.8	7888.9
10	0.03	96.3	25666.7

AC1 with 93.5%. Notably, AC2 demonstrated the most rapid dye removal during the initial adsorption period, reaching 87.3% removal within 8

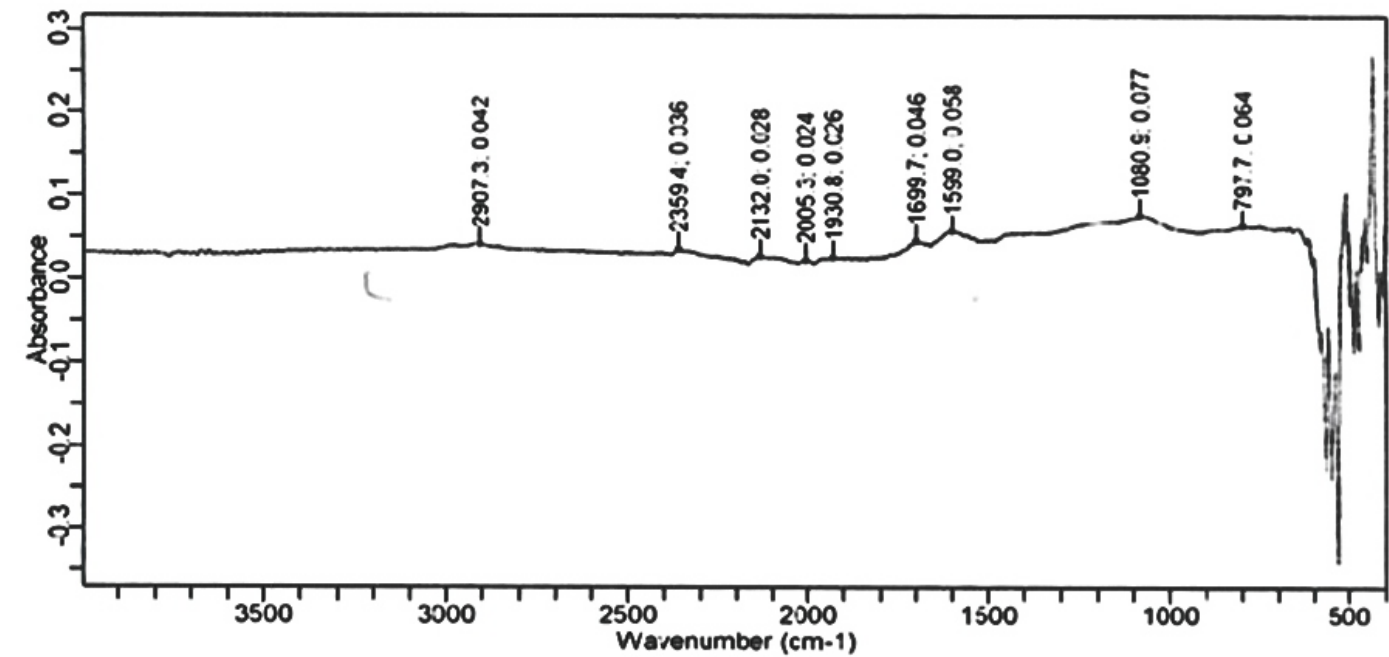


Figure 8 FTIR Spectrum of Date Seed Sample (AC3) after Carbonization

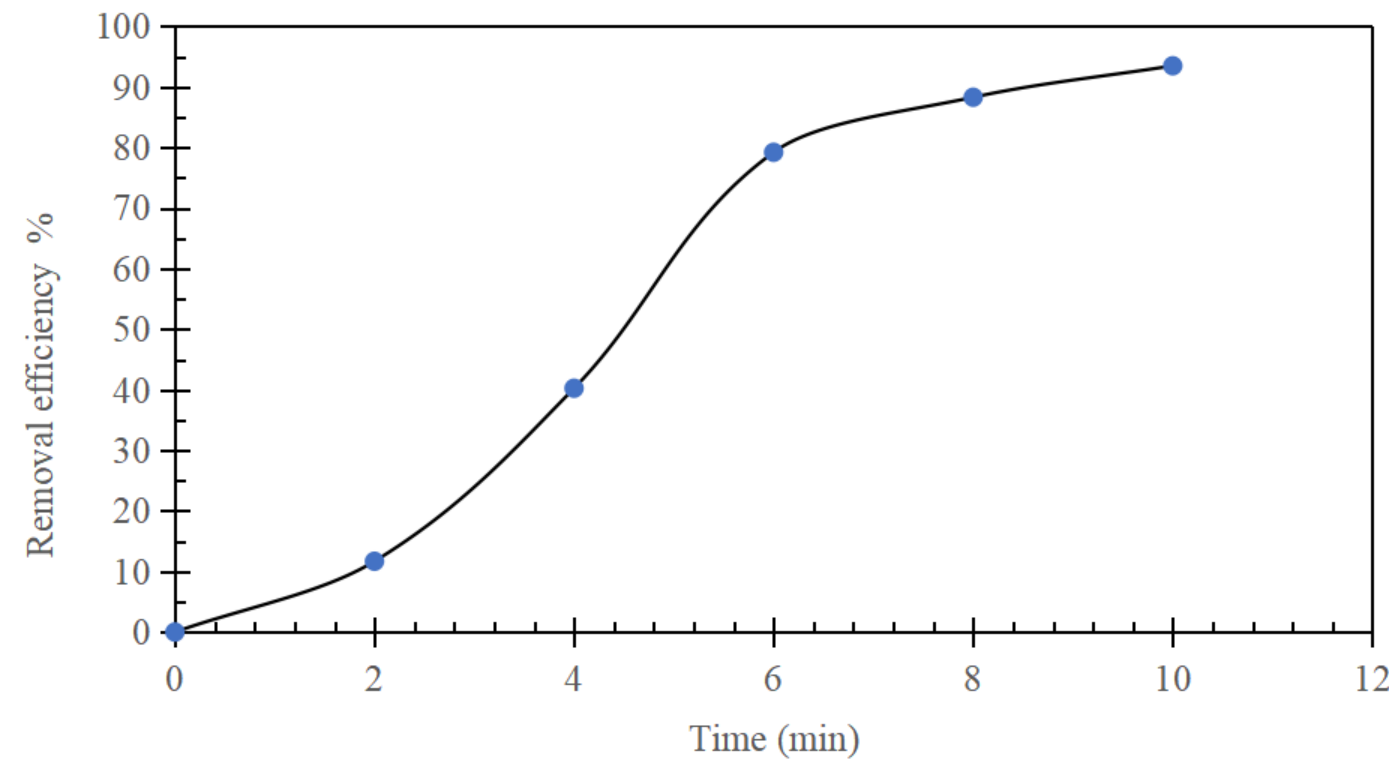


Figure 9 Removal Efficiency of Allura Red Dye Using AC1 as a Function of Contact Time

minutes. This observation indicates that AC2 enabled rapid dye uptake under the experimental conditions.

The superior performance of AC3 may be due to its developed porous structure, which increases the available surface area and facilitates dye diffusion. AC2, despite having slightly smaller pores, presents a surface chemistry and porosity that favor fast initial adsorption. In contrast, AC1's comparatively lower performance and slower kinetics suggest a less optimal pore network and fewer accessible active sites.

FTIR analyses support these observations by confirming successful car-

bonization and differences in surface functional groups and morphology that influence adsorption behavior. However, the practical implication is that AC3 is the most effective adsorbent overall, while AC2 is preferred for rapid dye removal applications. AC1, although less efficient, still demonstrates satisfactory performance.

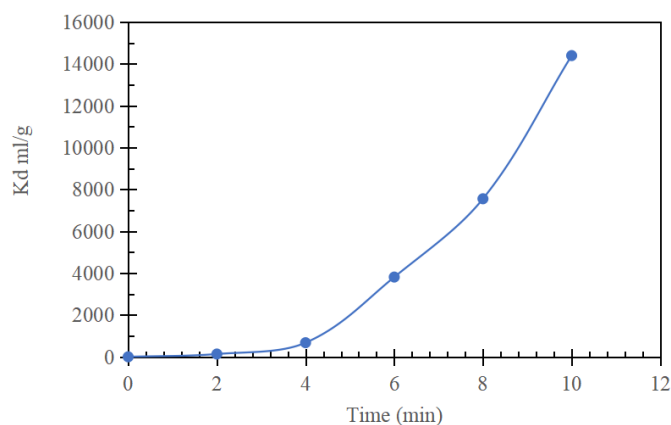


Figure 10 Distribution Coefficient (Kd) of Allura Red Dye Adsorbed by AC1 at Different Contact Times

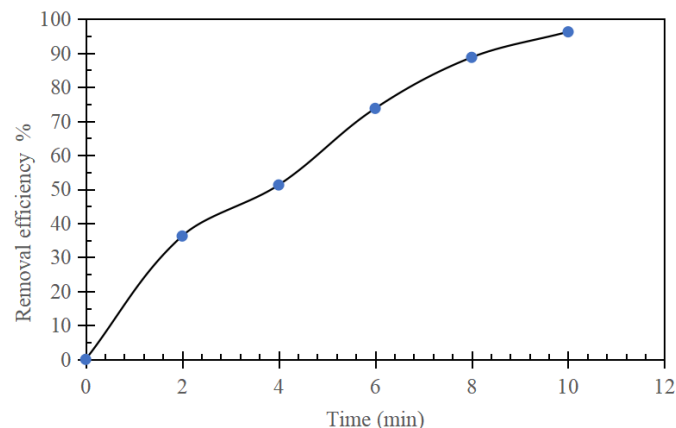


Figure 13 Removal Efficiency of Allura Red Dye Using AC3 as a Function of Contact Time

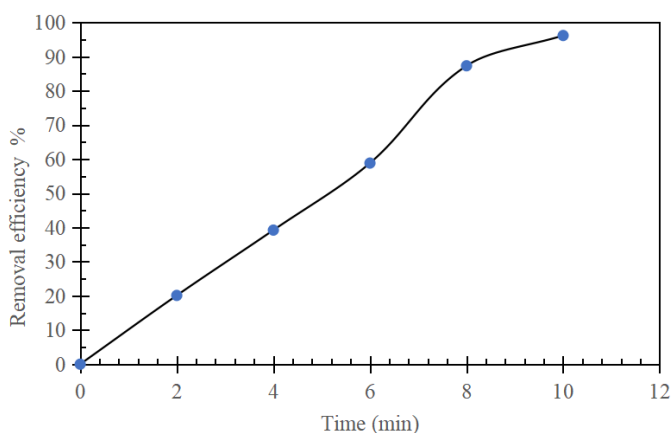


Figure 11 Removal Efficiency of Allura Red Dye Using AC2 as a Function of Contact Time

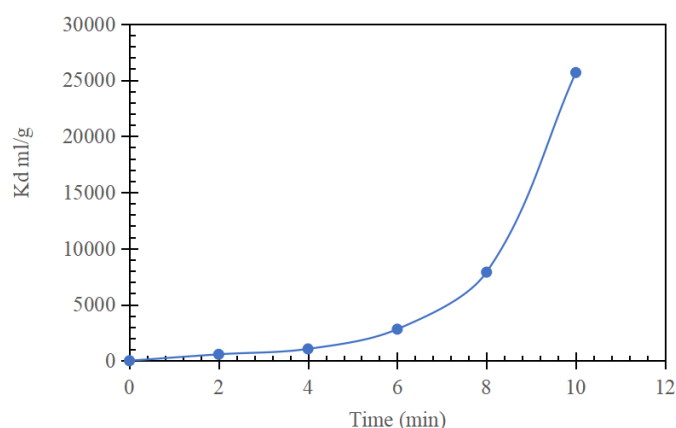


Figure 14 Distribution Coefficient (Kd) of Allura Red Dye Adsorbed by AC3 at Different Contact Times

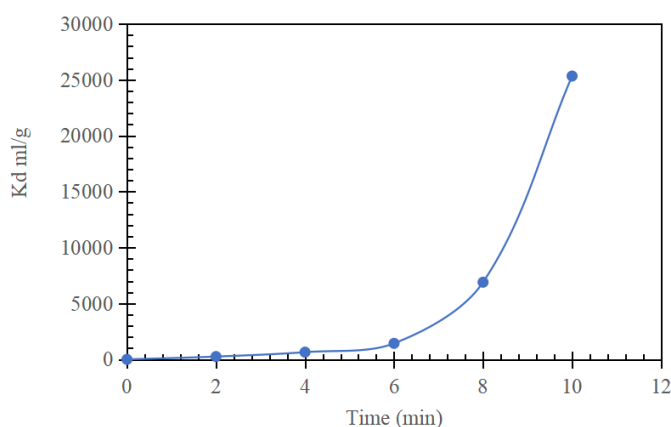


Figure 12 Distribution Coefficient (Kd) of Allura Red Dye Adsorbed by AC2 at Different Contact Times

3.3 Model Comparison and Discussion

To evaluate the adsorption behavior of Allura Red dye on the prepared activated carbon samples (AC1, AC2, and AC3), the experimental data were analyzed using the Langmuir and Freundlich isotherm models. The fitting performance of each model was assessed based on the coefficient of determination (R^2), and the corresponding values are presented in Table 4.

For AC1, the Freundlich model provided a better fit to the experimental data, with an R^2 value of 0.9255, compared with 0.7851 for the Langmuir model. This indicates that, based on the R^2 criterion, the adsorption data for AC1 were more closely represented by the Freundlich model.

For AC2, the Freundlich model also showed a higher R^2 value (0.8645) than the Langmuir model (0.7763). Thus, the experimental data for AC2 were better described by the Freundlich model according to the obtained R^2 values.

In contrast, AC3 exhibited a higher R^2 value for the Langmuir model (0.9186) than for the Freundlich model (0.8315). Therefore, the Langmuir model provided a better statistical fit for AC3 based on the coefficient of determination.

Overall, the R^2 values indicate that the Freundlich model provided a better fit for AC1 and AC2, whereas the Langmuir model showed a better fit for AC3. These differences may be related to variations in the physicochemical characteristics of the activated carbon samples, including surface heterogeneity and the distribution of adsorption sites. However, because the present analysis was limited to R^2 values, these differences should be interpreted as model-fitting trends rather than definitive evidence of a particular adsorption mechanism.

In the present study, the isotherm analysis was limited to the comparison of the determination coefficients (R^2) of the Langmuir and Freundlich models. The fitted isotherm parameters, including $Q_{\max}$ and K_L for the Langmuir model and K_F and n for the Freundlich model, were not determined from the available experimental dataset. Consequently, adsorption capacity values in mg/g were not reported, and direct quantitative comparison with literature values based on adsorption capacity was not performed. This

Table 4 Comparison of R2 Values for Langmuir and Freundlich Models for AC1, AC2, and AC3

Sample	R ² (Langmuir)	R ² (Freundlich)
AC1	0.7851	0.9255
AC2	0.7763	0.8645
AC3	0.9186	0.8315

limitation should be considered when interpreting the isotherm results.

CONCLUSION

In this study, activated carbon was successfully prepared from three types of Libyan date seeds using chemical activation with phosphoric acid followed by thermal carbonization. The prepared samples (AC1, AC2, and AC3) were characterized, and their performance in removing Allura Red dye from aqueous solutions was evaluated. FTIR analysis confirmed the presence of surface functional groups that may contribute to the adsorption process. Batch adsorption experiments demonstrated that all prepared samples were effective in removing Allura Red dye, achieving high removal efficiencies, with AC3 exhibiting the highest removal efficiency of 96.3%. Isotherm modeling showed that both Langmuir and Freundlich models provided a representation of the adsorption behavior, suggesting the involvement of adsorption on heterogeneous surfaces and the possible contribution of different adsorption mechanisms. These findings highlight the potential of agricultural waste, particularly Libyan date seeds, as a low-cost and sustainable precursor for activated carbon production. The prepared activated carbons demonstrated promising potential as sustainable adsorbents for Allura Red dye removal from aqueous solutions, highlighting the value of date seeds as an agricultural-waste precursor for water treatment applications.

REFERENCES

Ahmed, M. J. (2016). Preparation of activated carbons from date (Phoenix dactylifera L.) palm stones and application for wastewater treatments: Review. *Process Safety and Environmental Protection*, 102, 168–182.

https://doi.org/10.1016/j.psep.2016.03.010?utm_source=chatgpt.com

Al-Rub, F. A., Fares, M., & Al-Banna, L. N. (2024). Toward cleaner ecosystems: Elimination of paracetamol drug via mesoporous activated carbon date pits. *Chemical Science International Journal*, 33(3), 1–21. https://doi.org/10.9734/CSJI/2024/v33i3890?utm_source=chatgpt.com

Bennemla, M., Semaoune, T., Sari, M. C., Houhoune, F., Khemaissia, S., Bellaloui, M., Adjedar, H., Hammache, Y., & Ouattas, S. (2024). Preparation and characterization of activated carbon from medlar seed by chemical activation with phosphoric acid and its application in uranium adsorption. *Biomass Conversion and Biorefinery*, 15(9), 14325–14338. https://doi.org/10.1007/s13399-024-06161-5?utm_source=chatgpt.com

Bensaci, Z., Benabdesselam, S., & Laksaci, H. (2025). Efficient removal of Congo red from wastewater using date-pit activated carbon: Isotherm, kinetic, and thermodynamic studies. *Fibers and Polymers*, 27(3), 1285–1297. https://doi.org/10.1007/s12221-025-01277-5?utm_source=chatgpt.com

Food and Agriculture Organization (FAO). (2023). *FAOSTAT statistical database*. <https://www.fao.org/faostat/>

Hong, J., Bao, J., & Liu, Y. (2025). Removal of methylene blue from simulated wastewater based upon hydrothermal carbon activated by phosphoric acid. *Water*, 17(5), Article 733. https://doi.org/10.3390/w17050733?utm_source=chatgpt.com

Muhari, E. H., Silalahi, R. L., Puspita, N., Maryani, A. S., Sihombing, R. P., Adhitasari, A., & Kurnia, D. R. D. (2025). Phosphoric acid-activated carbon from coffee grounds and fly ash for efficient laundry wastewater adsorption. *Journal of Green Science and Technology*, 9(2), 171–177. https://doi.org/10.33603/jgst.v9i2.10649?utm_source=chatgpt.com

Soudani, A., Youcef, L., Youcef, S., Elbahi, S., Toumi, K., Guergazi, S., Sahli, A., & Soudani, N. (2024). High performance activated carbon based on date palm fibers for Cu²⁺ removal in water. *Chemistry Africa*, 7(7), 3903–3915. https://doi.org/10.1007/s42250-024-00974-7?utm_source=chatgpt.com