

Article

Adsorption of Amoxicillin Drug from its Aqueous Solution on the Surface of Activated Carbon Prepared from Date Pits: A Kinetic and Thermodynamic Study

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Abstract: This study addressed the use of activated carbon prepared from date pits as an adsorbent to remove the antibiotic amoxicillin from aqueous solutions, with the aim of evaluating its efficiency in treating water pollution with antibiotics. The results showed that the pH value had a significant impact on the adsorption efficiency, with the highest removal achieved at a pH value of 6.6. The results also showed that increasing the weight of the adsorbent within the range of (0.15–0.20) grams improved the adsorption efficiency due to the increase in the number of active sites, while the contact time indicated that the adsorption process reaches a quasi-equilibrium state within two hours. The concentration of the remaining amoxicillin was measured using UV spectroscopy at a wavelength of 230 nanometers for an initial concentration of 20 mg/L. The kinetics study indicated that the adsorption process follows a pseudo-second-order model, suggesting that the adsorption rate depends on the interaction between the adsorbent and the adsorbate. The equilibrium study also showed that the adsorption data fit well with the Langmuir model, indicating the formation of a monolayer on the surface of the activated carbon. Thermodynamic calculations showed that the values of Gibbs free energy (ΔG°) were negative, confirming that the adsorption process is spontaneous, while the thermal values indicated that the process is exothermic. The activation of the coal using potassium hydroxide (KOH) also contributed to increasing porosity and improving surface properties, which positively reflected on the adsorption efficiency.

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1. Introduction

In light of contemporary environmental challenges, environmental pollution ranks among the foremost global risks due to industrial expansion, population growth, and the excessive use of chemicals. Water pollution is one of the most prominent manifestations of this challenge, given its direct impact on human health, living organisms, and the future of freshwater resources [1,2].

In this context, pharmaceutical pollutants, including antibiotics, have emerged as an emerging problem threatening aquatic systems, as they seep into water through sewage, hospitals, pharmaceutical industries, and agriculture [3–5]. These compounds are characterized by their relative stability and resistance to degradation, leading to their accumulation in water sources even at low concentrations [6].

The continued presence of antibiotics in the aquatic environment warns of serious health and environmental consequences, the most important of which are the increasing resistance of bacteria to antibiotics, the negative impact on aquatic organisms, and the possibility of reaching humans through drinking water or the food chain, which in turn may lead to difficulties in treating certain infectious diseases in humans [7–9]. Therefore, the removal of these antibiotics from water is receiving increasing research attention.

The removal of antibiotics before their discharge into the aquatic environment is important and necessary to mitigate their hazardous effects on humans and the ecosystem.

Although traditional water treatment relies on physical, chemical, and biological processes, its effectiveness in completely removing antibiotics remains limited due to the complexity of their chemical structure and their high stability [10,11]. This has led to the development of advanced treatment technologies such as advanced oxidation, electrochemical treatment [12], and photolysis [13], in addition to adsorption technology, which is considered one of the promising options in terms of effectiveness, operational simplicity, ease of application, low cost, and absence of toxic by-products compared to original methods [14-15]

Activated carbon remains one of the most widely used materials in this field due to its large surface area, advanced porous structure, and abundance of active sites on its surface [16,17].

In the context of the shift towards sustainability, recent research has focused on preparing activated carbon from agricultural waste as an alternative to traditional materials, which reduces costs and enhances the utilization of locally available resources [18]. Date pits stand out as an ideal raw material for this purpose due to their high carbon content and abundant availability in date-producing countries, making them suitable for producing activated carbon with good adsorption properties [19,20].

Other studies have shown that activated carbon prepared from date pits possesses a high surface area and an advanced porous structure, which contributes to improving its efficiency in removing organic and inorganic pollutants from aqueous environments. These studies also showed that different preparation and activation methods play an important role in enhancing the chemical and physical properties of the produced charcoal and increasing its adsorption capacity.

The activation method plays a crucial role in determining the properties of the resulting coal, as chemical activation with potassium hydroxide (KOH) is considered one of the most successful methods for enhancing surface area, developing fine porous structure, and increasing the number of active sites for adsorbing organic pollutants, including pharmaceutical compounds [22,23].

Based on the above, this research aims to study the possibility of using activated carbon prepared from date pits and chemically activated with potassium hydroxide (KOH) to remove amoxicillin from aqueous solutions. This is in an effort to develop an effective, economical, and environmentally friendly adsorbent to combat antibiotic pollution in water [24-26].

2. Materials and Methods

2-1 Materials

Amoxicillin (AMX) was obtained from the General Company for Pharmaceutical and Medical Supplies in Samarra (Iraq) and was used as is without any additional purification processes.

Activated carbon prepared from date pits and activated with potassium hydroxide (KOH) was used as an adsorbent in the adsorption experiments.

All solutions were prepared using deionized water.

2-2 Preparation of Date Seeds and Nano Activated Carbon

A certain amount of date seeds was taken after cleaning and thoroughly washing them with distilled water, then drying them. After that, a certain amount of date seeds was manually ground and then using a mortar several times to ensure obtaining a material with good porosity.

2-3 Carbonization of Date Seeds (Charcoal)

A certain amount of date seeds was taken and placed in a mortar of a specific size, sealed well, and then placed in a burning furnace at a temperature of 700 degrees Celsius for 5 hours. After cooling, as explained below, the date seeds were ground well manually and electrically using an electric grinder to obtain finer granules and increase the surface area.



Figure 1. Initial preparation of charcoal from date seeds.

2-4 Activation of coal and its conversion to nano coal.

The coal is treated with a basic solution (potassium hydroxide), where a heat-resistant container is filled with the required amount of raw coal (date pits), which usually ranges between 50 and 100 grams. The coal is completely submerged in the basic solution (water + potassium hydroxide). The chemical reaction between the coal particles and potassium hydroxide in the aqueous solution improves the coal's ability to absorb materials in the subsequent stages. To ensure the best possible reaction between the coal and the alkaline solution, the sample is continuously stirred in the solution for a period ranging from 30 minutes to 2 hours, and then the coal is filtered to remove the excess solution after being treated with the alkaline solution. Then, after the treatment, the coal is transferred to a carbonization furnace and heated to a temperature ranging between 600 and 700 degrees Celsius. In the absence of oxygen, the coal reacts with potassium hydroxide during a thermal treatment process that takes one to two hours, increasing its porosity and producing activated carbon.

Then, 25 grams of the charcoal were taken and placed in 100 ml of deionized water, exposed to ultrasonic waves at a frequency of 50Hz for 3-4 hours, then filtered, dried, and ground again to obtain a good nano-sized texture and volume for use in the adsorption process



Figure 2. Activation of coal and its conversion into nano-coal: Ultrasonic washing stage.

2-5 Calibration Curve

For quantitative analysis purposes, a calibration curve for amoxicillin was created using a UV-Vis spectrophotometer. A series of solutions with different concentrations ranging from (5-25 mg/l) of the drug amoxicillin were prepared.

The absorbance of these solutions was measured at the maximum wavelength of 230 nanometers, then the relationship between absorbance and amoxicillin concentration was plotted by applying Beer's-Lambert law. The resulting calibration curve was used to determine the remaining concentrations of amoxicillin in the solutions after conducting adsorption experiments.

2-6 Adsorption Experiments

A standard stock solution of amoxicillin with a concentration of 250 mg/L was prepared by dissolving 0.025 grams of the antibiotic in distilled water and then completing the volume to 100 ml. The remaining concentrations were prepared by diluting the solution.

The effect of several key operational variables on the efficiency of amoxicillin adsorption from aqueous solutions using activated carbon as an effective adsorbent was evaluated. These variables included the effect of the solution's pH within a range of 3 to 10, the effect of the amount of adsorbent added, which ranged from 0.01 to 0.3 grams of activated carbon, in addition to studying the effect of the contact time between the adsorbent and the solution within a period extending from 10 to 180 minutes. The effect of the initial concentration of amoxicillin within the range of 20 to 100 mg/L was also analyzed, in addition to studying the effect of temperature within the range of 20 to 45 degrees Celsius.

All adsorption experiments were conducted using the batch method, where 100 ml conical flasks were used, each containing 25 ml of an amoxicillin solution with a known initial concentration. To ensure sufficient homogeneity and effective contact between the activated carbon particles and the solution, the flasks were placed in a tightly sealed shaking water bath at a constant shaking speed of 120 revolutions per minute. After the specified contact time for each experiment, the activated carbon was separated from the liquid phase using a centrifuge at a speed of 4000 revolutions per minute for 5 minutes, in order to obtain a clear solution free of solid particles.

The clear solution resulting from the centrifugation process was collected and analyzed to determine the concentration of residual amoxicillin in the aqueous medium. The measurements were conducted using the spectrophotometric method after fixing the wavelength at 230 nanometers to measure the absorbance of amoxicillin. The amount of adsorbed amoxicillin was calculated based on the difference between the initial concentration and the remaining concentration at equilibrium.

The pH of the amoxicillin solutions was adjusted before conducting the experiments using standard solutions of 0.1 M hydrochloric acid and 0.1 M sodium hydroxide, to ensure the pH values remained stable throughout all the experiments.

The adsorption efficiency and adsorption capacity were calculated based on the experimental values of the initial concentration and the equilibrium concentration or at a certain time, taking into account the volume of the solution and the mass of the activated carbon used, according to the following equations:

$$\% \text{ Adsorption} = (C_0 - C_e) / C_0 \times 100 \quad (1)$$

$$q_t = (C_0 - C_t) v / m \quad (2)$$

Where c_0 represents the initial concentration of amoxicillin (mg/L), C_e and C_t represent the concentration of amoxicillin (mg/L) at equilibrium and at time (t), m represents the weight of activated carbon (g), v is the volume of the amoxicillin solution (L), and q_t represents the adsorption capacity (mg/g).

The thermodynamic study of the adsorption process of amoxicillin on activated carbon was conducted with the aim of evaluating the nature of the adsorption process and its thermodynamic behavior. The change in Gibbs free energy (ΔG°), the change in enthalpy (ΔH°), and the change in entropy (ΔS°) were calculated based on equilibrium constant values and absolute temperature. Where ΔG° represents the change in Gibbs free energy, ΔH° represents the change in enthalpy, while ΔS° refers to the change in entropy. These values provide a comprehensive understanding of the possibility of the adsorption process occurring spontaneously and the nature of the accompanying thermal interaction.

$$\Delta G^\circ = -RT \ln K_e \quad (3)$$

$$\ln K_e = (\Delta S^\circ) / R - \Delta H^\circ / RT \quad (4)$$

Where R represents the universal gas constant (8.314 J/mol.k), T is the temperature measured in Kelvin, and ΔH (J/mol.k).

ΔS° (J/mol.k), ΔG° (J/mol), k_e represents the equilibrium constant, which is calculated through the ratio between the concentration of the adsorbed substance and the concentration of the remaining substance in the solution as shown in the following equation:

$$k_e = (c_0 - c_e) / c_e \quad (5)$$

The adsorption isotherms were analyzed based on the Langmuir and Freundlich models, which can be mathematically represented using the following equations, respectively:

$$1/q_e = 1/q_m + (1/(q_m k_L)) \cdot 1/C_e \quad (6)$$

$$\ln q_e = \ln k_F + 1/n \ln C_e \quad (7)$$

Where the constants K_F and n in the Freundlich model represent the adsorption capacity and intensity, respectively, with the value of n being an indicator of the suitability of the adsorption system and the nature of the interaction between the adsorbate and the adsorbent surface. When the value of n is less than one ($n < 1$), it indicates that the

adsorption process is of a chemical nature, while values greater than one ($n > 1$) indicate that the adsorption occurs physically [27].

In the Langmuir model, q_m represents the maximum adsorption capacity of the adsorbent, measured in (mg/g), while KL represents the Langmuir constant, which reflects the energy or affinity of adsorption between the adsorbate and the adsorbent surface, measured in (L/mg).

The kinetic studies for the adsorption of the antibiotic amoxicillin onto activated carbon were estimated using four kinetic models for the experimental data, which are: the pseudo-first-order model, the pseudo-second-order model [28], the intra-particle diffusion model [29], and the Elovich model [30]. The linear forms of these models are presented in equations (8-11):

$$\ln(q_e - q_t) = \ln(q_e) - k_1 t \quad (8)$$

$$t/q_t = (1/(k_2 q_e^2)) + (1/q_e) t \quad (9)$$

Where q_e is the adsorption capacity at equilibrium in units of (mg/g) and q_t represents the adsorption capacity at time in units of (mg/g), k_1 is the pseudo-first-order rate constant in units of (min^{-1}), and k_2 is the pseudo-second-order rate constant in units of ($\text{g} \cdot \text{mg}^{-1} \cdot \text{min}^{-1}$).

$$q_t = k_{int} t^{(1/2)} + C \quad (10)$$

$$q_t = 1/\beta \ln(\alpha\beta + 1/\beta \ln t) \quad (11)$$

k_{int} represents the diffusion rate constant within the particles in units of ($\text{mg} \cdot \text{g}^{-1} \cdot \text{min}^{-1/2}$) and C is a constant representing the intercept in units of (mg/g), while in the Elovich model, α represents the initial adsorption rate in units of ($\text{mg}/\text{g} \cdot \text{min}$), and β is the adsorption constant in units of (g/mg).

3. Results and Discussion

3-1 The Effect of pH

In this work, a study was conducted on the effect of pH on the adsorption efficiency of this drug. All experiments were conducted under fixed conditions, including a temperature of 20°C, an initial drug concentration of 20 mg/L, a time range of 120 minutes, and an amount of activated carbon (0.15 g). The effect of pH within a specific range (2 – 10) was studied, where it was observed that the pH value plays a crucial role in determining the efficiency of amoxicillin adsorption on the surface of activated carbon prepared from date pits, due to its direct impact on both the surface charge of the carbon and the ionization state of the drug molecules in the solution. Figure (3) illustrates the effect of pH on the adsorption of amoxicillin using activated carbon prepared from date pits.

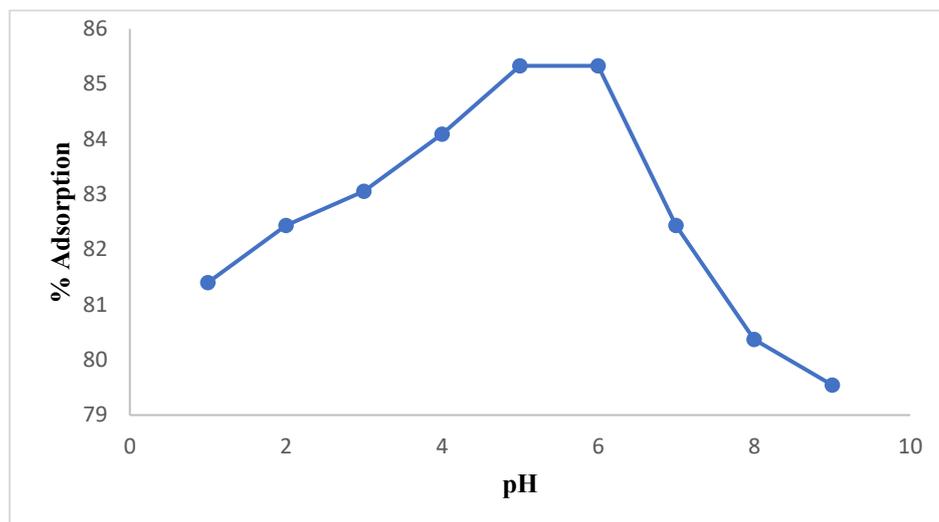


Figure 3. The effect of pH on the adsorption of amoxicillin using activated carbon prepared from date pits.

The experimental results showed that the adsorption efficiency was low under highly acidic conditions, then gradually increased with the rise in pH value, reaching the highest efficiency in the near-neutral range (pH = 6–7), where the removal percentage was about 85%, before decreasing again in the basic medium.

This behavior can be explained by the changes that occur in the functional groups on the surface of activated carbon and the ionization state of amoxicillin with changing pH. In an acidic medium, the protonation of surface groups increases the competition between hydrogen ions ($+H$) and amoxicillin molecules for adsorption sites, thereby reducing the efficiency of the process. As we approach a neutral pH, the surface state and ionization state in the solution become more favorable for the interaction between the coal surface and drug molecules, enhancing electrostatic attraction forces and surface interactions, leading to the highest adsorption efficiency within this range.

In the basic medium, the deprotonation of functional groups on the coal surface leads to the predominance of negative charges, while amoxicillin molecules are in an ionized form that reduces attractive forces, generating electrostatic repulsive forces that decrease the interaction of the drug with the adsorbent surface, thereby reducing adsorption efficiency[31].

3-2 The Effect of Adsorbent Weight (Activated Carbon)

The effect of the amount of adsorbent material (activated carbon prepared from date pits) on the adsorption efficiency of amoxicillin was studied under fixed conditions: pH = 6.6, drug concentration = 20 mg/L, temperature = 20°C, and contact time = 120 minutes. The weights of the adsorbent used ranged from 0.01 grams to 0.3 grams, to determine the optimal weight that provides the highest removal efficiency of the drug.

The results shown in Figure (4) indicated that the increase in the weight of the adsorbent led to a significant initial increase in the percentage of amoxicillin removal, due to the increase in the number of active sites available for adsorption on the surface of the activated carbon. With the gradual increase in weight, a slowdown in the rate of improvement was observed, as the additional increase beyond 0.15 grams did not lead to a significant increase in the adsorption rate. Indeed, the weight of 0.15 grams recorded the highest adsorption efficiency of about 85%, indicating that it experimental conditions[32].

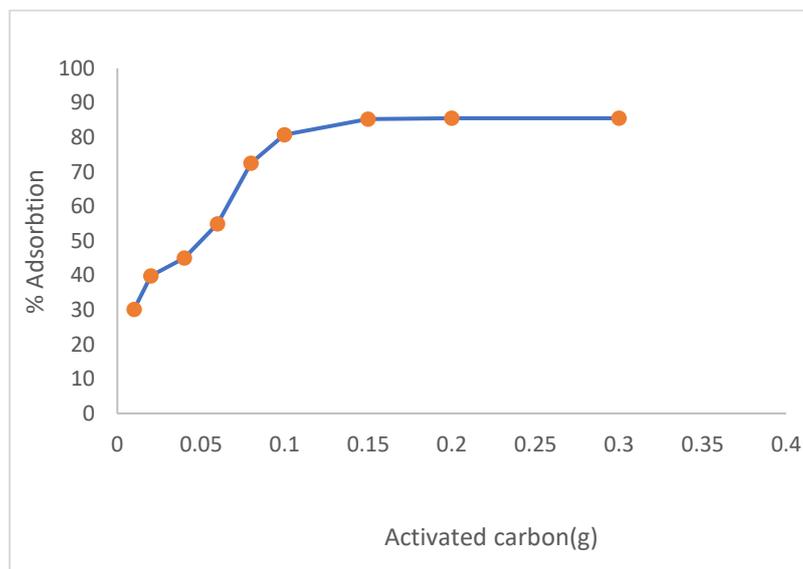


Figure 4. Effect of the amount of adsorbent (activated carbon prepared from date pits) on the adsorption of the drug amoxicillin.

3-3 Effect of Initial Concentration

The effect of the initial concentration of amoxicillin on adsorption efficiency was studied using activated carbon prepared from date pits under fixed operating conditions, including a temperature of 20 °C, a pH of 6.6, a contact time of 120 minutes, and an adsorbent weight of 0.15 grams.

Figure (5) showed that the adsorption percentage of amoxicillin is high at low initial concentrations, with the highest removal efficiency achieved at a concentration of 20 mg/L, reaching about 85%. This indicates that this concentration represents the optimal value for the adsorption process under the tested experimental conditions.

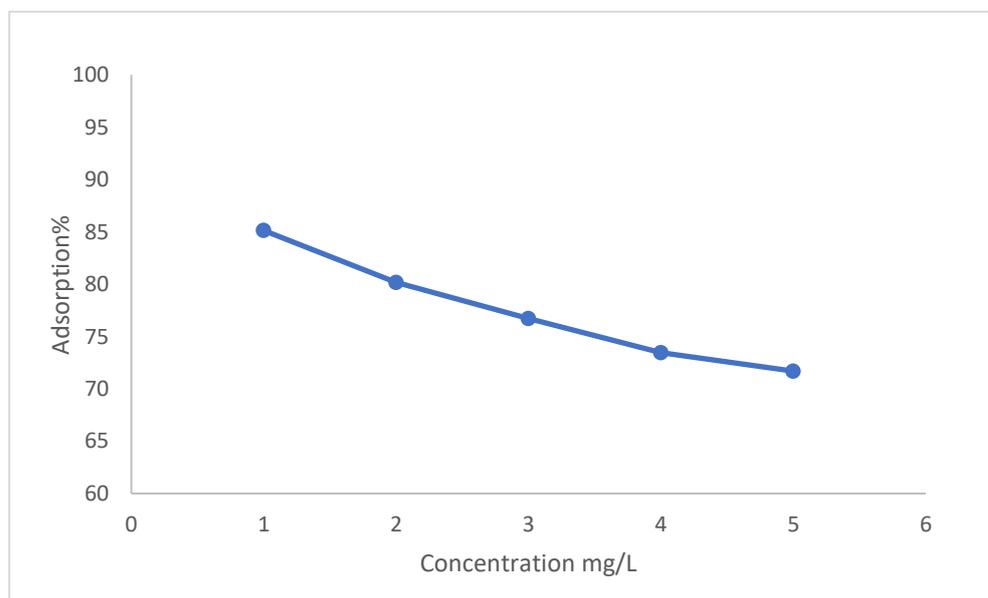


Figure 5. The effect of the initial concentration on the adsorption of amoxicillin onto the surface of activated carbon prepared from date pits.

This behavior can be explained by the fact that low initial concentrations provide a suitable ratio of amoxicillin molecules compared to the number of available active adsorption sites on the surface of the activated carbon, allowing for effective interaction and resulting in high removal efficiency. Conversely, increasing the initial concentration leads to an increase in the number of drug molecules in the solution compared to the

number of available sites, causing a gradual saturation of the adsorbent surface and a decrease in the removal percentage. Although the amount of adsorbed amoxicillin continues to increase with the weight of the adsorbent, the adsorption efficiency does not continue to rise at the same rate. This is attributed to the saturation and overlap of the active sites on the activated carbon surface[33].

3-4 Effect of Contact Time

The effect of contact time on the adsorption efficiency of amoxicillin using activated carbon prepared from date pits was studied under fixed conditions: drug concentration 20 mg/L, adsorbent weight 0.15 grams, temperature 20°C, and pH = 6.6.

Figure (6) showed that the adsorption percentage gradually increased with the contact time from 10 to 120 minutes, reaching maximum removal efficiency after exceeding a time of two hours. It was observed that the increase in removal percentage became limited, indicating that most of the active sites on the surface of the coal had already been occupied.

This behavior can be scientifically explained by the fact that the initial stages of adsorption are rapid due to the availability of a large number of vacant active sites on the adsorbent surface, allowing amoxicillin molecules to quickly bind to the surface. Over time, the available vacant sites decrease, and adsorption gradually slows down until equilibrium is reached, where there are not enough sites to effectively bind new drug molecules[34].

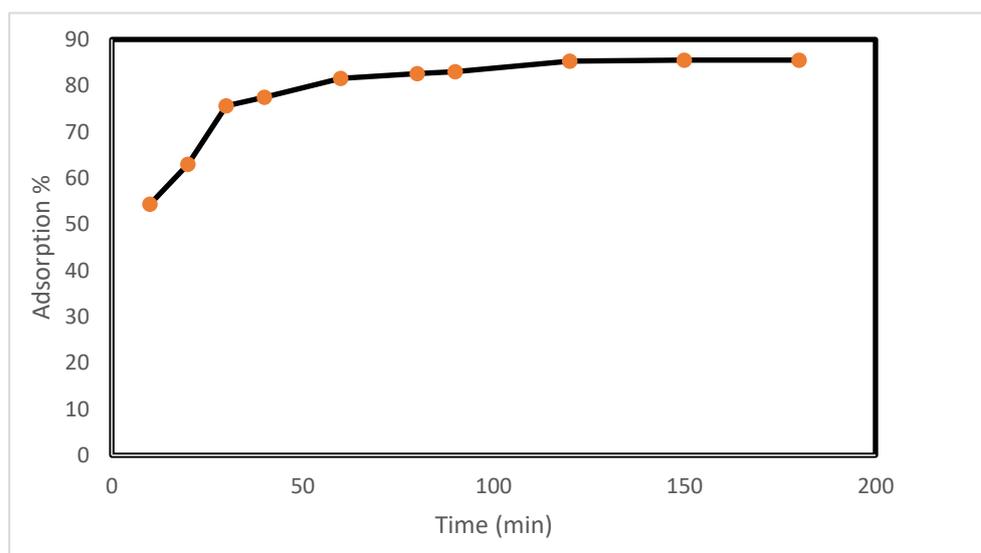


Figure 6. Effect of equilibrium time on the adsorption of amoxicillin on the surface of activated carbon prepared from date pits.

3-5 Effect of Temperature

The effect of temperature (20, 30, 40, 45, 50°C) on the adsorption of amoxicillin was evaluated under the same previous operating conditions. The results shown in Figure (7) and Table (1) indicated that the highest removal efficiency was achieved at 20°C, while the adsorption rate gradually decreased with increasing temperature, indicating that the process is favored at lower temperatures. Additionally, raising the temperature increases the kinetic energy of the amoxicillin molecules in the solution, making them less stable on the surface of the adsorbent and more likely to detach from it[35].

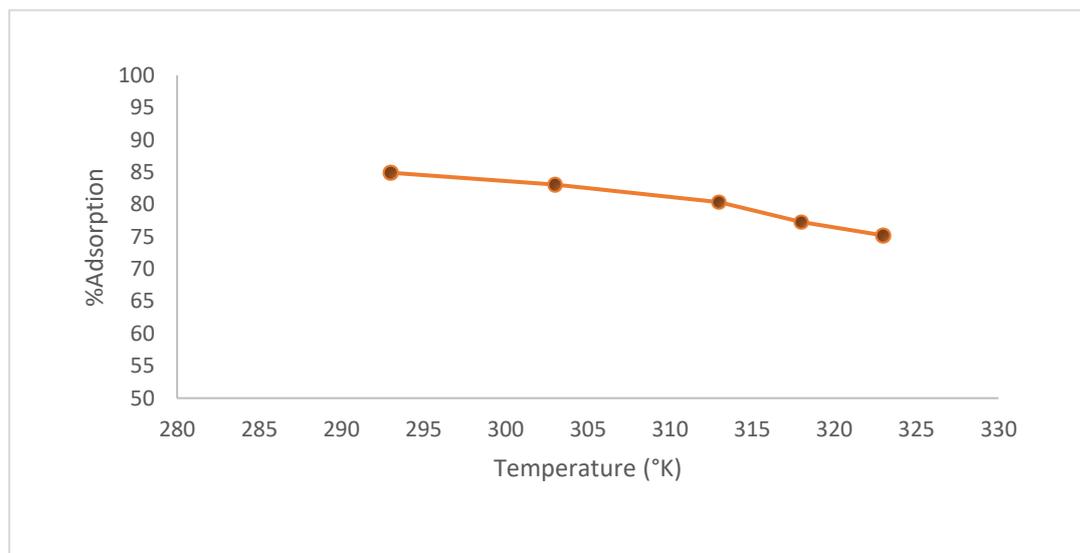


Figure 7. Effect of temperature on the adsorption of amoxicillin on the surface of activated carbon prepared from date pits.

The thermodynamic study indicated that the change in enthalpy (ΔH°) was negative, suggesting that the adsorption process is exothermic, which explains the decrease in removal efficiency with increasing temperature. The negative values of the Gibbs free energy (ΔG°) at different temperatures confirm that the adsorption process is spontaneous within the studied range.

As for the negative value of the change in entropy (ΔS°), it reflects the decrease in the freedom of movement of amoxicillin molecules when they transition from the solution to the surface of the adsorbent material, due to their fixation on the active sites, leading to an increase in the orderliness of the system at the surface compared to their state in the liquid phase. These results collectively indicate that the adsorption process is of a physical nature dominated by the influence of surface attraction forces, and it is more efficient at lower temperature[34].

Temperature(°K)	ΔH° (J/mol.k)	ΔG° (J/mol)	ΔS° (J/mol.k)	R^2
293	-16269.6666	-4209.737328	-40.8059	0.962
303		-4004.762769		
313		-3668.443316		
318		-3235.481122		
323		-2979.911083		

Table 1. Thermodynamic values for the adsorption of amoxicillin on the surface of activated carbon prepared from date pits.

Kinetic studies are an essential tool for understanding the adsorption rate and thus determining the appropriate model for the adsorption process. Where the kinetic data were analyzed using both the pseudo-first-order model (Equation 8) and the pseudo-second-order model (Equation 9), the intra-particle diffusion model (Equation 10), and the Elovich model (Equation 11) extensively to analyze the experimental data derived from adsorption processes[30].

In this work, these models were applied to the adsorption data of amoxicillin on the surface of activated carbon prepared from date pits, and the results are presented in Table 2.

Kinetic model	Parameter	Value
	$q_e/\text{experimental}(\text{mg}\cdot\text{g}^{-1})$	2.8168044
Pseudo-first order	$q_e/\text{theory}(\text{mg}\cdot\text{g}^{-1})$	1.226911
	$k_1 (\text{min}^{-1})$	0.087744
	R^2	0.9658
Pseudo-second order	$q_e/\text{theory}(\text{mg}\cdot\text{g}^{-1})$	0.475488565
	$k_2 (\text{min}^{-1})$	13.10139
	R^2	0.9998
Elovich	$\alpha (\text{mg}\cdot\text{g}^{-1}\cdot\text{min}^{-1})$	48856518.6
	$\beta (\text{g}\cdot\text{mg}^{-1})$	9.89119683
	R^2	0.758
Intraparticle diffusion	k_{int}	0.3022
	k_{int}	0.0578
	k_{int}	0.0142
	R^2	0.9673
	R^2	0.9102
	R^2	0.7747

Table (2) Kinetic parameters for the adsorption of amoxicillin on the surface of activated carbon prepared from date pits.

By comparing the correlation coefficient values (R^2), it appears that the second-order kinetic model is the most suitable for the adsorption data as shown in Figure (8), where the theoretically calculated capacity (q_e cal.) From this model, it is very close to the experimental value.

(q_e exp.). This indicates that the adsorption of amoxicillin on activated carbon prepared from date pits follows a chemical nature, involving the exchange or sharing of electrons between the drug molecules and the carbon surface.

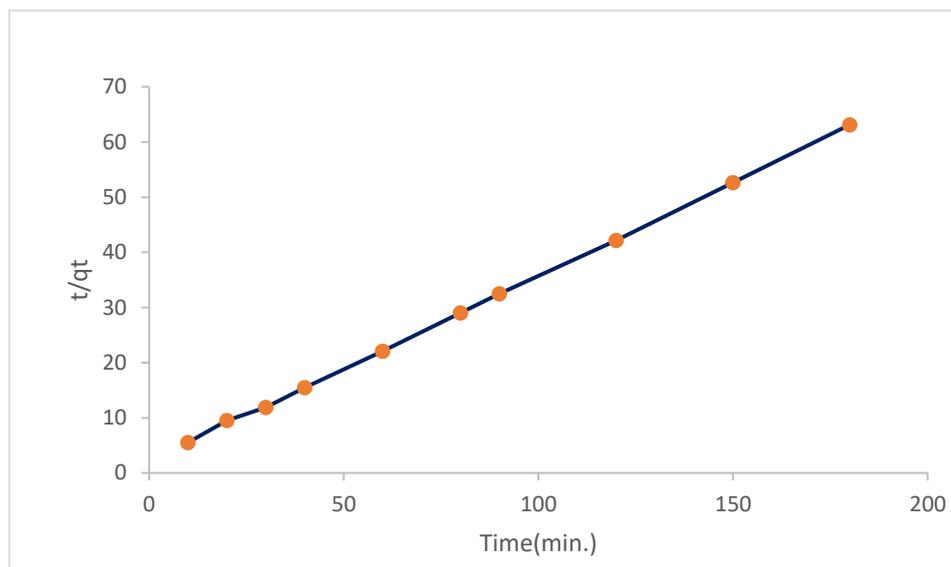


Figure 8. Pseudo-second-order model for the adsorption of amoxicillin on the surface of activated carbon prepared from date pits.

While the Elovich model is used to describe heterogeneous surfaces, the low R^2 value indicates that this model is less suitable, reflecting that the surface of the activated carbon prepared from date pits is relatively homogeneous.

To analyze the rate-limiting step of adsorption, the intraparticle diffusion model was also applied, where Figure (9) shows the amount of adsorbed amoxicillin versus the square root of time, distinguishing three distinct stages:

The first stage: Mass transfer across the boundary layer surrounding the surface of the coal.

Intermediate stage: diffusion within the particles of activated carbon.

Final stage: The beginning of reaching adsorption equilibrium with a slowdown in the adsorption rate due to the decrease in the concentration of amoxicillin in the solution[36].

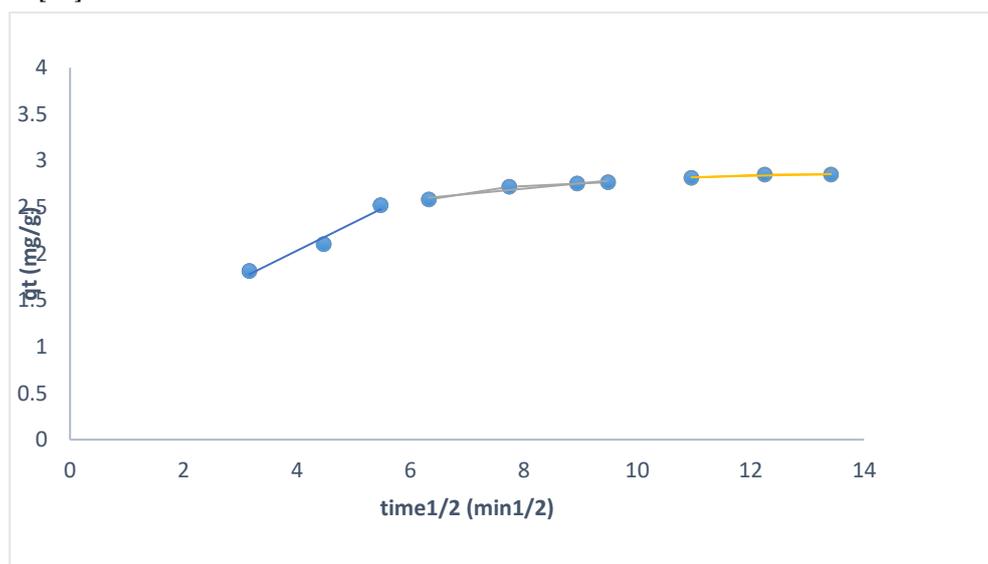


Figure 9. The intraparticle diffusion model for the adsorption of amoxicillin on the surface of activated carbon prepared from date pits.

This indicates that the diffusion within the particles contributed to the adsorption process, but it is not the rate-determining step responsible for controlling the process. This also confirms that the adsorption of amoxicillin on the surface of activated carbon is a multi-step process.

Adsorption Isotherm

In this work, the adsorption data of amoxicillin on the surface of activated carbon prepared from date pits were analyzed using two main models. The first is the Langmuir equation (Equation 6), which assumes that the surface of the material is homogeneous and that all adsorption sites are equal, so that each site on the adsorbent surface can bind only one molecule of the substance at any moment, occupying the entire site and preventing another molecule from using it simultaneously. This equation is used to determine the maximum adsorption capacity (q_{max}) and the adsorption constant of amoxicillin to the material (K_L). The dimensionless separation factor (R_L) was also calculated using Equation(12).

$$R_L = 1 / (1 + k_L c_0) \quad (12)$$

While the second model is the Freundlich equation (Equation 7), which is an empirical model suitable for heterogeneous surfaces where the adsorption site energies (K_F and $n/1$) vary and does not set a maximum adsorption limit, but is useful for interpreting the diversity in adsorption energies on the surface[17].

The results of the adsorption isotherm study to analyze the equilibrium data for the adsorption of the antibiotic amoxicillin on the surface of activated carbon are presented in Table 3, which were derived from the application of both the Langmuir and Freundlich models, and are visually represented in Figures (10) and(11).

Isothermal model	Parameter	Value
Langmuir	q_m (mg/g)	14.1844
	K_L (L.mg ⁻¹)	0.083294
	R^2	0.9963
	R_L (1)	0.37511
	R_L (2)	0.23085
	R_L (3)	0.16673
	R_L (4)	0.13048
	R_L (5)	0.10718
Freundlich	K_F (mg .g ⁻¹)	2.36174
	n	2.87273
	R^2	0.942

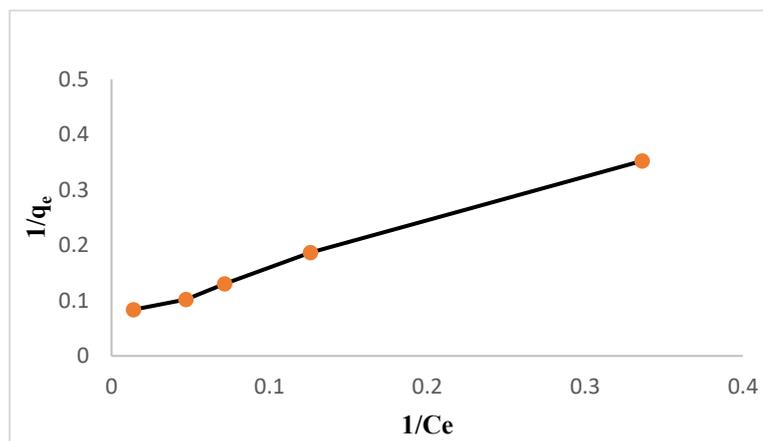


Figure 10. Langmuir model for the adsorption of amoxicillin on the surface of activated carbon prepared from date pits.

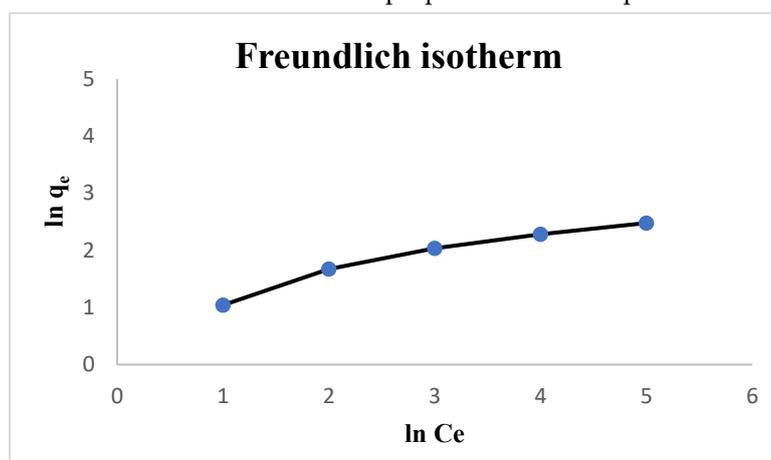


Figure 11. Freundlich model for the adsorption of amoxicillin on the surface of activated carbon prepared from date pits.

The results showed that the adsorption process of amoxicillin on the surface of activated carbon follows a good linear relationship for both models, but the data were more consistent with the Langmuir equation, as confirmed by the high correlation coefficient value ($R^2 = 0.9963$). The results of the Langmuir model also indicate that the maximum adsorption capacity that can be achieved is approximately 14.1844 (mg/g), and the values of the separation factor (RL) ranging between zero and one suggest that the adsorption process is favoured and occurs easily on the surface of activated carbon[37].

Conclusions

The study showed that activated carbon prepared from date pits is an effective and low-cost material for removing amoxicillin from water. The kinetic results showed that adsorption follows the pseudo-second-order model, indicating its chemical nature, with diffusion within the particles contributing without being the rate-controlling step. Adsorption isotherms also demonstrated that the data better fit the Langmuir model, indicating monolayer adsorption on a homogeneous surface and that the process is favored to occur.

The thermodynamic study showed that the negative values of the change in free energy (ΔG°) confirm that the adsorption process is spontaneous, while the enthalpy values (ΔH°) indicate the nature of the process (endothermic or exothermic according to the results). The entropy values (ΔS°) also reflect a change in the degree of order at the adsorbent surface during adsorption.

Based on this, it is recommended to apply this activated carbon in the treatment of actual wastewater, with further studies to evaluate the impact of temperature and improve operating conditions to increase removal efficiency on a broader scale.

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