

ADSORPTION EFFECTIVENESS OF ENROFLOXACIN ANTIBIOTIC WASTE USING KOH ACTIVATED (*CEIBA PENTANDRA*) HULL HYDROCHAR

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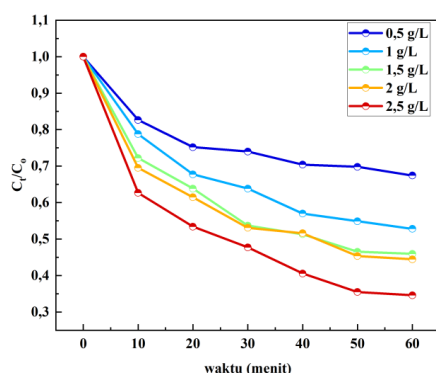
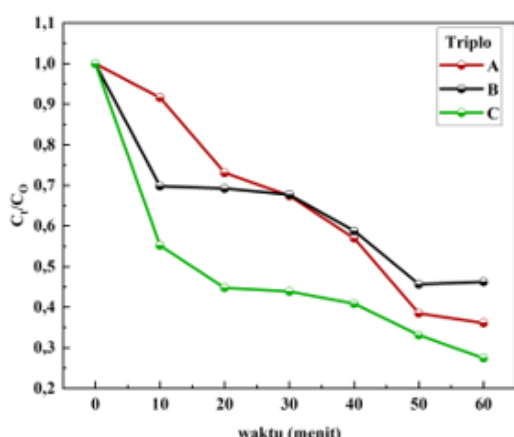
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ABSTRACT

Environmental contamination by the antibiotic enrofloxacin has become an increasing concern due to its extensive use in veterinary medicine and the limited capability of conventional wastewater treatment processes to remove it effectively. This study investigated the adsorption performance of KOH-activated hydrochar derived from kapok peel (*Ceiba pentandra*) for the removal of enrofloxacin from aqueous solutions. The effects of particle size (120, 140, and 160 mesh), adsorbent dosage (0.5–2.5 g L⁻¹), initial enrofloxacin concentration (5–20 mg L⁻¹), solution pH (3–11), water matrix (deionized water, rainwater, and river water), and adsorption kinetics were systematically evaluated. The optimum adsorption performance was achieved using 120-mesh hydrochar, an adsorbent dosage of 2.5 g L⁻¹, an initial enrofloxacin concentration of 5 mg L⁻¹, pH 7, and deionized water, yielding removal efficiencies of 37.3%, 65%, 64%, 73%, and 63%, respectively. Kinetic analysis demonstrated that the adsorption process was better described by the Pseudo-Second-Order model ($R^2 = 0.999$, $q_e = 2.33$ mg g⁻¹) than by the Pseudo-First-Order model ($R^2 = 0.969$), indicating that chemisorption was the dominant adsorption mechanism. FTIR characterization confirmed the presence of hydroxyl (–OH), ether (C–O–C), and aromatic (C=C) functional groups on the hydrochar surface, which facilitated hydrogen bonding and π – π interactions with enrofloxacin molecules. These findings demonstrate that KOH-activated kapok peel-derived hydrochar is a promising, sustainable, and cost-effective adsorbent for the removal of fluoroquinolone antibiotic residues from contaminated water.

Keywords: adsorption; enrofloxacin; hydrochar; kapok peel; KOH activation

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1. INTRODUCTION

Environmental contamination by antibiotic residues has emerged as a critical global concern, primarily due to the inadequate management of pharmaceutical and cosmetic industry wastewater (Zampelli & Verna, 2025). Enrofloxacin, a fluoroquinolone antibiotic widely administered in veterinary medicine to treat bacterial infections in poultry, cattle, and aquaculture, is recognized as a significant source of environmental pollution because a substantial fraction of the administered dose is excreted unchanged through animal urine and feces (Widiyanti et al., 2019). In Indonesia, fluoroquinolone residues, including enrofloxacin, have been detected in fresh chicken meat from several regions, indicating persistent contamination throughout the food supply chain (Widiastuti et al., 2022). Similar findings have also been reported in poultry meat and eggs, where residue concentrations in some cases exceeded internationally established maximum residue limits (MRLs), raising concerns regarding food safety and public health (Medina-pastor & Triacchini, 2020; Rohana et al., 2023).

Conventional wastewater treatment processes, including aeration and coagulation–flocculation, are generally insufficient for the complete removal of antibiotic residues. Consequently, adsorption using biomass-derived carbonaceous materials has emerged as a promising alternative due to its cost-effectiveness, abundant feedstock availability, and potential to valorize agricultural waste (Ajala & Akinawo, 2023). Numerous studies have demonstrated that modified biochar effectively adsorbs enrofloxacin through multiple mechanisms, including hydrogen bonding, electrostatic attraction, and π – π interactions between the aromatic rings of enrofloxacin and the carbonaceous surface of the adsorbent (Peng et al., 2016). Furthermore, the optimization of biochar derived from industrial biomass waste has been reported to substantially enhance the removal capacity of enrofloxacin from aqueous solutions and wastewater, highlighting its potential as an efficient and sustainable adsorbent for antibiotic remediation (Demarco et al., 2025).

Among the underutilized agricultural residues with considerable potential as adsorbent precursors is kapok peel (*Ceiba pentandra*), which is rich in cellulose and possesses structural characteristics suitable for conversion into carbon-based adsorbent materials (Futalan et al., 2022). Through the hydrothermal carbonization (HTC) process, lignocellulosic biomass can be converted into hydrochar under relatively mild operating conditions, producing a carbonaceous material enriched with oxygen-containing functional groups that play a crucial role in adsorption processes (Islam et al., 2022). Subsequent chemical activation using a strong alkaline agent such as potassium hydroxide (KOH) has been widely reported to enhance the specific surface area, pore structure, and adsorption capacity of biomass-derived adsorbents toward a variety of organic contaminants, including synthetic dyes (Ronggur et al., 2024; Zein et al., 2024). This enhancement is consistent with the established role of chemical modification in improving the adsorption performance of biochar for wastewater treatment applications (Parthasarathy et al., 2022).

Based on these considerations, this study aims to evaluate the effectiveness of KOH-activated hydrochar derived from kapok peel (*Ceiba pentandra*) for the adsorption of the antibiotic enrofloxacin from aqueous solutions. The findings are expected to contribute to the development of an efficient, cost-effective, and sustainable adsorption technology for the treatment of antibiotic-contaminated wastewater.

2. MATERIALS AND METHODS

This study was conducted over a six-month period (January–June 2026) at the Environmental Quality Laboratory, Department of Environmental Engineering, Nahdlatul Ulama University of Sidoarjo. The equipment used included a Teflon-lined hydrothermal reactor, drying oven, pH meter, analytical balance, magnetic stirrer, and sieves with particle sizes of 120, 140, and 160 mesh for hydrochar preparation. Hydrochar characterization was performed using Fourier Transform Infrared Spectroscopy (FT-IR), X-ray Diffraction (XRD), and a UV–Vis spectrophotometer at a wavelength of 324 nm. The primary materials consisted of dried kapok husk, potassium hydroxide (KOH), and analytical grade enrofloxacin standard. Hydrochar was synthesized via the hydrothermal carbonization process by placing 5 g of kapok husk powder into a Teflon-lined hydrothermal reactor containing 40 mL of deionized water. The reactor was heated at 200°C for 10 h, after which the resulting hydrochar was oven-dried at 100°C for 3 h. Chemical activation was subsequently carried out by immersing the hydrochar in KOH solutions with concentrations of 0.5, 1.0, and 1.5 M under continuous stirring for 4 h to enhance pore development and increase the number of active surface functional groups. The activated hydrochar was then thoroughly washed with deionized water until a neutral pH was achieved and dried again at 110°C for 1 h.

Adsorption experiments were performed by adding 10 mg of hydrochar to 10 mL of enrofloxacin solution with an initial concentration of 10 mg/L. The mixtures were agitated under different contact times (10–60 min), adsorbent dosages (0.5–2.5 g/L), and initial enrofloxacin concentrations (5–20 mg/L). Following adsorption, the suspensions were filtered through a 0.45 µm membrane filter, and the residual enrofloxacin concentration was determined using a UV–Vis spectrophotometer. The functional groups, crystalline structure, and porosity of the hydrochar were characterized using FT-IR and XRD analyses. The adsorption efficiency (%RE) was calculated using the following equation: $RE (\%) = [(C_0 - C_t)/C_0] \times 100$, where C_0 is the initial concentration and C_t is the enrofloxacin concentration after adsorption. The adsorption efficiencies obtained under different experimental conditions were compared to determine the optimum conditions for enrofloxacin removal using KOH-activated kapok husk hydrochar.

3. RESULT AND DISCUSSION

Effect of Contact Time and Particle Size (Mesh) on the Adsorption Efficiency of Enrofloxacin Using Kapok Peel-Derived Hydrochar

Table 1 Average Removal Efficiency (%) from Triplicate Measurements: Effect of Contact Time and Particle Size (Mesh)

Menit	120 mesh	140 mesh	160 mesh
10	31%	19%	19%
20	36%	22%	21%
30	38%	26%	23%
40	39%	29%	25%
50	41%	30%	26%
60	46%	32%	29%

The triplicate experimental results demonstrated that the removal efficiency of enrofloxacin increased consistently with increasing contact time across all particle sizes, following the order of 120 mesh > 140 mesh > 160 mesh throughout the entire adsorption period. For the 120-mesh hydrochar, the removal efficiency increased from 19.0% at 10 min to 37.3% at 60 min, substantially outperforming the 140-mesh sample (4.7–19.3%) and the 160-mesh sample (3.7–15.7%). The variation in enrofloxacin adsorption efficiency with contact time for each particle size (mesh) is presented in Figure 1.

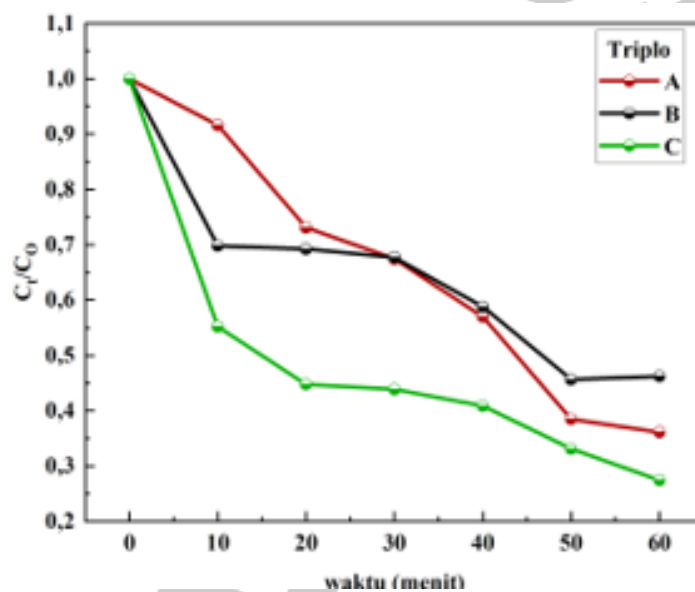


Figure 1 The variation in enrofloxacin adsorption efficiency with contact time

Moreover, the performance gap between the coarser and finer particles became more pronounced as the contact time increased. The rapid initial increase followed by a gradual approach to equilibrium is characteristic of carbon-based adsorbents, where abundant vacant active sites are readily occupied during the early stage of adsorption before progressively approaching saturation. This behavior is consistent with a chemisorption-controlled mechanism described by the pseudo-second-order kinetic model (Guo *et al.*, 2024). Interestingly, the superior adsorption performance of the coarser particles (120 mesh) compared with the finer particles (160 mesh) contrasts with the trend commonly reported for biochar and hydrochar adsorbents, where smaller particle sizes generally provide a larger accessible surface area and consequently achieve higher adsorption efficiencies (Kamarudin, 2024).

Several factors may explain this unexpected trend. First, the coarser particles (120 mesh) may better preserve the macroporous structure generated during hydrothermal carbonization and KOH activation, minimizing excessive mechanical damage and maintaining open diffusion pathways that facilitate the transport of enrofloxacin molecules to internal adsorption sites (Guo *et al.*, 2024). Second, the finer particles (160 mesh) are more susceptible to agglomeration when dispersed in aqueous media, which can reduce the effective surface area and block pore accessibility, thereby limiting adsorption performance (Li *et al.*, 2025). Third, the unique hollow fiber (lumen) structure of kapok peel may result in a pore architecture that responds differently to particle-size reduction compared with conventional biochar feedstocks such as hardwood or rice husk, which are more commonly reported in the literature (Guo *et al.*, 2024).

The FTIR analysis performed in this study indirectly supports this interpretation, as the observed shifts in the characteristic absorption bands of oxygen-containing functional groups ($-\text{OH}$ and $-\text{COOH}$) following KOH activation indicate enhanced surface reactivity of the hydrochar regardless of particle size. These findings suggest that pore accessibility may play a more significant role than surface area alone in governing the adsorption of enrofloxacin under the present experimental conditions. Nevertheless, further verification through morphological and textural characterizations, particularly scanning electron microscopy (SEM) and Brunauer–Emmett–Teller (BET) surface area analysis, is recommended to quantitatively elucidate the underlying adsorption mechanism.

From a practical perspective, these findings suggest that the optimum particle size of biomass-derived adsorbents should be determined based on the intrinsic structural characteristics of the precursor material rather than the common assumption that finer particles invariably provide superior adsorption performance. Consequently, the 120-mesh hydrochar was selected as the optimum particle size for subsequent adsorption experiments involving variations in adsorbent dosage, solution pH, and initial enrofloxacin concentration. Although the influence of particle size on adsorption performance has been extensively investigated for palm oil- and rice husk-derived biochars in pesticide removal (Kamarudin, 2024) and for hydrochar in antibiotic-related photocatalytic applications (Guo *et al.*, 2024), studies specifically examining the combined effects of kapok peel-derived hydrochar, KOH activation, and particle-size variation on enrofloxacin adsorption remain scarce. Therefore, the superior performance of the coarser particle fraction observed in this study represents a potentially novel finding that warrants further investigation and validation through comprehensive physicochemical characterization.

Effect of Adsorbent Dosage on the Adsorption Efficiency of Enrofloxacin by Kapok Peel-Derived Hydrochar

The adsorbent dosage experiments (0.5 , 1.0 , 1.5 , 2.0 , and 2.5 g L^{-1}) demonstrated that the removal efficiency of enrofloxacin increased consistently with increasing adsorbent dosage across the entire range of contact times evaluated. At 60 min, the removal efficiency increased from **33%** at 0.5 g L^{-1} to **47%**, **54%**, **56%**, and reached a maximum of **65%** at 2.5 g L^{-1} . A similar trend was observed throughout the adsorption period (10–60 min), with the 2.5 g L^{-1} dosage consistently exhibiting the highest removal efficiency among all tested conditions.

Table 2 Relationship between Contact Time (min) and Enrofloxacin Removal Efficiency (%) at Different Adsorbent Dosages

Menit	0,5 g/L	1 g/L	1,5 g/L	2 g/L	2,5 g/L
10	17%	21%	28%	30%	37%
20	25%	32%	36%	39%	47%
30	26%	36%	46%	47%	52%
40	30%	43%	49%	48%	59%
50	30%	45%	53%	55%	65%
60	33%	47%	54%	56%	65%

The progressive increase in removal efficiency with increasing adsorbent dosage is consistent with the fundamental principles of adsorption, whereby a higher adsorbent mass provides a greater number of available active sites for interaction with enrofloxacin molecules in solution, thereby enhancing the overall removal efficiency (Ajala & Akinawo, 2023). A similar trend has been reported for iron-modified biochar derived from orange peel waste used for the adsorption of the antibiotics levofloxacin and amoxicillin, where increasing the adsorbent dosage significantly improved removal efficiency until the optimum adsorption capacity was reached (Ullah *et al.*, 2026).

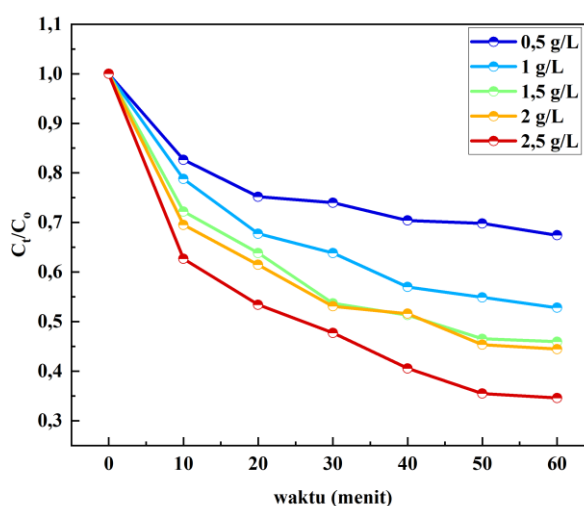


Figure 2. Variation of the Enrofloxacin Concentration Ratio (C_t/C_0) with Contact Time at Different Adsorbent Dosages.

Removal efficiency (%) with increasing adsorbent dosage does not necessarily correspond to an increase in the adsorption capacity per unit mass of adsorbent (q_e , mg g^{-1}). In many studies on antibiotic adsorption, increasing the adsorbent dosage increases the total number of available adsorption sites, whereas the amount of enrofloxacin in solution remains constant. As a result, the adsorption capacity per gram of adsorbent generally decreases despite an improvement in the overall removal efficiency. This phenomenon has also been reported for tetracycline adsorption using silica-based adsorbents. Furthermore, excessively high adsorbent dosages may promote particle aggregation, leading to partial blockage of active sites through steric hindrance and consequently limiting further improvements in adsorption efficiency even when additional adsorbent is introduced (Wahyu *et al.*, 2025).

Since the present study evaluated adsorbent dosages only up to 2.5 g L^{-1} , this saturation effect was not clearly observed. Nevertheless, it should be considered when determining the practical upper dosage limit for large-scale applications, particularly from the perspective of adsorbent utilization efficiency and economic feasibility. Based on these findings, an adsorbent dosage of 2.5 g L^{-1} was selected as the optimum operating condition for the subsequent experiments investigating the effects of solution pH and initial enrofloxacin concentration, as it consistently achieved the highest removal efficiency throughout the investigated contact-time range.

Effect of Initial Enrofloxacin Concentration on the Adsorption Efficiency of Kapok Peel-Derived Hydrochar

Table 3 Relationship between Contact Time (min) and Enrofloxacin Removal Efficiency (%) at Different Initial Enrofloxacin Concentrations

Menit	5 mg/L	10 mg/L	15 mg/L	20 mg/L
10	39%	27%	23%	24%
20	46%	44%	33%	25%
30	53%	45%	33%	28%
40	58%	50%	37%	28%
50	63%	55%	39%	30%
60	64%	57%	38%	31%

The experiments investigating the effect of the initial enrofloxacin concentration (5, 10, 15, and 20 mg L⁻¹) revealed a trend opposite to that observed for adsorbent dosage. Specifically, the removal efficiency decreased as the initial concentration of enrofloxacin increased. After 60 min of contact time, the highest removal efficiency (64%) was achieved at an initial concentration of 5 mg L⁻¹, followed by 57% at 10 mg L⁻¹, 38% at 15 mg L⁻¹, and only 31% at 20 mg L⁻¹. This decreasing trend was consistently observed throughout the entire contact-time range investigated, indicating that higher initial enrofloxacin concentrations reduced the adsorption efficiency of the kapok peel-derived hydrochar.

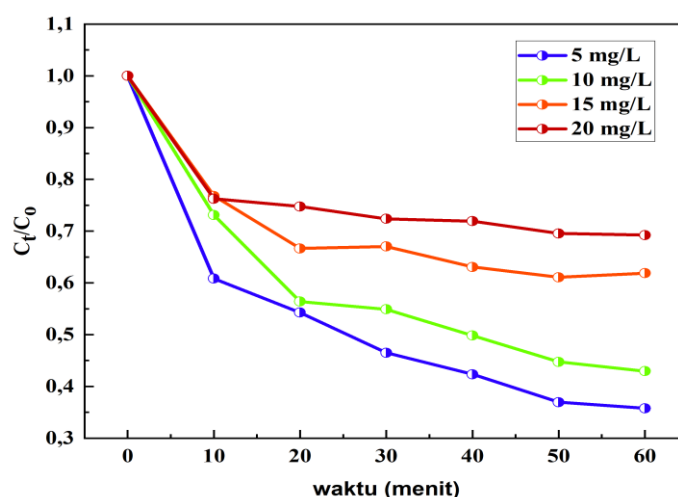


Figure 3. Relationship between Contact Time (min) and Enrofloxacin Removal Efficiency (%) at Different Initial Concentrations

The decline in removal efficiency with increasing initial enrofloxacin concentration can be attributed to the finite number of active adsorption sites available on the hydrochar surface, which is constrained by the adsorbent dosage and its accessible surface area. As the initial concentration increases, the number of enrofloxacin molecules competing for these adsorption sites also increases, resulting in a lower proportion of molecules being adsorbed, although the absolute amount of enrofloxacin retained by the adsorbent may still increase (Ajala & Akinlawo, 2023). A similar trend has been reported for iron-modified biochar derived from orange peel waste, where the highest removal efficiencies for levofloxacin and amoxicillin were achieved at the lowest initial concentrations investigated. This behavior was attributed to a more favorable ratio of available adsorption sites to adsorbate molecules under dilute conditions, which enhanced adsorption efficiency (Wahyu *et al.*, 2025).

Based on these findings, an initial enrofloxacin concentration of 5 mg L⁻¹ provided the optimum adsorption performance for KOH-activated kapok peel-derived hydrochar. This result indicates that the adsorbent is particularly effective for the removal of enrofloxacin under low-concentration conditions, which are representative of the residual antibiotic levels commonly detected in natural water bodies and in domestic or small-scale livestock wastewater.

Effect of Solution pH on the Adsorption Efficiency of Enrofloxacin by Kapok Peel-Derived Hydrochar

Table 4 Relationship between Contact Time (min) and Enrofloxacin Removal Efficiency (%) at Different Solution pH Values

Menit	pH 3	pH 5	pH 7	pH 9	pH 11
10	38%	50%	45%	30%	22%
20	44%	52%	55%	33%	25%
30	45%	56%	56%	35%	28%
40	47%	57%	59%	36%	30%
50	51%	62%	67%	43%	40%
60	58%	69%	73%	47%	41%

The effect of solution pH (3, 5, 7, 9, and 11) on enrofloxacin adsorption exhibited a characteristic bell-shaped trend, in which the removal efficiency increased from acidic to neutral conditions, reached a maximum, and subsequently declined under alkaline conditions. After 60 min of contact time, the removal efficiency was 58% at pH 3, increased to 69% at pH 5, reached the highest value of 73% at pH 7, and then decreased to 47% at pH 9 and 41% at pH 11.

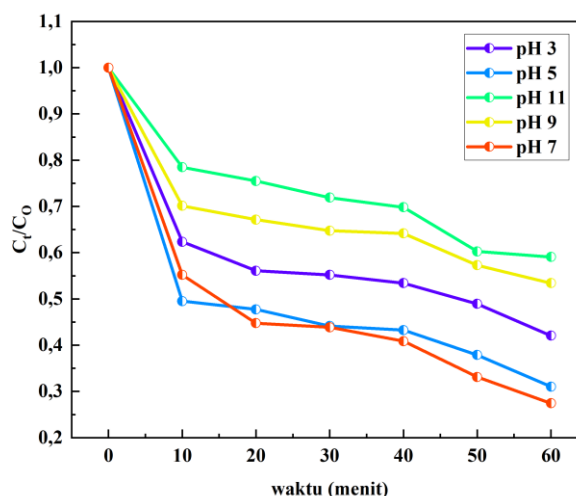


Figure 4. Relationship between Contact Time (min) and Enrofloxacin Removal Efficiency (%) at Different Solution pH Values

This bell-shaped trend is closely associated with the amphoteric (zwitterionic) nature of enrofloxacin, a fluoroquinolone antibiotic containing both carboxylate and piperazine functional groups that undergo protonation and deprotonation depending on the solution pH. Consequently, enrofloxacin exists predominantly as a cation under acidic conditions, as a zwitterion near neutral pH, and as an anion under alkaline conditions (Aparicio & Alonso, 2023). Under acidic conditions, both the hydrochar surface and enrofloxacin molecules tend to carry positive charges, resulting in electrostatic repulsion that hinders adsorption. Conversely, under alkaline conditions, the hydrochar surface and the anionic form of enrofloxacin become negatively charged, leading to renewed electrostatic repulsion and a corresponding decline in adsorption efficiency. The maximum removal efficiency observed at pH 7 indicates that enrofloxacin predominantly exists in its zwitterionic form, which favors both electrostatic interactions and hydrogen bonding with the oxygen-containing functional groups ($-\text{OH}$ and $-\text{COOH}$) on the surface of KOH-activated hydrochar. Similar behavior has been reported for the adsorption of other fluoroquinolone antibiotics using bamboo-derived biochar, where the highest adsorption capacity was likewise achieved under neutral conditions because the zwitterionic species exhibited the greatest affinity toward the adsorbent surface (Ouyang *et al.*, 2024).

Based on these findings, pH 7 was identified as the optimum operating condition for enrofloxacin adsorption by KOH-activated kapok peel-derived hydrochar. From a practical standpoint, this represents a significant advantage because most natural surface waters and municipal wastewater typically exhibit near-neutral pH values. Therefore, the adsorbent has strong potential for direct application in water treatment processes without requiring substantial pH adjustment, thereby reducing operational complexity and treatment costs.

Effect of Water Matrix on the Adsorption Efficiency of Enrofloxacin by KOH-Activated Kapok Peel-Derived Hydrochar

Table 5 Relationship between Contact Time (min) and Enrofloxacin Removal Efficiency (%) in Different Water Matrices

Menit	A/Aquades	A/Hujan	A/Sungai
10	45%	28%	18%
20	48%	42%	22%
30	52%	49%	32%
40	53%	51%	34%
50	58%	53%	35%
60	63%	60%	37%

The adsorption performance of KOH-activated kapok peel-derived hydrochar was evaluated using three different water matrices—deionized water, rainwater, and river water—to assess its effectiveness under conditions that more closely resemble real environmental systems. The results showed that the highest enrofloxacin removal efficiency was achieved in deionized water, reaching 63% after 60 min of contact time, followed by rainwater with 60%, whereas river water exhibited the lowest removal efficiency of only 37%. This substantial reduction in adsorption performance demonstrates that the composition of the water matrix has a significant influence on the removal efficiency of enrofloxacin.

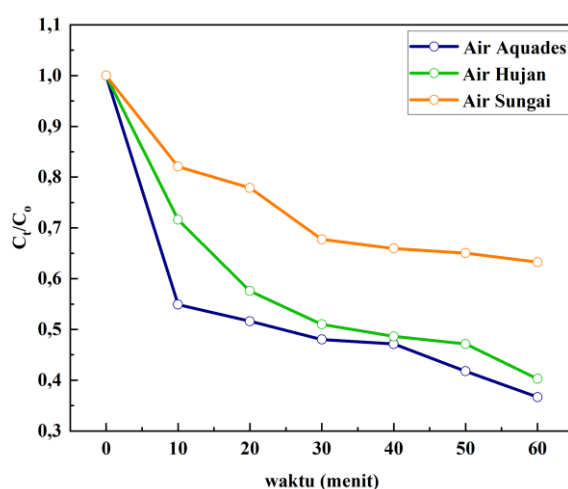


Figure 5. Relationship between Contact Time (min) and Enrofloxacin Removal Efficiency (%) in Different Water Matrices

The reduced adsorption efficiency observed in rainwater and, more prominently, in river water demonstrates the influence of non-target constituents naturally present in real water

matrices, including dissolved inorganic ions (e.g., Ca^{2+} , Mg^{2+} , and Na^+) and natural organic matter (NOM), which are absent in deionized water. These constituents compete directly with enrofloxacin molecules for the available active sites on the hydrochar surface, thereby decreasing the number of adsorption sites accessible to the target contaminant and reducing the overall removal efficiency (Niinipuu *et al.*, 2020). River water typically contains substantially higher concentrations of NOM and suspended solids than rainwater or deionized water, explaining the pronounced decline in adsorption performance observed in this matrix. This finding is consistent with previous studies demonstrating that increasing water matrix complexity—from purified water to natural surface water—generally impairs the adsorption performance of carbon-based adsorbents due to competitive adsorption and pore blockage (Fang *et al.*, 2025).

These findings have important implications for practical applications. The adsorption achieved under laboratory conditions using deionized water should not be directly extrapolated to real environmental waters. Consequently, the application of KOH-activated kapok peel-derived hydrochar for treating actual wastewater may require higher adsorbent dosages and/or longer contact times to compensate for the competitive effects of dissolved ions and natural organic matter present in complex water matrices.

Adsorption Kinetic Study of Enrofloxacin by KOH-Activated Kapok Peel-Derived Hydrochar

The adsorption kinetics were evaluated over a contact-time range of 3–180 min to investigate the adsorption rate of enrofloxacin ($C_0 = 10 \text{ mg L}^{-1}$) until equilibrium was approached. The results revealed a rapid increase in removal efficiency during the initial adsorption stage, reaching 38% within the first 3 min, followed by a gradual increase until a near-equilibrium (steady-state) condition was established, with removal efficiencies stabilizing at approximately 57–58% between 140 and 180 min. This adsorption behavior is characteristic of a two-stage process. The initial rapid stage is attributed to the abundance of readily accessible vacant active sites on the external surface of the adsorbent, whereas the subsequent slower stage is governed by the gradual diffusion of enrofloxacin molecules into the internal pore structure of the hydrochar, where intraparticle diffusion and mass transfer limitations become increasingly significant (Sangoremi, 2025)

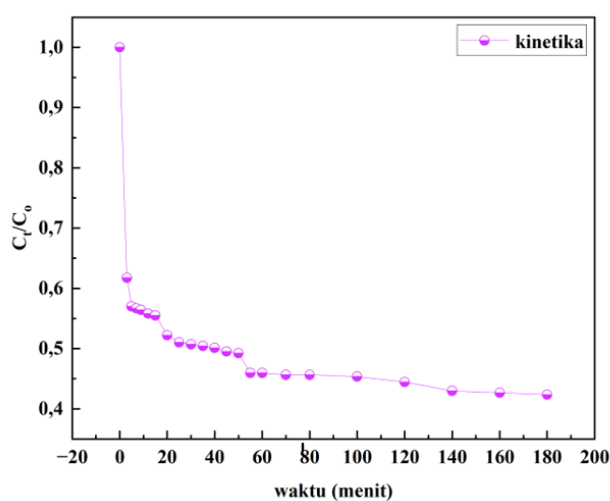


Figure 6. Relationship between Contact Time (min) and the Enrofloxacin Concentration Ratio (C_t/C_0).

To elucidate the adsorption mechanism, the kinetic data were analyzed using two widely applied kinetic models: the Pseudo-First-Order (PFO) and Pseudo-Second-Order (PSO) models. The adsorption capacity at time t (q_{t_t}) was calculated from the experimental concentration data according to the following equation (q_t) :

$$q_t = \frac{C_0 - C_t}{m} \times v \quad (1)$$

(The following calculations assume an adsorbent dosage of 2.5 g/L, corresponding to the optimum conditions; please re-verify the actual dosage used in this kinetic test, as it will proportionally affect the q_t and q_e values.)

With $C_0 = 10$ mg/L, the q_t value was calculated at each contact time, yielding an experimental equilibrium capacity (q_e) of 2.31 mg/g at 180 minutes.

1) Pseudo-First-Order (PFO) Model :

$$\ln (q_e - q_t) = \ln (q_e) - k_1 t \quad (2)$$

Linear regression analysis of all data points yielded:

$$k_1 = 0.0183 \text{ min}^{-1}$$

$$q_e \text{ (calculated)} = 0.66 \text{ mg/g}$$

$$R^2 = 0.969$$

2) Pseudo-Second-Order (PSO) Model:

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e} \quad (3)$$

The linear regression results are:

$$k_2 = 0.0938 \text{ g}/(\text{mg} \cdot \text{min})$$

$$q_e \text{ (calculated)} = 2.33 \text{ mg/g}$$

$$R^2 = 0.999$$

Based on the coefficient of determination (R^2), the Pseudo-Second-Order (PSO) kinetic model ($R^2 = 0.999$) provided a substantially better fit to the experimental data than the Pseudo-First-Order (PFO) model ($R^2 = 0.969$). In addition to its superior goodness of fit, the equilibrium adsorption capacity predicted by the PSO model ($q_e = 2.33 \text{ mg g}^{-1}$) closely matched the experimental value ($q_{e, \text{exp}} = 2.31 \text{ mg g}^{-1}$), whereas the PFO model considerably underestimated the adsorption capacity ($q_e = 0.66 \text{ mg g}^{-1}$). The excellent agreement between the PSO model and the experimental data suggests that the adsorption of enrofloxacin onto KOH-activated kapok peel-derived hydrochar is predominantly governed by chemisorption, involving electron sharing or electron exchange between enrofloxacin molecules and the oxygen-containing functional groups ($-\text{OH}$ and $-\text{COOH}$) on the adsorbent surface, rather than by weak physical interactions alone (Ho & McKay, 1999). This kinetic behavior is consistent with numerous studies on the adsorption of fluoroquinolone antibiotics using modified biochar and hydrochar, where chemisorption mechanisms involving

hydrogen bonding and π – π interactions have been identified as the dominant adsorption pathways (Ajala & Akinnawo, 2023).

Characterization of Functional Groups of KOH-Activated Kapok Peel-Derived Hydrochar Using FTIR

Fourier Transform Infrared Spectroscopy (FTIR) analysis was performed to identify the surface functional groups of KOH-activated kapok peel-derived hydrochar and to verify the presence of active sites responsible for enrofloxacin adsorption. The FTIR spectrum exhibited several characteristic absorption bands corresponding to oxygen-containing and carbonaceous functional groups on the hydrochar surface. These characteristic peaks, which are summarized in the following figure, provide evidence of the chemical functionalities involved in the adsorption process.

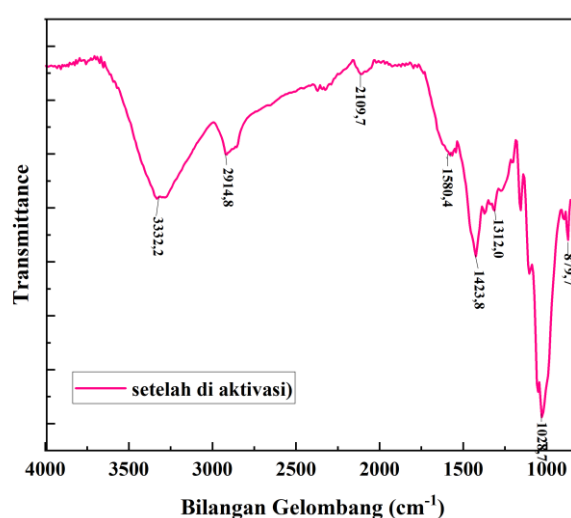


Figure 7. FTIR Spectrum of KOH-Activated Kapok Peel-Derived Hydrochar (4000–650 cm^{-1})

The prominent absorption bands at 3332.2 cm^{-1} and 1028.7 cm^{-1} , with the latter exhibiting the strongest absorption intensity (lowest transmittance of 60.6%), indicate that the KOH-activated kapok peel-derived hydrochar retained a substantial amount of hydroxyl ($-\text{OH}$) and ether/alcohol ($\text{C}-\text{O}-\text{C}$) functional groups despite undergoing hydrothermal carbonization and chemical activation. This characteristic is typical of hydrothermal carbonization (HTC) products, which generally preserve a higher abundance of oxygen-containing functional groups than conventional pyrolysis-derived biochar because HTC is conducted at relatively low temperatures, resulting in incomplete decomposition of oxygenated moieties (Gale et al., 2021). In addition, the absorption bands observed at 1580.4 cm^{-1} and 879.7 cm^{-1} confirm the formation of condensed aromatic structures, indicating that the carbonization process successfully generated a relatively stable carbon framework (Goel et al., 2024).

The coexistence of hydroxyl, ether, and aromatic functional groups provides direct evidence supporting the adsorption mechanism proposed in the previous sections. The $-\text{OH}$ and $\text{C}-\text{O}$ groups can act as hydrogen-bond donors or acceptors, facilitating hydrogen-bond formation with the functional groups of enrofloxacin, particularly its carboxylate and piperazine moieties. Meanwhile, the aromatic domains on the hydrochar surface promote π – π electron donor–acceptor interactions with the quinolone aromatic ring of enrofloxacin (Ajala & Akinnawo, 2023). Therefore, the FTIR

characterization corroborates the kinetic analysis, indicating that the adsorption of enrofloxacin onto KOH-activated kapok peel-derived hydrochar is predominantly governed by chemisorption, involving hydrogen bonding and π - π interactions rather than simple physisorption.

4. CONCLUSION

This study demonstrated that KOH-activated kapok peel-derived hydrochar is an effective adsorbent for the removal of enrofloxacin from aqueous solutions. The optimum adsorption conditions were achieved using 120-mesh hydrochar, an adsorbent dosage of 2.5 g L^{-1} , an initial enrofloxacin concentration of 5 mg L^{-1} , and neutral pH (7). Adsorption efficiency decreased with increasing initial concentration and water matrix complexity, indicating that dissolved ions and natural organic matter negatively affected adsorption performance. Kinetic analysis showed that the adsorption process was best described by the Pseudo-Second-Order model, suggesting that chemisorption predominated, while FTIR characterization confirmed the presence of oxygen-containing and aromatic functional groups responsible for hydrogen bonding and π - π interactions. Overall, KOH-activated kapok peel-derived hydrochar shows promising potential as a sustainable and cost-effective adsorbent for the treatment of enrofloxacin-contaminated water.

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