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Adsorption of Enrofloxacin from Aqueous Solution Using Teak Wood Powder Hydrocarbon: Effect of Particle Size, Adsorbent Dose, Contact Time, and Water Matrix

Uswatun Khabiba Amalia[1], Muchammad Tamyiz[2]

Nahdlatul Ulama University, Sidoarjo, Indonesia
Email correspondence: m_tamyiz.tkl@unusida.ac.id

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Abstract

Water pollution due to antibiotic residues is worsening and endangering the environment because it can cause antibiotic exhaustion and damage aquatic ecosystems. One antibiotic frequently found in the environment is enrofloxacin, which originates from livestock activities and household waste. This study aimed to determine how well hydrochar from teak sawdust can absorb enrofloxacin and to determine the optimal conditions for this absorption process. Hydrochar was made through a hydrothermal carbonization process using teak sawdust at a temperature of 200 degrees Celsius for 10 hours. Testing was carried out by assessing the impact of particle size (120, 140, and 160 mesh), solution acidity level, amount of adsorbent used, initial enrofloxacin concentration, type of water medium, and contact duration. Enrofloxacin concentration was measured using a UV-Vis spectrophotometer with a wavelength of 340 nm, while adsorbent properties were analyzed using Fourier Transform Infrared Spectroscopy (FTIR). The study showed that hydrochar with a 120 mesh size had the best and most consistent absorption capacity compared to other sizes. FTIR analysis showed the presence of hydroxyl groups (O–H), aliphatic C–H compounds, aromatic C=C bonds, and C–O groups involved in the adsorption process. Adsorption efficiency increased with increasing contact time and reached its highest level of 37% at 180 minutes. The study showed that hydrochar from teak wood powder can be used as an environmentally friendly alternative adsorbent for removing enrofloxacin from water.

Keywords Enrofloxacin Absorption; Teak Wood Powder Hydrocarbons; FTIR Characterization; Antibiotic Contamination; Water Matrix

INTRODUCTION

Antibiotics are one of the pollutants increasingly found in aquatic environments due to their widespread use in healthcare and animal husbandry. One antibiotic frequently found in the environment is enrofloxacin, a fluoroquinolone. This antibiotic is highly resistant and difficult to decompose naturally. The presence of

residual enrofloxacin in the environment can make bacteria more resistant to the drug and negatively impact aquatic life (Akhtar et al., 2016). Adsorption methods are often used to remove antibiotic residues in water because they are efficient, have low operational costs, and are relatively simple to use. Several types of biomass-based adsorbent materials have been shown to be capable of absorbing antibiotic compounds, such as biochar derived from rice husks, coconut shells, and other agricultural waste (Yousef & Qiblawey, 2020). Research by Nguyen et al (2019), shows that hydrochar produced from the hydrothermal carbonization process has oxygen functional groups which may increase the ability to interact with organic pollutants in water.

Previous research has shown that adsorbent properties such as particle size, surface area, and type of functional groups significantly influence the efficiency of the adsorption process. Das et al (2022), said that changes in particle size can affect the ease of access to pores and the number of sites that can be used during the adsorption process. However, most research still focuses on biochar or hydrochar from agricultural waste, while the use of hydrochar from teak wood dust (Tectona grandis) to remove enrofloxacin is still limited. Teak wood dust is a lignocellulose-based biomass waste consisting of cellulose, hemicellulose, and lignin, so it can be converted into hydrochar that has adsorbent capabilities. Using this waste as an adsorbent can increase the value of biomass and help develop environmentally friendly water treatment technologies. Based on the explanation, this study aims to evaluate the ability of hydrochar from teak wood powder to absorb enrofloxacin, determine the most effective particle size, analyze the impact of contact duration on absorption efficiency, and identify the types of functional groups in the adsorbent using Fourier Transform Infrared Spectroscopy (FTIR).

METHODS

This research was conducted from April to June 2026 at the University Environmental Laboratory to make hydrochar and test its adsorption capacity, the Mojokerto Regency Environmental Service Laboratory to analyze water properties, and the Instrumentation Laboratory of the Sepuluh Nopember Institute of Technology (ITS) Surabaya to examine characteristics using the Fourier Transform Infrared Spectroscopy (FTIR) technique. The water used as samples came from rainwater, brackish water, PDAM water, and river water. The samples were taken on April 28, 2026 from various locations in East Java.

The study began with the preparation of dried teak wood powder and shaken using mesh sizes of 120, 140, and 160. Hydrochar was synthesized using the

hydrothermal carbonization (HTC) method. 20 grams of teak wood powder was shaken with 400 mL of distilled water (1:20 weight-to-volume ratio) and then inserted into a hydrothermal reactor made of stainless steel with a capacity of 500 mL. The HTC process was carried out at a temperature of 200 degrees Celsius for 10 hours. After the process was complete, the reactor was cooled to room temperature. The resulting solid product was separated from the residual solution, washed with pure water until completely clean, then dried in an oven at a temperature of 100 degrees Celsius for 3 hours until the hydrochar was ready for use. The initial stage of the study was carried out to determine the best particle size of the hydrochar. Tests were carried out using hydrochar with sizes of 120, 140, and 160 mesh. Eight milligrams of adsorbent was mixed into eight milliliters of enrofloxacin solution, then thoroughly mixed using an ultrasonic cleaner for three minutes. The mixture was then mixed at room temperature and tested for 60 minutes. After the contact time was complete, the sample was separated using a centrifuge for 1 to 3 minutes, then the filtrate was analyzed with a UV-Vis spectrophotometer at a wavelength of 340 nm. The particle size that showed the best and most stable adsorption performance was determined as the most suitable size.

Based on the results of particle size selection, hydrochar with a size of 120 mesh was selected as the best adsorbent and was used in all subsequent tests. The test was repeated three times to ensure the results were more representative of real-world conditions. The variables examined included the solution acidity level (3, 5, 7, 9, and 11), the initial concentration of enrofloxacin (5, 10, 15, 20, and 25 mg/L), the amount of adsorbent used (5, 10, 15, 20, and 25 mg/10 mL), the type of water used (rainwater, brackish water, PDAM water, and river water), and the contact duration (3 to 180 minutes). The concentration of enrofloxacin before and after the adsorption process was measured using a UV-Vis spectrophotometer with reference to the calibration curve of the standard solution at a wavelength of 340 nm. The adsorption efficiency was calculated using Equation (1).

$$\text{Adsorption Efficiency (\%)} = \frac{C0 - Ct}{C0} \times 100 \qquad (1)$$

Information:

A : C0 is the initial concentration of enrofloxacin (mg/L)

B : Ct is the concentration of enrofloxacin after the adsorption process (mg/L).

Hydrocarbon characteristic analysis was carried out using an Agilent Cary 630 FTIR instrument at a wavelength range of 4000 to 650 $cm^{-}1$with a resolution of 16 $cm^{-}1$FTIR analysis was used to determine the types of functional groups present on the hydrochar surface, which may be involved in the enrofloxacin adsorption

process. The test results were presented in tables and graphs, then analyzed descriptively. The optimal conditions were determined by observing the highest adsorption efficiency values obtained from each test. The results of the 120-mesh hydrochar test, performed three times, show the average value across the three iterations.

FINDINGS AND DISCUSSION

Effect of Hydrochar Particle Size on Enrofloxacin Adsorption

Particle size affects adsorbent performance, including surface area, pore distribution, and adsorbate transfer to active sites. Research shows that 120-mesh teak wood powder hydrochar has better and more consistent adsorption capacity than 140-mesh and 160-mesh hydrochar (Figure 1).

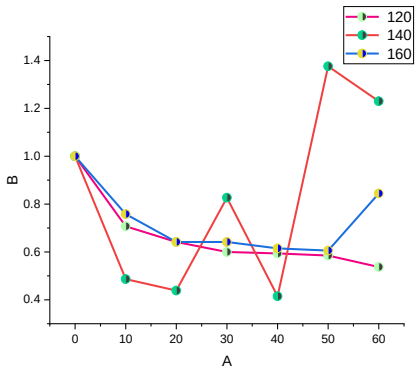

Figure 1. Performance test results

Although smaller particles theoretically have a larger surface area, a size reduction of up to 160 mesh did not improve the adsorption capacity. These results indicate that finer particles do not always improve adsorption efficiency. In addition to size, the adsorption capacity of hydrochar is also influenced by the pore structure, surface area, and functional groups formed during the hydrothermal carbonization process. Therefore, the physical and chemical properties of the adsorbent determine its interaction with the adsorbate (Ajala & Akinnawo, 2023). In general, the smaller the particle size, the greater the specific surface area and number of adsorption sites, resulting in faster adsorbate diffusion. This is supported by Fahmi et al (2018), who reported that biochar refining can open pores and increase surface area, as well as (Tan et al., 2015) which states that smaller particle size shortens the adsorbate diffusion path so that adsorption becomes more efficient. However, the results of this study showed that hydrochar with a size of 140 mesh and 160 mesh was not more effective than 120 mesh. This difference indicates that the adsorption capacity is not only determined by particle size, but also by the physical properties of the hydrochar

after the hydrothermal carbonization process. Particles that are too fine can experience agglomeration, thus blocking pores, reducing the effective surface area, and inhibiting mass transfer to active sites. Masoumi et al (2021) stated that hydrochar performance is influenced by surface area, pore distribution, and functional groups, while Monfared et al. (2025) reported that fine particle agglomeration can reduce contaminant removal capacity. Therefore, a 120 mesh size is thought to be the optimum size because it maintains a balance between effective surface area, particle structure, and pore access. In addition to agglomeration, the pore structure of hydrochar also plays an important role. Excessive refinement can damage or block pores, thus inhibiting adsorbate diffusion. Consequently, a larger surface area does not always increase adsorption capacity. Hydrochar with a 120 mesh size has the best adsorption capacity because it maintains a balance between surface area, pore access, and structural resistance. In addition, adsorption capacity is also influenced by surface functional groups resulting from hydrothermal carbonization. A good pore structure facilitates adsorbate diffusion, while hydroxyl and carboxyl groups enhance interactions with organic compounds (Ajala & Akinnawo, 2023). The superiority of 120-mesh hydrochar is also supported by FTIR results showing the presence of O–H, C=C aromatic, and C–O groups that play a role in the formation of hydrogen bonds, π–π interactions, and electrostatic interactions with enrofloxacin. Therefore, a particle size of 120 mesh was selected as the optimum condition for all subsequent optimization stages.

Effect of pH on Enrofloxacin Adsorption

Table 1 pH Variation

time	7	9	11
0	1	1	1
10	0.707164	0.987761	0.787761
20	0.641493	0.74597	0.75791
30	0.599701	0.72806	0.748955
40	0.593731	0.686269	0.698209
50	0.569851	0.578806	0.686269
60	0.510149	0.542985	0.662388

Table 1 shows that the Ct/C0 value at pH 7 was always lower than at pH 9 and pH 11 during the contact time of 10–60 minutes. At the 60th minute, the Ct/C0 values were 0.510 (pH 7), 0.543 (pH 9), and 0.662 (pH 11), respectively, indicating that the highest ENR adsorption occurred at pH 7. This pattern has been seen from the 10th to the 20th minute, where the decrease in Ct/C0 at pH 7 occurred more rapidly than in alkaline conditions, indicating that the active sites of hydrochar were more easily

accessible by ENR molecules at neutral pH. The increasing difference in Ct/C0 between pH 7 and pH 11 until the 60th minute indicates that the effect of pH was consistent throughout the adsorption process. These results indicate that the surface charge of the adsorbent and the speciation of ENR at pH 7 are more supportive of the adsorption process, so pH 7 was chosen as the optimal condition for further parameter optimization. The decrease in adsorption capacity at pH 9 and pH 11 is shown in Figure 2.

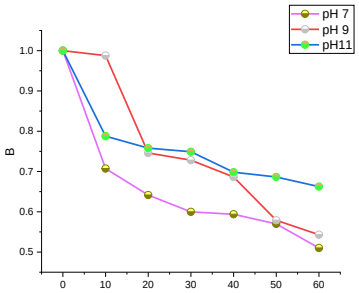

Figure 2. Results of pH variations

In this study, the decrease in adsorption capacity under alkaline conditions is likely due to changes in ENR speciation. ENR has carboxyl and piperazinyl groups, so at high pH the anionic form becomes more dominant and experiences electrostatic repulsion with the negatively charged hydrochar surface. This condition is consistent with the Ct/C0 value at pH 11 which remains high (0.662) after 60 minutes, indicating that adsorption occurs more slowly than at pH 7. These results are in line with Alma (2022), who reported a decrease in ENR adsorption efficiency at pH 11 due to negative ionization of ENR, and Li et al.(2025)who found that ENR adsorption reached a maximum at pH 7 and decreased with increasing anionic species.

The lower Ct/C0 value at pH 7 is thought to be related to the dominance of the zwitterionic form of ENR, allowing its cationic charge to still interact with the oxygen groups on the hydrochar surface through cation exchange and bridging. At pH 9, some of the ENR begins to convert to the anionic form, reducing these interactions. This is consistent withTeixidó (2013), which showed that the adsorption of ENR at pH around 7 was influenced by the cation exchange mechanism, as well as Galvis et al.(2024), which states that the zwitterion form makes a major contribution to adsorption on porous adsorbents. In addition to ENR speciation, the difference in Ct/C0 decrease at various pH values indicates that adsorption at pH 7 also involves hydrogen bonding and π–π interactions between the aromatic rings of ENR and the carbon surface of the hydrochar. This combination of mechanisms maintains efficient adsorption at neutral pH. This finding is supported by Peng et al (2016), which states that the adsorption of antibiotics on carbon materials involves hydrophobic, π–π,

hydrogen bonding, and electrostatic interactions, and Wu et al (2022) which confirms that the functional groups on the biochar surface also influence the adsorption process. The faster decrease in Ct/C0 at pH 7 during the first 10 minutes indicates that adsorption equilibrium is reached more quickly than under alkaline conditions. This is thought to be due to the smaller electrostatic barrier and the availability of active sites on the hydrochar, resulting in more efficient ENR diffusion. These results align with those of Madhusudhan et al (2025), which states that pH, amount of adsorbent, and pore structure affect the initial adsorption rate, Acelas et al (2021), which explains that a pH close to neutral provides maximum adsorption capacity due to the balance between the adsorbent charge and the dominant form of the adsorbate. Based on all the data in Table 1, it can be concluded that pH 7 is the optimum condition for ENR adsorption using teak sawdust hydrochar. This is indicated by the Ct/C0 value which is consistently the lowest at all contact times, so pH 7 was chosen as the optimum condition for testing the next parameters, namely variations in adsorbent dosage, particle size, contact time, and type of water matrix.

The Effect of Initial Concentration of Enrofloxacin on Adsorption Efficiency

Table 2 ENR Concentration Removal

Time	5	15	25
10	62%	32%	38%
20	64%	49%	39%
30	65%	51%	46%
40	68%	56%	47%
50	70%	58%	48%
60	77%	58%	51%

Table 3 Ct/C0 pH variation

time	7	9	11
0	1	1	1
10	0.707164	0.987761	0.787761
20	0.641493	0.74597	0.75791
30	0.599701	0.72806	0.748955
40	0.593731	0.686269	0.698209
50	0.569851	0.578806	0.686269
60	0.510149	0.542985	0.662388

The data in Tables 2 and 3 show that the ability of teak sawdust hydrochar to remove ENR increased with increasing contact time at all initial concentration variations. However, the increase differed at concentrations of 5, 15, and 25 mg/L. At a concentration of 5 mg/L, the removal percentage increased from 62% to 77%, with the Ct/C0 value decreasing from 0.381 to 0.232 over 60 minutes. Meanwhile, at a concentration of 25 mg/L, the removal efficiency only increased from 38% to 51%,

with a final Ct/C0 value of 0.487. The 15 mg/L concentration showed results in between, namely 32% at the 10th minute and 58% at the 60th minute. This pattern indicates that the higher the initial ENR concentration, the lower the removal percentage even though the hydrochar's active sites remained functional. Based on these results, an initial concentration of 5 mg/L consistently provided the highest removal efficiency throughout the contact time, and was therefore selected as the optimum concentration in this study. The initial concentration graph is shown in

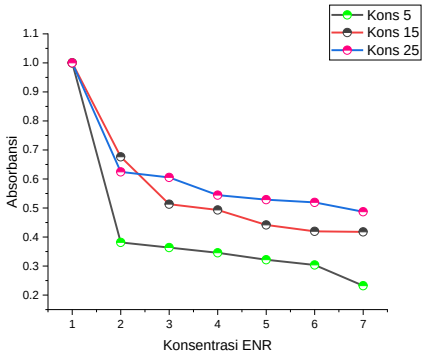

Figure 3. ENR concentration graph

The decreasing trend in removal efficiency in this study is thought to be caused by an imbalance between the number of ENR molecules and active sites on the hydrochar surface. At higher initial concentrations, more ENR molecules compete for limited active sites, resulting in faster adsorbent saturation. Consequently, a concentration of 25 mg/L showed the highest Ct/C0 value observed. These results are in line with Nguyen et al (2025), who reported that increasing the initial concentration of antibiotics decreased the adsorption rate due to intermolecular competition, and Singh & Lundborg (2022), which states that removal efficiency decreases at high concentrations due to the limitation of active sites.

The difference in Ct/C0 values at various concentrations indicates that at 5 mg/L, the ratio between ENR molecules and active sites is at its most balanced state, resulting in more efficient adsorption. Conversely, at 25 mg/L, despite the greater mass transfer driving force, the active site capacity has approached saturation, resulting in decreased removal efficiency. This phenomenon is consistent with Teo et al (2022), who stated that increasing the initial concentration accelerated the mass transfer but decreased the removal efficiency, as well as Enyinnaya et al (2023), which explains that the mechanisms of pore filling, hydrogen bonding, and electrostatic interactions will reach saturation at a certain concentration. Although the removal efficiency at a concentration of 25 mg/L was lower, all concentration

variations showed the same pattern of decreasing Ct/C0, which was rapid in the first 10–20 minutes and then slowed down until equilibrium was reached. This pattern indicates that the initial adsorption was rapid due to the large number of active sites that were still empty, while the subsequent stages were controlled by the reduction of active sites and intraparticle diffusion. These results are in line with Wakejo et al (2022) and Oumabady et al (2022), which explains that the initial stage is controlled by the availability of active sites, while the subsequent stages are limited by diffusion within the pores of the adsorbent.

These findings indicate that at lower ENR concentrations, ENR molecules have a greater opportunity to interact with the hydroxyl (-OH) and carboxyl (-COOH) groups in the hydrochar. Conversely, at higher concentrations, some molecules are prevented from reaching the active sites because the pores and surfaces are filled, resulting in decreased removal efficiency. This condition is in accordance with Ajala & Akinnawo (2023), which states that the performance of hydrothermal carbonization adsorbents depends on the balance between active surface area, pore volume, and adsorbate concentration. Based on all research results, an initial concentration of 5 mg/L was selected as the optimum condition because it produced the highest removal efficiency (77%) with the lowest Ct/C0 value (0.232), so it was used in the next research stage.

Effect of Adsorbent Dose on Enrofloxacin Adsorption

Table 4 Presentation of adsorbent dosage results

Time	**1**	**1.5**	**2**
10	29%	-6%	16%
20	36%	2%	28%
30	40%	4%	29%
40	41%	23%	40%
50	42%	33%	45%
60	46%	37%	51%

The data in Tables 4 and 5 show that a 2-gram adsorbent dose provided the highest ENR removal efficiency during the contact time, with an R value of 51% and a Ct/C0 of 0.486 at the 60th minute. A 1-gram dose produced an R of 46% (Ct/C0 = 0.537), while a 1.5-gram dose only achieved an R of 37% (Ct/C0 = 0.630).

Table 5 Ct/C0 results of adsorbent dose

time	1	1.5	2
0	1	1	1
10	0.707164	1.056418	0.841493
20	0.641493	0.981791	0.719104
30	0.599701	0.963881	0.713134
40	0.593731	0.766866	0.599701

50	0.584776	0.671343	0.548955
60	0.537015	0.629552	0.486269

Interestingly, at a dose of 1.5 grams, the Ct/C0 value at the 10th minute reached 1.056, higher than the initial concentration, indicating the possibility of temporary desorption or unstable distribution of hydrochar particles at the initial stage. However, the Ct/C0 value continued to decrease until the 60 th minute, but the removal efficiency remained lower than the doses of 1 gram and 2 grams. Based on these results, the 2 gram dose was determined as the optimum dose because it produced the lowest Ct/C0 value and the highest removal percentage. The increase in adsorption efficiency from 1 gram to 2 grams is thought to be due to the increase in the number of active sites on the hydrochar surface, allowing more ENR molecules to be adsorbed. Consequently, the removal value at 60 minutes increased from 46% to 51%. This result is consistent with Nguyen et al (2025)and Katiyar et al (2022), which states that increasing the biochar dose increases the number of active sites and increases the adsorption efficiency until it reaches optimum conditions.

The anomaly at the 1.5 gram dose, indicated by a Ct/C0 value > 1 at the 10th minute, was likely caused by the temporary release of organic compounds from the hydrochar surface or uneven particle distribution at the start of stirring. However, the Ct/C0 value then decreased consistently until the 60 th minute, thus not affecting the study's conclusions. A similar phenomenon was also reported by Ajala & Akinnawo (2023) which relates to the distribution of carbon-based adsorbent particles which is not yet stable in the initial stage of adsorption. The difference in efficiency between doses of 1 gram (46%) and 2 grams (51%) indicates that increasing the dose does not always result in a comparable increase in efficiency. This is likely due to the agglomeration of hydrochar particles at higher doses, which partially obscures the active sites. Nguyen et al.(2025)also explained that the addition of excess adsorbent can cause agglomeration and reduce the utilization of active sites. Based on the balance between removal efficiency and adsorbent utilization, a dose of 2 grams was selected as the optimum condition because it produced the lowest Ct/C0 value (0.486) and the highest removal percentage (51%). The results of the ENR concentration graph are shown in Figure 4.

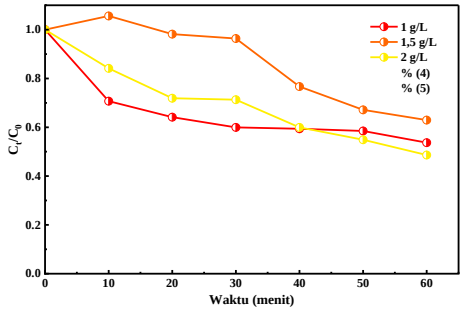

Figure 4. Adsorbent dosage graph

Enrofloxacin Adsorption Kinetics Study

Table 6 ENR concentration ratio (Ct/C0) and contact time removal percentage (kinetic study)

Time	Removal	Time	Ratio
3	-4%	0	1
5	5%	3	1.041493
7	7%	5	0.94597
9	7%	7	0.931045
12	9%	9	0.925075
15	11%	12	0.907164
20	18%	15	0.892239
25	21%	20	0.817612
30	22%	25	0.793731
35	23%	30	0.778806
40	24%	35	0.772836
45	25%	40	0.763881
50	25%	45	0.754925
55	26%	50	0.75194
60	26%	55	0.742985
70	27%	60	0.74
80	27%	70	0.731045
100	28%	80	0.725075
120	30%	100	0.716119
140	30%	120	0.704179
160	33%	140	0.695224
180	37%	160	0.674328
		180	0.632537

The data in Table 6 shows the ENR adsorption process by teak sawdust hydrochar during a contact time of 3–180 minutes. At the 3rd minute, the Ct/C0 value of 1.041 (R = -4%) indicates a slight increase in ENR concentration, which is thought to be caused by the instability of the hydrochar particle distribution or measurement uncertainty. After 5 2 minutes, the Ct/C0 value decreased gradually from 0.946 to 0.633 at the 180th minute with a removal percentage of 37%. The

decrease occurred in two stages, namely rapidly at the 5 th to 20th minute (0.946 to 0.818), then slowed down until the 180th minute (0.818 to 0.633). Although the contact time was extended to 180 minutes, the Ct/C0 value had not reached a stable condition, indicating that the adsorption process was still ongoing. This two-stage pattern is the basis for understanding the kinetics of ENR adsorption by hydrochar.

The kinetic profile shows a rapid decrease in Ct/C0 in the initial stage followed by a slowdown over time, indicating rapid adsorption at surface active sites, which is then controlled by intraparticle diffusion. In the initial stage, the large number of active sites still available facilitates the adsorption of ENR molecules. This result is in accordance with Esteves et al (2023), which states that the adsorption of antibiotics on carbon materials begins with surface adsorption and is then controlled by intraparticle diffusion, as well as Ajala & Akinnawo (2023), who reported a similar pattern with kinetics following a pseudo-second-order model. The Ct/C0 value which continued to decrease from 0.740 at the 60th minute to 0.633 at the 180th minute without reaching a stable condition indicated that the ENR–hydrochar adsorption system had not reached equilibrium until the end of the observation. The results of the kinetic test graph are shown in Figure 5.

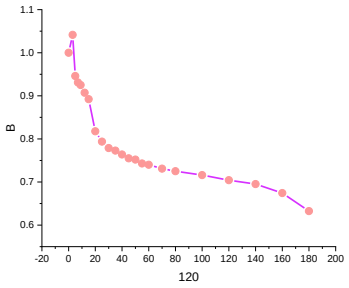

Figure 5. Kinetic test results

The continued decrease in the slow phase (60–180 min) indicates that ENR diffusion from the surface to the mesopores and micropores of the hydrochar is still ongoing, requiring a longer time due to internal mass transfer barriers. This phenomenon is consistent with Rangasamy et al (2026), who reported that approximately 90% of the hydrochar adsorption capacity was achieved within ±47 min, while subsequent stages were slower due to intraparticle diffusion. Ajala & Akinnawo(2023)also stated that the adsorption of antibiotics on biomass-based carbon adsorbents generally follows a pseudo-second-order kinetic model, with the equilibrium time being influenced by the pore structure of the adsorbent.

To identify the ENR adsorption mechanism, the experimental data were analyzed using the pseudo-first order (PFO), pseudo-second order (PSO), and Weber–Morris intraparticle diffusion (IPD) models. The results in Tables 5b and 5c

show that the PSO model provided the best fit with an R^2 value of 0.9811 and a calculated qe value (0.1982 mg/g) close to the experimental qe (0.1837 mg/g), while the PFO model produced a lower R^2 (0.8840). These results indicate that the PSO model best describes the ENR adsorption kinetics, indicating chemisorption as the rate-controlling mechanism through electrostatic interactions, ligand exchange, and π–π interactions between ENR and the active sites of hydrochar. These findings are in line with Ajala & Akinnawo (2023) and Esteves et al (2023), who reported that the adsorption of quinolone antibiotics on carbon materials generally follows the PSO model with an R^2 value approaching 1.

Table 7 Fitting results of PFO and PSO kinetic models

Parameter	PFO	PSO
qe calculation (mg/g)	0.2017	0.1982
qe experiment	0.1837	0.1837
k	0.009861 min-1	0.1592 g/(mg.min)
h (mg/(g.min))	-	0.006254
R2	0.8840	0.9811

Table 8 Fitting results of the Weber-Morris intraparticle diffusion (IPD) model

Parameter	Phase 1 (5-20 minutes)	Phase
Kid (mg/(g.min0.5))	0.02609	0.00777
C (intercept)	-0.03722	0.06787
R2	0.8722	0.9564

Information:

PFO = pseudo-first order;

PSO = pseudo-second order;

IPD = intraparticle diffusion;

qe = equilibrium adsorption capacity;

k = adsorption rate constant;

h = initial adsorption rate;

kid = intraparticle diffusion rate constant;

C = intercept which reflects the boundary layer thickness.

The IPD model analysis showed two stages of adsorption, namely the fast stage at 5 to 20 minutes (kid1 = 0.02609 mg/(g·$min^{0.5}$)) which reflects adsorption on surface active sites, and a slow stage at 25 to 180 minutes (kid2 = 0.00777 mg/(g·$min^{0.5}$)) which shows the diffusion of ENR into the hydrochar pores. The intercept value is non-zero at both stages (C1 =-0.037; C2 = 0.068) indicates that intraparticle diffusion is not the sole controlling mechanism, but occurs simultaneously with film diffusion

and surface reactions. These results are in line with Rangasamy et al.(2026), who reported a similar mechanism in adsorption using industrial sludge-based hydrochar.

Effect of Water Matrix on Enrofloxacin Adsorption

Table 9 Water matrix removal results

Time	Aquades	PDAM	river
10	10%	-1%	11%
20	13%	5%	12%
30	16%	6%	13%
40	22%	9%	13%
50	25%	16%	19%
60	28%	25%	21%

Table10 Ct/C0 watermatrix results

Time	Aquades	PDAM	River
0	1	1	1
10	0.898209	1.005672	0.886269
20	0.865373	0.94597	0.880299
30	0.841493	0.942985	0.874328
40	0.784776	0.910149	0.871343
50	0.754925	0.844478	0.814627
60	0.719104	0.754925	0.793731

The data in Table 3 shows that the type of water matrix affects the effectiveness of ENR removal by teak sawdust hydrochar. At the 60th minute, the highest removal efficiency was obtained in distilled water with an R of 28% (Ct/C0 = 0.719), followed by PDAM water at 25% (Ct/C0 = 0.755), and river water at 21% (Ct/C0 = 0.794). These results indicate that the more complex the water matrix, the lower the ENR adsorption efficiency. At the 10th minute, PDAM water showed a Ct/C0 value of 1.006, indicating possible initial interference from water components on the hydrochar surface. However, the Ct/C0 values in all matrices continued to decrease until the 60th minute, with the largest decrease occurring in distilled water, indicating that adsorption took place most efficiently without interference from competing matrix components, as shown in Figure 6. Based on these results, distilled water was selected as the matrix with the best adsorption conditions in this study.

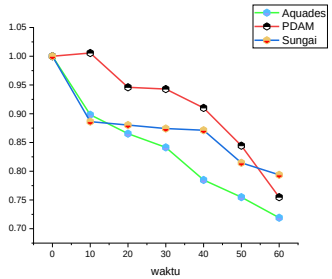

Figure 6. Watermatrix graph

The difference in adsorption efficiency between matrices is thought to be caused by the presence of natural organic matter (NOM), dissolved inorganic ions, and suspended particles in PDAM water and river water that are not present in distilled water. These components compete with ENR molecules for hydrochar active sites, thus reducing adsorption capacity. In PDAM water, residual chlorine, calcium, magnesium, and dissolved organic compounds also affect efficiency, while the greater decrease in river water indicates the influence of higher matrix complexity. These results are in line with Li et al.(2022)AndWu et al(2022),which stated that NOM, which reported that NOM can inhibit antibiotic adsorption through pore blockage and competition at the active site.

The decrease in adsorption effectiveness in river water is also thought to be influenced by the high ionic strength due to the presence of ions such as Ca^{2+}, Mg^{2+}, Na^{+}, and Cl^{-}. Multivalent cations can compete with ENR molecules to bind to negatively charged sites on the hydrochar surface, thereby reducing the adsorption capacity. This finding is in accordance withAjala & Akinnawo (2023)and Liu et al.(2022),which states that ions in natural water reduce the adsorption efficiency of antibiotics due to competition at the active site. The slower decrease in Ct/C0 in river water compared to distilled water for 10–60 minutes indicates a greater mass transfer barrier in the complex water matrix. Organic and inorganic components are thought to inhibit the diffusion of ENR towards the hydrochar active sites. Nevertheless, the continuously decreasing Ct/C0 values across all matrices indicate that teak sawdust hydrochar still has the potential to adsorb ENR under real water conditions, although with lower efficiency than distilled water. Therefore, its application to PDAM water and river water is still possible, but requires dosage optimization or adsorbent surface modification to reduce the influence of the water matrix.

Characterization of Functional Groups of Teak Sawdust Hydrochar Using Infrared Spectroscopy (FTIR)

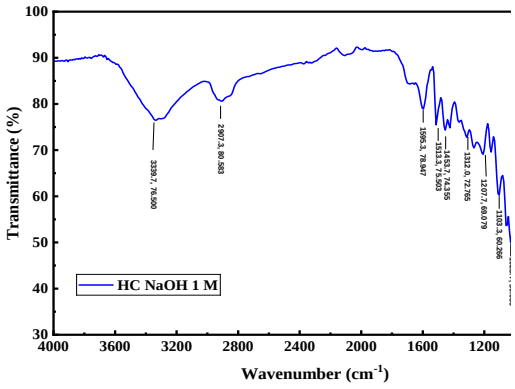

Figure 7. Characterization results FTIR

FTIR analysis of teak sawdust hydrochar showed ten absorption peaks in the range of 820–3340 cm^{-1}. Peak at 3339.7 cm^{-1}(intensity 76,500) indicates O strain–H from the hydroxyl group (-OH) associated with cellulose and hemicellulose that remains after the hydrothermal carbonization (HTC) process. This characteristic is in line withHossain et al. (2025),which reports the O–H band at around 3309 $cm^{-1}$and C–H approximately 2928 cm^{-1}as a characteristic of lignocellulosic material, as well asJesus et al (2024),which also identified the O–H band around 3400 $cm^{-1}$and C–H around 2900 cm^{-1}. The intensity and width of the bands reflect the presence of intermolecular hydrogen bonds.

Peak at 1595.3 cm^{-1}(intensity 78.947) and 1513.3 cm^{-1}(75.503) shows aromatic C=C stretching originating from lignin and the carbon structure resulting from HTC, while the peak at 1453.7 cm^{-1}(74.355) shows the C bend–H from methylene and methyl groups. These aromatic groups play an important role in ENR adsorption through π–π interactions with the aromatic rings of ENR molecules. These characteristics are in accordance withNguyen et al (2025),which ties the ribbon to about 1590 $cm^{-1}$with aromatic C=C stretching in lignin, as well asChaudhary et al (2025),who reported the formation of condensed aromatic structures in teak seed-based hydrochar during the HTC process.

In the range of 1028.7–1312.0 cm^{-1}there are four peaks indicating C strain–O and C–O–C from alcohol, ether, and lignocellulose groups. Peaks at 1028.7 and 1103.3 cm^{-1}related to strain C–O and C–O–C from cellulose and lignin, while the peak is 1207.7 cm^{-1}shows the C strain–O–C is typical of lignin. These groups increase the hydrophilic nature of the hydrochar surface and provide active sites for hydrogen bond formation with ENR. Peak at 820.0 cm^{-1}indicates a C bend–The out-of-plane aromatic H confirms the presence of aromatic structures. Overall, the FTIR profiles indicate that the hydrochar possesses oxygenated functional groups (O–H, C–O, and C–O–C) as well as condensed aromatic structures that support adsorption mechanisms through hydrogen bonding, electrostatic interactions, and π–π interactions. These findings are in line with Ottah et al.(2022)who reported similar FTIR patterns on woody biomass-based hydrochars and attributed them to a multimode adsorption mechanism for aromatic organic compounds.

CONCLUSION

This study shows that teak sawdust hydrochar synthesized through hydrothermal carbonization (HTC) at 200°C for 10 hours has the potential as an environmentally friendly adsorbent for removing enrofloxacin (ENR) from aqueous

solutions. The optimum adsorption conditions were obtained at a particle size of 120 mesh, pH 7, initial ENR concentration of 5 mg/L, adsorbent dosage of 2 g, and contact time of 120–180 minutes. The adsorption efficiency was influenced by the water matrix, with the order of distilled water > PDAM water > river water due to the competition of natural organic matter and dissolved ions in real water. Kinetic analysis showed that the adsorption process followed a pseudo-second-order model (R^2 = 0.9811), which indicated a chemisorption mechanism involving intraparticle diffusion. FTIR characterization results confirmed the presence of aromatic O–H, C–H, C=C, and C–O/C–O–C functional groups that play a role in the formation of hydrogen bonds, electrostatic interactions, and π–π interactions during the adsorption process. Overall, teak sawdust hydrochar has good potential as an alternative adsorbent for ENR removal from water.

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