



Adsorption of Ciprofloxacin onto Lotus Stem-Derived Biochar: Effects of Solution pH, Temperature, and Coexisting Cations

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Abstract

The discharge of ciprofloxacin (CFX) into aquatic environments threatens ecosystem health. In this study, biochar derived from lotus stem (*Nelumbo nucifera*) was evaluated as a low-cost adsorbent for CFX removal from aqueous solution. The biochar was characterized by FESEM/EDX, N₂ adsorption-desorption isotherms, FTIR, and point of zero charge (pH_{pzc}). Batch sorption experiments examined the effects of solution pH (3, 7, and 10), temperature (20, 26, and 32 °C), and coexisting cations. The sorption kinetics were best described by a two-stage intraparticle diffusion model, and the equilibrium isotherms were fitted to the Langmuir model. The maximum adsorption capacity (Q_{max}) was 22.96 mmol kg⁻¹ at pH 7 and 26 °C. Solution pH influenced the sorption capacity, yet substantial sorption was maintained across the entire pH range studied. Thermodynamic analysis revealed an endothermic, entropy-driven, and spontaneous process at all temperatures. Divalent Ca²⁺ suppressed Q_{max} by 49.0% through competition with CFX for adsorption sites. The sorption process at pH 7 was facilitated by electrostatic attraction, hydrogen bonding, and π - π stacking interactions. Overall, unmodified lotus stem biochar proved to be a promising and cost-effective adsorbent for CFX removal from water.

Keywords:

ciprofloxacin; biochar; lotus stem; adsorption; coexisting cations; thermodynamic analysis

1. Introduction

Antibiotics have become ubiquitous aquatic pollutants owing to their increasing use in agriculture and medicine. As a large portion is excreted unmetabolized, antibiotics enter water bodies through hospital, pharmaceutical, and municipal wastewater streams [1,2]. Conventional biological treatments fail to mineralize the stable structures of antibiotics, leading to their persistent presence in the environment [3,4]. Consequently, sub-inhibitory concentrations exert sustained selective pressure on aquatic microbiomes, accelerating antimicrobial resistance (AMR), a critical

global health threat [5–7]. Effective post-treatment technologies are therefore urgently needed.

Ciprofloxacin (CFX; C₁₇H₁₈FN₃O₃; $M = 331.34$ g mol⁻¹), a widely prescribed broad-spectrum fluoroquinolone, is frequently detected in environmental waters at nanogram- to microgram-per-liter levels. CFX resists biodegradation because it targets bacterial DNA gyrase and topoisomerase IV. The environmental fate of CFX is governed by its amphoteric character ($pK_{a1} \approx 6.1$; $pK_{a2} \approx 8.7$), where pH-dependent speciation yields a large fraction of CFX⁺ at pH < 6.1, CFX[±] at pH 6.1–8.7, and CFX⁻ at pH > 8.7 [8]. This speciation significantly affects CFX

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interactions with adsorbent surfaces, an important consideration when designing removal systems.

Despite achieving high CFX removal rates, advanced oxidation and membrane technologies remain limited by prohibitively high capital costs and operational complexity. This limitation is especially relevant in resource-constrained settings in developing countries, where antibiotics are widely used and contribute significantly to pollution. Sorption using inexpensive solid sorbents therefore remains a feasible option from both economic and efficiency standpoints. Among various solid sorbents, biochar has emerged as a promising material for carbon sequestration and antibiotic removal; however, feedstock and pyrolysis conditions significantly influence its sorption characteristics. At moderate pyrolysis temperatures (e.g., 400 °C), biochar retains a substantial amount of oxygen-containing functional groups that act as active sites for hydrogen bonding and electrostatic interactions with polar adsorbates while also developing incipient aromatic domains capable of π - π electron donor-acceptor interactions [9–11].

Among various biomasses, lotus (*Nelumbo nucifera*) is abundant in Asia and serves as an important precursor for biochar production [12]. Lotus-derived biochar exhibits exceptional versatility in remediating diverse environmental contaminants, effectively eliminating heavy metals [13], adsorbing organic dyes such as methyl orange [14], capturing carbamate pesticides [15], and catalyzing heavy oil degradation [16]. However, no reports exist on using unmodified lotus stem biochar to remove CFX, despite its demonstrated effectiveness against a variety of other pollutants. Consequently, it remains unclear how factors in solution chemistry, such as pH and background cations, influence CFX sorption onto this material, particularly given that pH-modulated antibiotic speciation and biochar surface charge can alter removal pathways and binding affinity [10,17].

CFX adsorption has been investigated on pinewood biochar [11], chitosan/biochar composites [18], and surface-modified biochars [3,19,20], with widely varying capacities reported. Adsorption is known to be highly sensitive to CFX speciation [4], and divalent cations exhibit competitive electrostatic interactions and chelation with the carboxylate and amine groups of CFX [21,22]. No research to date, however, has examined these factors for unmodified lotus stem biochar.

Therefore, this study aimed to investigate the adsorption behavior of CFX onto biochar (BC) derived from *Nelumbo nucifera* stem petioles produced by slow pyrolysis at 400 °C. Sorption kinetics and equilibrium isotherms were evaluated at three pH levels (3, 7, 10), three temperatures (20, 26, 32 °C), and in the presence of coexisting

mono- and divalent cations (Na^+ and Ca^{2+}). Thermodynamic parameters were calculated using the Van't Hoff equation. This study represents the first systematic investigation of CFX adsorption by unmodified lotus stem biochar, integrating solution speciation and competitive ionic matrix effects within a unified mechanistic framework and contributing to the valorization of agricultural residues as cost-effective adsorbents for antibiotics.

2. Materials and Methods

2.1. Reagents and Materials

Ciprofloxacin (CFX; purity $\geq 98\%$, Acros Organics) was used as the target adsorbate without further purification. Stock solutions of 1000 mg L⁻¹ were prepared by dissolving CFX in doubly distilled water and stored at 4 °C in the dark. Working solutions were prepared daily by serial dilution. Sodium hydroxide (NaOH, AR grade, Xilong Chemical) and hydrochloric acid (HCl, AR grade, Xilong Chemical) were used to adjust the pH. Sodium chloride (NaCl, AR, Xilong Chemical) and calcium chloride (CaCl_2 , AR, Xilong Chemical) were used in background ionic strength experiments. All solutions were prepared with doubly distilled water.

2.2. Preparation of Biochar

Lotus stems (*Nelumbo nucifera*) were collected from local ponds in the Mekong Delta region of Vietnam. The raw material was washed thoroughly with tap water, followed by doubly distilled water, to remove surface impurities; cut into small pieces (~3–5 cm); and oven-dried at 105 °C for 24 h. The dried biomass was placed in a muffle furnace (without N₂ gas protection) and pyrolyzed at 400 °C at a heating rate of 10 °C min⁻¹, then held at the target temperature for 2 h. Pyrolysis in a muffle furnace provides a simple, cost-effective approach for producing biochars with sorption performance comparable to biochars produced using tube furnaces and traditional kilns [23,24]. The resulting biochar was allowed to cool naturally to room temperature and was then ground and sieved. The product was washed until the solution reached a pH of 7 and subsequently stored in a desiccator until use.

2.3. Characterization of Biochar

The specific surface area (SSA), total pore volume, and average pore diameter of BC were determined by N₂ adsorption-desorption at 77 K using a surface area analyzer (Quantachrome NOVA 1000e, USA). Surface morphology and elemental composition were examined by field-emission scanning electron microscopy coupled with

energy-dispersive X-ray spectroscopy (FESEM/EDX; HITACHI S-4800, Japan; HORIBA EDX H-7593, UK). Surface functional groups were identified by Fourier-transform infrared spectroscopy (FTIR; PerkinElmer NIR/MIR Frontier) in the range 400–4000 cm^{-1} at 1 cm^{-1} resolution and 50 scans per spectrum. FTIR spectra were collected for both pristine biochar and samples recovered after CFX adsorption.

The point of zero charge (pH_{pzc}) was determined by the pH drift method [25]. A series of 25 mL aliquots of 0.1 M KCl solution was adjusted to initial pH values (pH^0) of 2–11 using 0.1 M NaOH and 0.1 M HCl. To each, 0.1 g of biochar was added, and suspensions were agitated at 120 rpm for 24 h at room temperature. Final pH (pH^f) was recorded after filtration, and ΔpH ($= \text{pH}^f - \text{pH}^0$) was plotted against pH^0 . The pH_{pzc} was identified as the intercept of the ΔpH versus pH^0 curve with the x-axis.

2.4. Adsorption Experiments

2.4.1. Sorption Kinetics

Adsorption kinetics were studied by preparing a CFX solution with an initial concentration of 16 mg L^{-1} in a 250 mL beaker. The solution pH was adjusted to 7 using 0.1 M NaOH and 0.1 M HCl solutions. Subsequently, 0.5 g of biochar was added to the beaker, and the mixture was stirred with a magnetic stirrer at 120 rpm at 26 $^{\circ}\text{C}$ (room temperature). The biochar dosage was fixed at 2.0 g L^{-1} [26]. Aliquots were withdrawn at predetermined time intervals from 0 to 1440 min, immediately filtered through 0.45 μm syringe filters, and analyzed by UV–Vis spectrophotometry (Jasco V-730, Japan). For aqueous solutions at pH 7, absorbance was measured at 271 nm [27] and quantified using the calibration equation ($R^2 = 0.9999$). Kinetic data were fitted to the nonlinear pseudo-first order (PFO), pseudo-second order (PSO), and two-stage intraparticle diffusion model (two-stage IPD) [28] (Equations (1)–(4)):

$$\text{PFO : } q_t = q_{\text{max}}(1 - e^{-k_1 t}) \quad (1)$$

$$\text{PSO : } q_t = (q_e^2 k_2 t) / (1 + q_e k_2 t) \quad (2)$$

$$\text{two-stage-IPD : } q_t = k_1^{\text{stage1}} t^{1/2} \quad 0 \leq t \leq t_1 \quad (3)$$

$$q_t - q_{t=t_1} = k_2^{\text{stage2}} (t - t_1)^{1/2} \quad t_1 < t \leq t_2 \quad (4)$$

where q_{max} and q_e (mmol kg^{-1}) are the sorption capacities of the PFO and PSO models, respectively.

q_t (mmol kg^{-1}) is the sorption capacity at time t ; k_1 (min^{-1}) and k_2 ($\text{kg mmol}^{-1} \text{min}^{-1}$) are the rate constants for PFO and PSO, respectively.

k_1^{stage1} and k_2^{stage2} ($\text{mmol kg}^{-1} \text{min}^{-1/2}$) are the rate constants of the two-stage IPD;

t_1 is the time required for quasi-equilibrium of solute concentrations to be reached.

Several criteria have been established to select the appropriate model, including the second-order Akaike Information Criterion (AIC_c), the Shapiro–Wilk test, the p -value, and Adjusted R-squared (Adj-R^2) [4].

2.4.2. Adsorption Isotherms

Equilibrium isotherm experiments were performed in centrifuge tubes containing 10 mL of CFX solution at initial concentrations of 12–80 mg L^{-1} . A 0.02-g portion of biochar was added, and the tubes were shaken at 26 $^{\circ}\text{C}$. Samples were agitated at 120 rpm in a temperature-controlled shaker at the target temperature until adsorption equilibrium was confirmed (≥ 8 h, based on kinetic results). After equilibration, suspensions were filtered through 0.45 μm syringe filters and analyzed by UV–Vis spectrophotometry. Equilibrium data were described by the nonlinear Langmuir isotherm (Equation (5)):

$$Q_e = (Q_{\text{max}} K_L C_e) / (1 + K_L C_e) \quad (5)$$

where Q_{max} (mmol kg^{-1}) is the maximum monolayer adsorption capacity, K_L (L mmol^{-1}) is the Langmuir affinity constant, and C_e (mmol L^{-1}) is the equilibrium liquid-phase concentration. The Freundlich model was also applied. Parameter estimation was performed by nonlinear least-squares regression.

2.4.3. Effect of Solution pH

To evaluate the effect of solution pH on adsorption capacity, isotherm experiments were conducted at pH 3, 7, and 10, following the general procedure described above. pH was adjusted using 0.1 M NaOH and 0.1 M HCl and verified with a calibrated pH meter (Hanna Instruments HI 2210, USA). Experiments were conducted at 26 $^{\circ}\text{C}$ in the temperature-controlled shaker. For aqueous solutions at pH 3 and 10, absorbance was measured at 277 nm and 272 nm, respectively [27].

2.4.4. Effect of Background Cations

The influence of coexisting cations on CFX adsorption was investigated by separately adding 1 mL of a 0.1 M

NaCl or CaCl₂ solution to each adsorption system, yielding final cation concentrations of 10 mM for monovalent (Na⁺) and divalent (Ca²⁺) species. Experiments were conducted at pH 7 and 26 °C. CFX concentrations were quantified using matrix-specific calibration curves at 270 nm for the Na⁺-containing solutions and 272 nm for the Ca²⁺-containing solutions. A control system without added cations was run in parallel under the same adsorption conditions and was quantified using the CFX calibration curve established at pH 7 (271 nm).

2.5. Thermodynamic Calculations

Thermodynamic parameters were derived from thermodynamic equilibrium constants obtained at three temperatures (20, 26, and 32 °C; pH 7) using the Van't Hoff equation (Equation (6)):

$$\ln K_c = -\Delta H^\circ / (RT) + \Delta S^\circ / R \quad (6)$$

where K_c (dimensionless) is the thermodynamic equilibrium constant obtained by converting the Langmuir K_L (L mmol⁻¹) to a dimensionless form, R is the universal gas constant (8.314 J mol⁻¹ K⁻¹), and T is the absolute temperature (K).

The estimated K_L (L mmol⁻¹) was converted to an approximate K_c value (Equation (7)) using the activity co-

efficient (γ_e) of the adsorbate and the molar concentration of the standard reference solution (C_s), which is equal to 1 mol L⁻¹.

$$K_c = (1000 K_L C_s) / \gamma_e \quad (7)$$

According to the Debye-Hückel law, the activity coefficient $\gamma_e \approx 1$ for neutral or weakly charged adsorbates and $K_c \approx 1000 K_L$.

The standard Gibbs free energy change (ΔG° , kJ mol⁻¹), standard enthalpy change (ΔH° , kJ mol⁻¹), and standard entropy change (ΔS° , J mol⁻¹ K⁻¹) were calculated at each temperature as (Equation (8)):

$$\Delta G^\circ = \Delta H^\circ - T \Delta S^\circ \quad (8)$$

3. Results and Discussion

3.1. Characterization of BC

As shown in Figure 1a, the SEM image revealed a mixed porous and compact surface morphology for biochar produced at a pyrolysis temperature of 400 °C. EDX analysis confirmed that carbon was the dominant element (Figure 1b), accounting for 87.65 ± 0.11 wt%, while oxygen accounted for 11.30 ± 0.11 wt% (Table 1).

Table 1: Selected physicochemical properties of the biochar.

Parameters	Units	
Pyrolysis temperatures	°C	400
Residence time	h	2
Heating rate	°C min ⁻¹	10
N ₂ gas protection	-	None
Biochar yield	%	29.92 ± 0.68
EDX and Surface Properties		
C using EDX	wt%	87.65 ± 0.11
O using EDX	wt%	11.30 ± 0.11
O/C ratio (mass ratio)	-	0.13
S using EDX	wt%	0.32 ± 0.02
Ca using EDX	wt%	0.73 ± 0.05
SSA using Langmuir	m ² g ⁻¹	53.175

The low O/C ratio (0.13) suggests significant removal of oxygen-containing functionalities during pyrolysis. Small amounts of sulfur (0.32 ± 0.02 wt%) and calcium (0.73 ± 0.05 wt%) were also detected. The O/C ratio of BC (0.13) is markedly lower than that of other biochars pyrolyzed at comparable moderate temperatures (300–500 °C with N₂ gas), including coconut shell biochar CN400 (O/C = 0.17) [28], corncob biochar CC400 (O/C

≈ 0.27) [29], and cassava peel biochar CP500 (O/C = 0.18) [4].

This suggests that lotus stem biomass undergoes more extensive thermal decomposition of oxygenated functionalities than conventional lignocellulosic and marine feedstocks, likely reflecting the hemicellulose-rich nature of aquatic macrophyte stems. The FTIR spectra further confirmed that pyrolysis significantly changed the surface chemistry (Figure 1c). In the raw biomass, a broad

and intense band centered at 3447 cm^{-1} was observed, which weakened and shifted to 3416 cm^{-1} in BC, indicating a reduction in hydroxyl-related structures during carbonization. The band at 1633 cm^{-1} in the raw lotus stem shifted to 1612 cm^{-1} after pyrolysis, suggesting structural reorganization of the carbon matrix and increased contributions from unsaturated or aromatic C=C vibrations. A more noticeable change was seen for the C–O-related band, which moved from 1108 cm^{-1} in the raw material to 1163 cm^{-1} in BC. This reflects modifications to oxygen-containing functionalities after thermal treatment.

As shown in Figure 1d, the N_2 adsorption-desorption data were further analyzed using the Langmuir equation to determine the surface area. The linear plot showed excellent linearity with $y = 65.50x + 13.69$ ($R^2 = 0.997$). The Langmuir surface area was estimated to be $53.175\text{ m}^2\text{ g}^{-1}$, indicating that the biochar possesses

a measurable accessible surface. The Langmuir-derived SSA is higher than that of other biochars pyrolyzed at 400°C , including coconut shell biochar ($4.06\text{ m}^2\text{ g}^{-1}$) [28], corncob ($4.8\text{ m}^2\text{ g}^{-1}$) [29], and *Sargassum polycystum* ($11.7\text{ m}^2\text{ g}^{-1}$) [30], and even exceeds that of cassava peel ($29.45\text{ m}^2\text{ g}^{-1}$) pyrolyzed at a higher temperature of 500°C [4]. The pH_{pzc} of the biochar was determined to be approximately 6.0 by the pH-drift method (Table 1). Overall, lotus biochar produced at moderate-temperature pyrolysis exhibited a carbon-rich composition with a low O/C ratio, and the Langmuir surface area indicated a moderately developed pore structure. FTIR analysis confirmed that pyrolysis reduced hydroxyl-related groups while promoting aromatic C=C and C–O groups. The coexistence of residual oxygen-containing functional groups and accessible porosity suggests that this biochar may support both surface-driven interactions and pore-filling mechanisms.

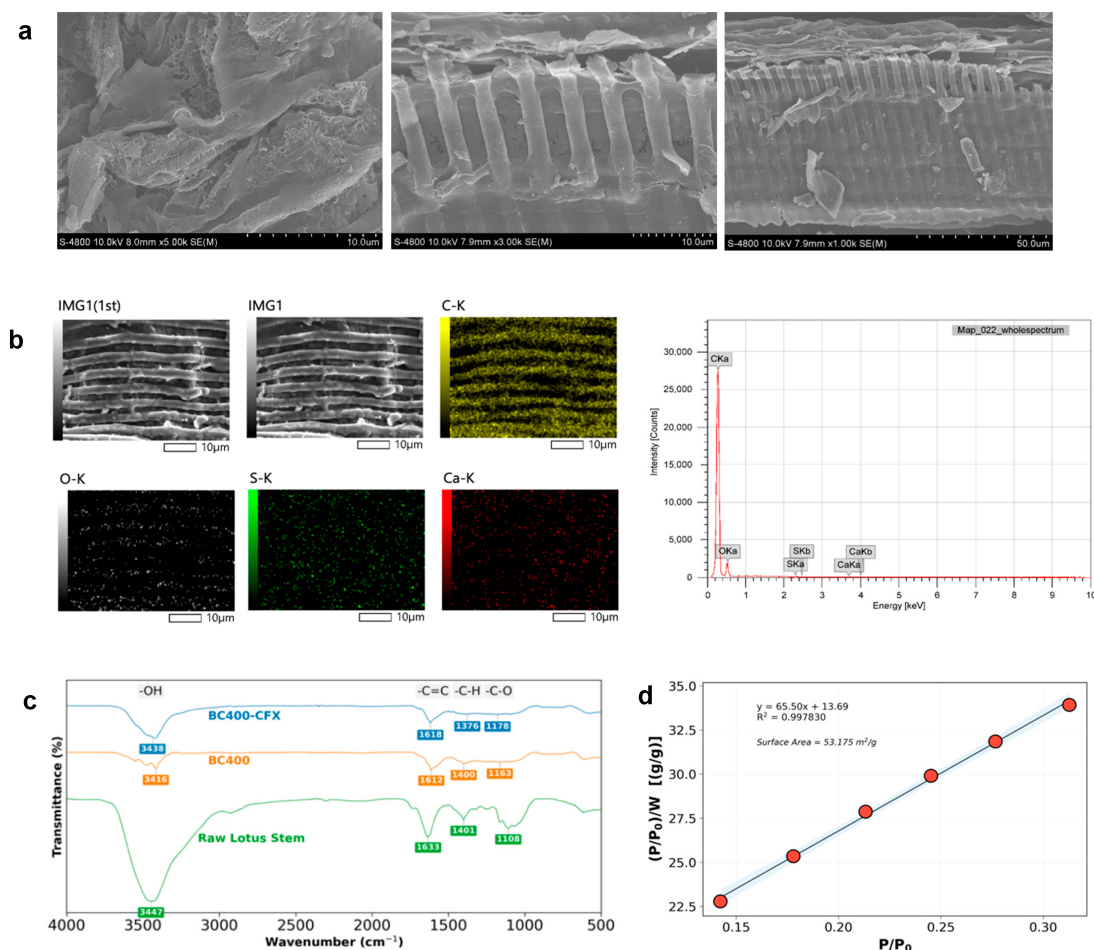


Figure 1: Physicochemical characterization of lotus stem-derived biochar: (a) FESEM images showing the surface morphology at different magnifications; (b) EDX elemental mapping and spectrum; (c) FTIR spectra of raw lotus stem, pristine biochar (BC400), and biochar after ciprofloxacin adsorption (BC400-CFX); and (d) Langmuir linear plot derived from N_2 adsorption-desorption data for determination of the specific surface area.

3.2. Sorption Kinetics at pH 7 and 26 °C

Table 2 presents the nonlinear kinetic fitting results for CFX sorption. The PSO model provided a better fit than the PFO model, with the higher adjusted coefficient of determination (Adj-R^2 : 0.904 vs. 0.738). However, the two-stage IPD model provided the best overall fit, with the highest Adj-R^2 (0.984) and the lowest AICc (−14.598). This suggests that CFX uptake did not proceed through a single kinetic step. The fitted IPD parameters showed a much faster first stage ($k_1 = 2.775 \pm 0.112 \text{ mmol kg}^{-1} \text{ min}^{-1/2}$) followed by a slower second stage ($k_2 = 0.117 \pm 0.010 \text{ mmol kg}^{-1} \text{ min}^{-1/2}$), with a transition time t_1 of 11 min. This pattern indicates a rapid initial uptake, likely associated with pore diffusion, followed by a slower diffusion-controlled stage.

3.3. Effect of pH on the Adsorption Isotherm

The adsorption isotherms of CFX were evaluated at pH 3, 7, and 10 to analyze the effect of solution pH (**Figure 2a**). The equilibrium data were fitted using both the Langmuir and Freundlich models, and the fitted parameters are summarized in **Table 3**. Both models described the data well, with Adj-R^2 values ranging from 0.874 to 0.986. The Freundlich model gave a slightly better fit at pH 3 and 10, whereas the Langmuir model performed better at pH 7 ($\text{Adj-R}^2 = 0.974$). The Langmuir maximum adsorption capacity, Q_{max} , varied with pH and followed the order pH 7 ($22.96 \text{ mmol kg}^{-1}$) $\approx$ pH 10 ($22.88 \text{ mmol kg}^{-1}$) > pH 3 ($20.70 \text{ mmol kg}^{-1}$); notably, BC maintained high CFX uptake across acidic, neutral, and alkaline conditions, a promising result for practical pollutant removal applications. At pH 7, lotus stem biochar exhibited a Q_{max} that exceeded the capacities reported for conventional biochar derived from agricultural waste such as groundnut shell (6.9 mmol kg^{-1}) [31], cassava peel ($10.5 \text{ mmol kg}^{-1}$) [4], and rice straw ($11.2 \text{ mmol kg}^{-1}$) [32].

According to **Table 3**, K_L was also highest at pH 7 ($65.16 \text{ L mmol}^{-1}$), suggesting stronger overall affinity at near-neutral pH. By contrast, the lower uptake at pH 3 can

be attributed to less favorable surface–solute interactions under acidic conditions, interpretable in relation to the pH-dependent speciation of CFX and the surface charge of BC. At pH 3, CFX is expected to occur mainly in its cationic form (CFX^+ , 99%), while the BC surface is also positively charged; under these conditions, electrostatic attraction is reduced. The adsorption capacity nonetheless remained substantial, suggesting that non-electrostatic interactions still contributed significantly. At pH 7, CFX is expected to be predominantly zwitterionic ($\text{CFX}^\pm$, 87.2%), a condition that may provide a more favorable balance between electrostatic effects and other interactions. FTIR analysis of BC after CFX sorption at pH 7 revealed shifts in the –OH stretching band ($3416 \rightarrow 3438 \text{ cm}^{-1}$), aromatic C=C vibration ($1612 \rightarrow 1618 \text{ cm}^{-1}$), and C–O stretching ($1163 \rightarrow 1178 \text{ cm}^{-1}$), accompanied by a reduction in overall peak intensity. This is attributed to hydrogen bonding, π – π interactions, and oxygen-containing functional groups in CFX sorption.

3.4. Effect of Temperature on Adsorption

Adsorption isotherm experiments were conducted at 20, 26, and 32 °C to investigate the thermal dependence of CFX uptake on BC (**Figure 2b**, **Table 3**). At constant pH 7, Q_{max} showed a non-monotonic response to temperature. Q_{max} increased from $19.75 \text{ mmol kg}^{-1}$ at 20 °C to $22.96 \text{ mmol kg}^{-1}$ at 26 °C, then decreased to $16.26 \text{ mmol kg}^{-1}$ at 32 °C. The initial increase from 20 to 26 °C is consistent with the endothermic characteristic of adsorption. The elevated temperature provides additional thermal energy to overcome activation barriers for surface site occupancy and intraparticle diffusion. The subsequent decline at 32 °C is attributed to the increasing desorption rate at higher thermal energy. The inverse trend between K_L and Q_{max} at 32 °C suggests that elevated temperature strengthened individual binding interactions, while simultaneously reducing the number of weak sorption sites. Across the tropical temperature range (20–32 °C), Q_{max} exhibited a moderate coefficient of variation of 17.1%, yet remained consistently above 16 mmol kg^{-1} under all conditions tested.

Table 2: PFO, PSO, and two-stage IPD kinetic parameters ($C_0 = 16 \text{ mg L}^{-1}$, pH 7, 26 °C).

Model	Parameter	Estimate	Std. Error	p-Value	Adj-R ²	AICc	Shapiro.p
PFO	q_e	11.090	0.499	0.000	0.738	45.112	0.801
	k_1	0.158	0.038	0.003			
PSO	q_e	11.770	0.350	0.000	0.904	34.033	0.693
	k_2	0.0187	0.004	0.001			
Two-Stage IPD	k_1 (Stage 1)	2.775	0.112	0.002	0.984	−14.598	0.323
	k_2 (Stage 2)	0.117	0.010	0.000			
	t_1	11					

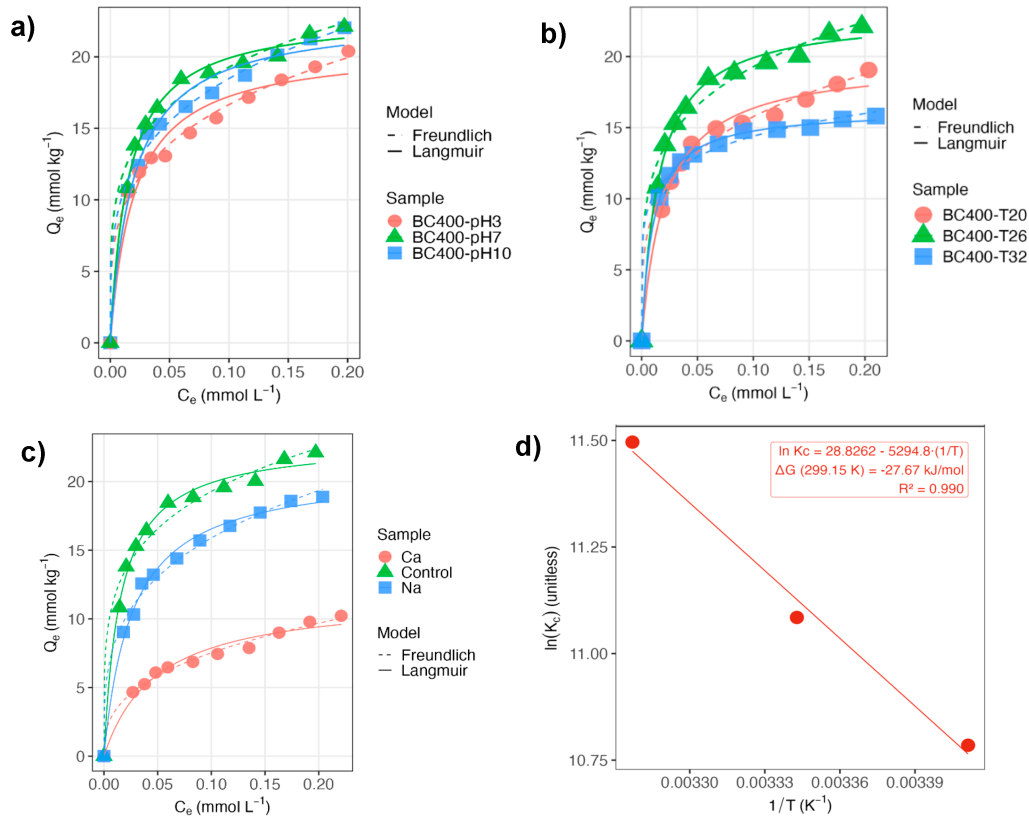


Figure 2: Langmuir and Freundlich isotherm models under varying solution pH (a); temperature (b), and ionic composition (c), and the van't Hoff plot (d).

Table 3: Isotherm parameters of the Langmuir and Freundlich isotherms under varying solution pH, temperature, and ionic composition.

Sample	Model	Parameter	Estimate	SD	p-Value	Adj-R ²	AICc	Shapiro-p
pH 3	Langmuir	Q_{max}	20.698	0.951	0.000	0.874	39.495	0.376
		K_L	49.578	9.693	0.001		39.495	0.376
	Freundlich	K_f	30.279	0.813	0.000	0.986	17.393	0.277
		n	3.852	0.161	0.000		17.393	0.277
pH 7	Langmuir	Q_{max}	22.962	0.418	0.000	0.974	25.197	0.375
		K_L	65.168	5.495	0.000		25.197	0.375
	Freundlich	K_f	31.934	1.651	0.000	0.938	33.885	0.688
		n	4.563	0.415	0.000		33.885	0.688
pH 10	Langmuir	Q_{max}	22.876	0.693	0.000	0.946	33.311	0.578
		K_L	50.966	6.475	0.000		33.311	0.578
	Freundlich	K_f	33.334	1.020	0.000	0.983	22.073	0.663
		n	3.902	0.185	0.000		22.073	0.663
T20	Langmuir	Q_{max}	19.749	0.517	0.000	0.958	27.026	0.900
		K_L	48.290	5.332	0.000		27.026	0.900
	Freundlich	K_f	27.983	1.269	0.000	0.958	26.824	0.977
		n	4.015	0.295	0.000		26.824	0.977
T26	Langmuir	Q_{max}	22.962	0.418	0.000	0.974	25.197	0.375
		K_L	65.168	5.495	0.000		25.197	0.375
	Freundlich	K_f	31.934	1.651	0.000	0.938	33.885	0.688
		n	4.563	0.415	0.000		33.885	0.688

Table 3: *Cont.*

Sample	Model	Parameter	Estimate	SD	p-Value	Adj-R ²	AICc	Shapiro-p
T32	Langmuir	Q_{max}	16.260	0.141	0.000	0.986	6.145	0.573
		K_L	98.331	5.357	0.000	0.986	6.145	0.573
	Freundlich	K_f	20.431	0.668	0.000	0.945	19.492	0.836
		n	6.573	0.547	0.000	0.945	19.492	0.836
Ca	Langmuir	Q_{max}	11.704	0.651	0.000	0.926	22.595	0.381
		K_L	20.526	3.459	0.000	0.926	22.595	0.381
	Freundlich	K_f	17.374	0.743	0.000	0.978	10.440	0.519
		n	2.751	0.146	0.000	0.978	10.440	0.519
Control	Langmuir	Q_{max}	22.962	0.418	0.000	0.974	25.197	0.375
		K_L	65.168	5.495	0.000	0.974	25.197	0.375
	Freundlich	K_f	31.934	1.651	0.000	0.938	33.885	0.688
		n	4.563	0.415	0.000	0.938	33.885	0.688
Na	Langmuir	Q_{max}	20.911	0.441	0.000	0.980	21.476	0.430
		K_L	37.896	3.002	0.000	0.980	21.476	0.430
	Freundlich	K_f	30.555	1.208	0.000	0.975	23.822	0.365
		n	3.520	0.201	0.000	0.975	23.822	0.365

^a The units are as follows: Q_{max} in mmol kg⁻¹, K_L in L mmol⁻¹, K_f in mmol¹⁻ⁿ Lⁿ kg⁻¹. K_f is the Freundlich affinity coefficient, and n is the heterogeneity factor (dimensionless).

3.5. Sorption Thermodynamics

Thermodynamic parameters derived from Van't Hoff analysis at pH 7 are presented in Table 4 and Figure 2d. Specifically, ΔG° ranged from -26.24 kJ mol⁻¹ (20 °C) to -29.11 kJ mol⁻¹ (32 °C). ΔG° was negative at all temperatures examined, confirming that CFX adsorption onto BC is spontaneous, and the increase in $|\Delta G^\circ|$ with temperature confirms that higher temperature enhances the thermodynamic driving force for sorption. The maximum adsorption capacity, however, increased from 20 to 26 °C and then decreased at 32 °C. This can be explained because ΔG° is governed by K_c [28–30], which varies with temperature, and its trend may not coincide with that of Q_{max} , which is instead influenced by specific interactions inherent to the heterogeneous surface [28–30]. Increased thermal energy, coupled with entropy gain, facilitates desorption, thereby reducing Q_{max} . Similar phenomena have been observed for other materials, such as micronized oil shale, ferrite-doped lignin biochar, hematite, and humic acid, used to adsorb antibiotics or other substances [33–36]. The standard enthalpy ΔH° was positive (+44.02 kJ mol⁻¹), establishing the endothermic nature of CFX adsorption onto BC. Endothermic adsorption arises when the thermal energy required to desorb water molecules from both the adsorbent surface (hydration sphere disruption) and the CFX hydration shell exceeds the enthalpy released upon CFX–surface bond formation. The ΔH° value of 44.02 kJ mol⁻¹ exceeds the typical physisorption threshold (<20 kJ mol⁻¹), indicating the involvement of stronger, chemically specific interactions in addition to physical forces, consistent with a

mixed physico-chemical adsorption mechanism involving simultaneous electrostatic, π – π stacking, and hydrogen-bonding interactions [9,19]. ΔS° was large and positive (+239.66 J mol⁻¹ K⁻¹); large positive ΔS° values are attributed to structural rearrangement at the solid–liquid interface. This large positive $T\Delta S^\circ$ term overcomes the energetic cost of $\Delta H^\circ > 0$, rendering $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$ negative and adsorption spontaneous.

3.6. Effect of Coexisting Cations

Figure 2c and Table 3 summarize the influence of background mono- and divalent cations on CFX adsorption at pH 7 and 26 °C. In the absence of added cations (control), Q_{max} was 22.96 mmol kg⁻¹. Addition of monovalent Na⁺ caused only modest reductions, to 20.91 mmol kg⁻¹, corresponding to a capacity decrease of ~9%, while K_L decreased by 42%. This suppression by Na⁺ suggests competitive adsorption at the surface sites of biochar; however, the minor effect observed is also attributable to ionic strength effects, since increased ionic strength compresses the electrical double layer around the biochar surface, partially screening the electrostatic attraction between the piperazinyl nitrogen of CFX[±] and negatively charged surface sites [21,22]. Our observed 9% capacity loss under higher Na⁺ concentrations is consistent with previous studies [37], which similarly report that higher electrolyte levels weaken the attraction between the negative surface of the adsorbent and the antibiotic's amino groups.

In sharp contrast, divalent cations caused severe and differentiated suppression of Q_{max} and K_L (Figure 3). In the presence of Ca²⁺, Q_{max} decreased by 49.0%, while K_L

decreased by up to ~68%. The overall inhibition order was Control > Na⁺ > Ca²⁺, consistent with competitive interactions reported for fluoroquinolone adsorption on carbonaceous materials [21,22]; divalent cations are known

to cause much stronger inhibition, as seen, for example, in bamboo biochar, where Ca²⁺ disrupted adsorption far more severely than Na⁺ [38].

Table 4: Thermodynamic parameters for CFX adsorption onto BC.

Temperature (K)	K_L (L.mmol ⁻¹)	ΔH^0 (kJ.mol ⁻¹)	ΔS^0 (J/mol.K)	ΔG^0 (kJ.mol ⁻¹)	Adj-R ²
293.15	48.29	44.021	239.661	-26.236	0.979
299.15	65.168			-27.674	
305.15	98.331			-29.112	

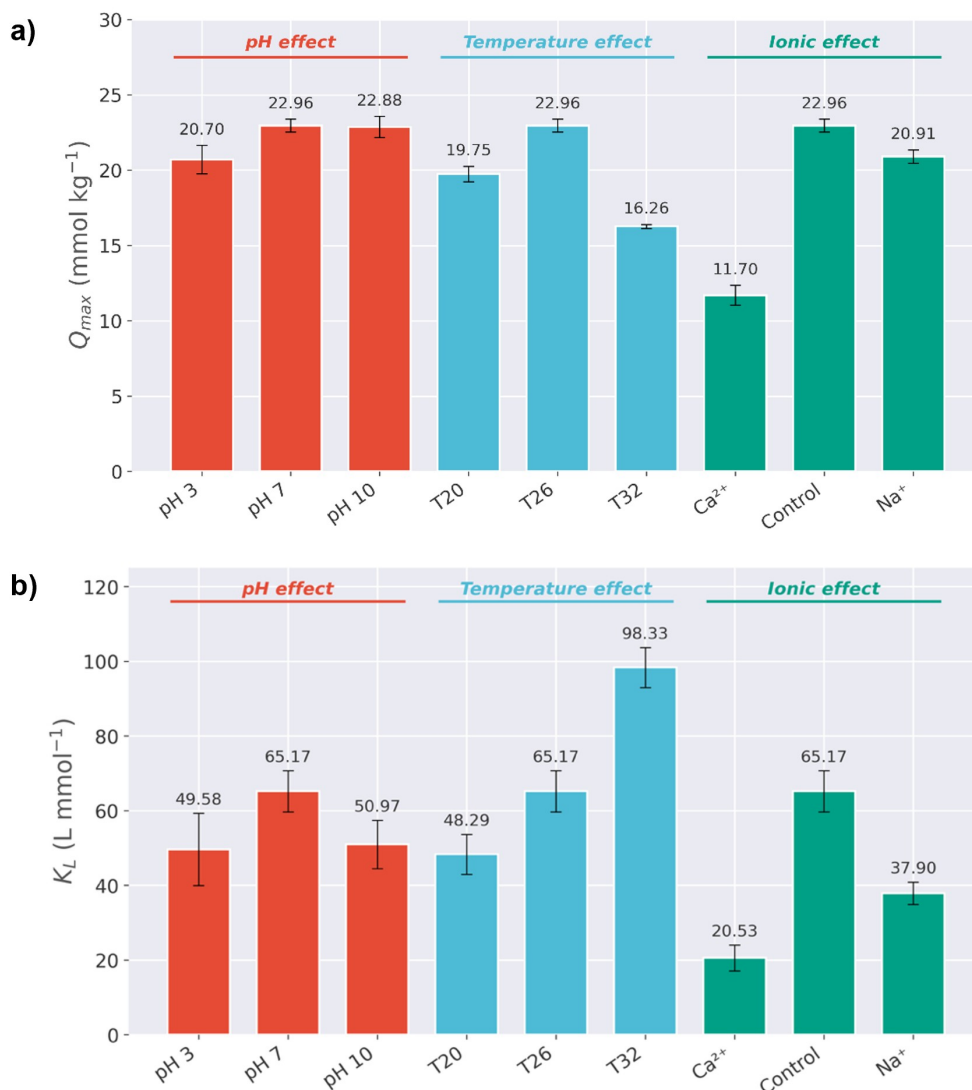


Figure 3: Comparison of Langmuir adsorption parameters under different experimental conditions: (a) maximum adsorption capacity (Q_{max}) and (b) Langmuir affinity constant (K_L) as affected by solution pH, temperature, and coexisting cations.

The strong inhibition by Ca^{2+} is attributable to the substantially larger hydration sphere (hydrated ionic radius $\sim 4.12 \text{ \AA}$ for Ca^{2+} vs. $3.6 \text{ \AA}$ for Na^+) and its stronger Lewis acid character, which confer two mechanistically distinct inhibitory pathways. First, Ca^{2+} can form stable bidentate chelates with the adjacent 3-carboxyl and 4-keto (oxo) groups on the quinolone core of CFX in solution [39,40], converting free CFX into poorly reactive Ca–CFX complexes and reducing the effective CFX concentration accessible to the adsorbent surface. Second, Ca^{2+} competes directly for the same –COOH and –OH surface sites on the biochar that would otherwise engage in electrostatic attraction and hydrogen bonding with CFX.

Because a divalent cation can occupy two adjacent functional sites simultaneously, its site-blocking efficiency is inherently greater than that of the monovalent Na^+ [41]. The stronger affinity of Ca^{2+} for both surface functional groups and CFX functional groups explains its greater inhibitory capacity compared with sodium ions (Na^+). Pretreatment to remove divalent cations or the use of biochar with a higher degree of aromatization, thereby reducing reliance on functional group-mediated mechanisms, may be necessary to maintain adequate performance under such conditions.

3.7. Proposed Sorption Mechanism

A mechanistic framework is proposed here, integrating evidence from biochar characterization, sorption kinetics, pH- and temperature-dependent isotherms, thermodynamic analysis, and ionic competition experiments. The carbon-rich composition (87.65 wt%) and the Langmuir surface area of $53.175 \text{ m}^2 \text{ g}^{-1}$ indicate a moderately developed pore structure. Sorption kinetics were rapid during the first stage of the IPD model ($k_1 = 2.775 \text{ mmol kg}^{-1} \text{ min}^{-1/2}$), corresponding to external surface adsorption and diffusion through macropores, indicating that CFX sorption onto lotus biochar (BC) is governed by surface-driven interactions.

Electrostatic attraction and hydrogen bonding are considered the dominant mechanisms for BC. At pH 7, the negatively charged BC surface ($\text{pH} > \text{pH}_{\text{pzc}} = 6.0$) attracts the positively charged piperazinyl nitrogen of zwitterionic $\text{CFX}^\pm$ ($\text{CFX}^\pm$, 87.2%) via Coulombic attraction. The Langmuir model yielded the highest Q_{max} ($22.96 \text{ mmol kg}^{-1}$) and K_L ($65.17 \text{ L mmol}^{-1}$). The FTIR shifts ob-

served after CFX sorption at pH 7—specifically the blue shift of the –OH band ($3416 \rightarrow 3438 \text{ cm}^{-1}$), the shift of the aromatic C=C vibration ($1612 \rightarrow 1618 \text{ cm}^{-1}$), and the displacement of the C–O stretching band ($1163 \rightarrow 1178 \text{ cm}^{-1}$)—collectively confirm the involvement of hydrogen bonding and π – π stacking. The positive ΔH° ($+44.02 \text{ kJ mol}^{-1}$) established the endothermic nature of CFX adsorption, indicating that energy is required to disrupt the hydration shells surrounding both the CFX molecules and the biochar surface.

The large positive ΔS° ($+239.66 \text{ J mol}^{-1} \text{ K}^{-1}$) compensated for this enthalpic cost, rendering the process spontaneous ($\Delta G^\circ < 0$) across all temperatures. Na^+ reduced Q_{max} by only 9% while divalent Ca^{2+} caused severe suppression of Q_{max} (49%). The stronger inhibition by Ca^{2+} compared to Na^+ confirms that functional-group-mediated interactions (electrostatic attraction and hydrogen bonding) constitute a significant fraction of the total adsorption capacity.

Table 5 compares the Q_{max} of lotus stem biochar for CFX removal against values reported for other lignocellulosic and marine-derived biochars. At neutral pH, lotus stem biochar exhibited a Q_{max} of $\sim 23.0 \text{ mmol kg}^{-1}$, exceeding the capacities reported for conventional agricultural-waste biochars such as corncob (1.2 mmol kg^{-1}) [42], macadamia nutshell (7.4 mmol kg^{-1}) [8], groundnut shell (6.9 mmol kg^{-1}) [31], cassava peel ($10.5 \text{ mmol kg}^{-1}$) [4], and rice straw ($11.2 \text{ mmol kg}^{-1}$) [32]. The Q_{max} of lotus stem biochar was also comparable to that of Cupuaçu bark AC (H_3PO_4 , 88%) ($18.2 \text{ mmol kg}^{-1}$) and KOH-modified rice straw biochar ($26.4 \text{ mmol kg}^{-1}$) [32], and it is noteworthy that the lotus stem biochar was produced without any chemical activation or metal impregnation. Even when benchmarked against brown-algae biochars, which are known for their abundant nitrogen- and oxygen-containing surface functionalities, lotus stem biochar outperformed the 400°C and 600°C seaweed biochars (11.4 – $15.2 \text{ mmol kg}^{-1}$) [30]. The robustness of BC across a wide pH window (Q_{max} of 20.6, 23.0, and $22.9 \text{ mmol kg}^{-1}$ at pH 3, 7, and 10, respectively) further differentiates it from most reported biochars. These comparisons are for reference only, given significant differences in experimental conditions such as temperature, particle size, and ion concentration. The purpose of this comparison is, therefore, only to demonstrate the potential of lotus stem biochar, and not to assert absolute superiority.

Table 5: Comparison of the Q_{max} of lotus stem biochar with various lignocellulosic and algal biochars reported in the literature.

No.	Biochar	Temp. Pyrolysis	Initial pH	Conc. Range (mg L ⁻¹)	Adsorbent Dose (g L ⁻¹)	Isotherm Model	Q_{max} (mmol kg ⁻¹) (Unit Conversion)	References
1	Rice straw biochar (B5)	500 °C	7	2–15	1.5	Langmuir	11.2	[32]
2	KOH-modified rice straw biochar (KB5)	500 °C	7	2–15	1.5	Langmuir	26.4	[32]
3	Corn cob	600 °C	7	0.1–1.2	1.08	Langmuir	1.2	[42]
4	Cassava peel (CP500)	500 °C	7	4–60	2.0	Langmuir	10.5	[4]
5	Cassava peel (CP700)	700 °C	7	4–60	2.0	Langmuir	11.6	[4]
6	Macadamia nutshell	600 °C	7	4–60	8	Langmuir	7.4	[8]
7	Brown algae (SW400)	400 °C	7	4–60	4	Langmuir	11.4	[30]
8	Brown algae (SW600)	600 °C	7	4–60	4	Langmuir	15.2	[30]
9	Groundnut shell (GNS500)	500 °C	7	5–30	0.8	Langmuir	6.9	[31]
10	Groundnut shell (GNS900)	900 °C	7	5–30	0.8	Langmuir	19.3	[31]
11	Wheat straw (WS)	700 °C	7	1–30	0.1–2.2	Langmuir	25.9	[43]
12	Cupuaçu bark AC (H ₃ PO ₄ , 88%)	600 °C	5.0	30–330	0.4–0.8	Langmuir	18.2	[44]
13	Lotus stem	400 °C	3	12–80	2.0	Langmuir	~20.6	This study
14	Lotus stem	400 °C	7	12–80	2.0	Langmuir	~23.0	This study
15	Lotus stem	400 °C	10	12–80	2.0	Langmuir	~22.9	This study

4. Conclusions

This study investigated the adsorption of CFX onto unmodified biochar derived from lotus stem pyrolyzed at 400 °C. Adsorption kinetics followed the Two-Stage IPD model, with $k_1 = 2.775 \pm 0.112 \text{ mmol kg}^{-1} \text{ min}^{-1/2}$, and the adsorption isotherms could be described by the Langmuir model, with Q_{max} reaching 22.96 mmol kg⁻¹ at pH 7 and 26 °C. Solution pH governed adsorption performance through the interplay of CFX speciation and biochar surface charge, and unmodified biochar adsorbed CFX across the entire studied pH range (3, 7, 10). The highest capacity, observed at pH 7, was attributed to electrostatic attraction, hydrogen bonding, and π - π electron donor-acceptor

interactions. Thermodynamic analysis revealed that CFX sorption onto BC is a spontaneous ($\Delta G^\circ < 0$), endothermic ($\Delta H^\circ = +44.02 \text{ kJ mol}^{-1}$), and entropy-driven ($\Delta S^\circ = +239.66 \text{ J mol}^{-1} \text{ K}^{-1}$) process. The presence of divalent Ca²⁺, however, suppressed Q_{max} through competitive sorption with CFX. Overall, unmodified lotus stem biochar stands out as an affordable adsorbent that performs effectively across a broad pH range (3–10) and under tropical conditions. Nonetheless, while Q_{max} is comparable across this range, the underlying interactions differ, and long-term stability at extreme pH warrants further study. These findings provide a sustainable pathway for valorizing lotus agricultural residues into biochar for the removal of antibiotics from water.

List of Abbreviations

AICc	Second-order Akaike Information Criterion
Adj-R ²	Adjusted Coefficient of Determination
AMR	Antimicrobial Resistance
BC	Biochar (lotus stem-derived biochar pyrolyzed at 400 °C)
CFX	Ciprofloxacin
EDX	Energy-Dispersive X-ray Spectroscopy
FESEM	Field-Emission Scanning Electron Microscopy
FTIR	Fourier-Transform Infrared Spectroscopy
IPD	Intraparticle Diffusion
PFO	Pseudo-First Order kinetic model
pH _{pzc}	Point of Zero Charge
PSO	Pseudo-Second Order kinetic model
SSA	Specific Surface Area
UV-Vis	Ultraviolet Visible spectrophotometry
ΔG°	Standard Gibbs free energy change
ΔH°	Standard enthalpy change
ΔS°	Standard entropy change

Author Contributions

Conceptualization, Writing—original draft, Writing—review & editing: P.D.T., L.Q.N.K.; Investigation, Formal analysis, Data curation, Writing—original draft, Writing—review & editing: V.N.L.U., V.D.H., D.T.M.K.; Methodology, Software, Visualization, Validation, Resources, Supervision, Project administration, Writing—original draft, Writing—review & editing: B.-T.D.; Writing—original draft, Writing—review & editing: N.L.T.Q., N.T.B., P.T.H. All authors have read and agreed to the published version of the manuscript.

Availability of Data and Materials

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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References

- [1] Chu, L.; Wang, J.; He, S.; Chen, C.; Wojnárovits, L.; Takács, E. Treatment of Pharmaceutical Wastewater by Ionizing Radiation: Removal of Antibiotics, Antimicrobial Resistance Genes and Antimicrobial Activity. *J. Hazard. Mater.* **2021**, *415*, 125724. [[CrossRef](#)]
- [2] Huang, A.; Yan, M.; Lin, J.; Xu, L.; Gong, H.; Gong, H. A Review of Processes for Removing Antibiotics from Breeding Wastewater. *Int. J. Environ. Res. Public Health* **2021**, *18*, 4909. [[CrossRef](#)]
- [3] Mahmud, F.; Banhi, T.S.; Roy, H.; Dihan, M.R.; Islam, M.S.; Cai, Y.; Asiri, A.M.; Rahman, M.M.; Hasan, M.M.; Shenashen, M.A.; et al. Antibiotic-Contaminated Wastewater Treatment and Remediation by Electrochemical Advanced Oxidation Processes (EAOPs). *Groundw. Sustain. Dev.* **2024**, *25*, 101181. [[CrossRef](#)]
- [4] Dang, B.-T.; Tran, C.H.B.; Pham, T.L.N.; Duong, N.H.N.; Do, T.-A.-S.; Nguyen, T.S.; Huynh, K.P.H. Hierarchical Factors Governing the Removal of Ionizable Pharmaceuticals by Cassava Peel-Derived Biochar: Bayesian Modeling and DFT Approaches. *Results Eng.* **2026**, *30*, 110528. [[CrossRef](#)]
- [5] Ghanadi, M.; Milke, M.; Larcher, S.; Mackey, H.R.; Bello-Mendoza, R. Critical Review of Antimicrobials, Antimicrobial Resistance, and Their Associated Genes in Decentralized Wastewater Treatment Systems. *J. Environ. Chem. Eng.* **2026**, *14*, 121039. [[CrossRef](#)]
- [6] The Lancet. Antimicrobial Resistance: An Agenda for All. *The Lancet* **2024**, *403*, 2349. [[CrossRef](#)]
- [7] Sambaza, S.S.; Naicker, N. Contribution of Wastewater to Antimicrobial Resistance: A Review Article. *J. Glob. Microb. Resist.* **2023**, *34*, 23–29. [[CrossRef](#)]
- [8] Le Na, P.T.; Tuyen, N.D.K.; Dang, B.-T. Sorption of Four Antibiotics onto Pristine Biochar Derived from Macadamia Nutshell. *Bioresour. Technol.* **2024**, *394*, 130281. [[CrossRef](#)]
- [9] Yang, Z.; Xing, R.; Zhou, W.; Zhu, L. Adsorption Characteristics of Ciprofloxacin onto g-MoS₂ Coated Biochar Nanocomposites. *Front. Environ. Sci. Eng.* **2020**, *14*, 41. [[CrossRef](#)]
- [10] Zhao, B.; O'Connor, D.; Zhang, J.; Peng, T.; Shen, Z.; Tsang, D.C.W.; Hou, D. Effect of Pyrolysis Temperature, Heating Rate, and Residence Time on Rape-seed Stem Derived Biochar. *J. Clean. Prod.* **2018**, *174*, 977–987. [[CrossRef](#)]
- [11] Xue, Y.; Guo, Y.; Zhang, X.; Kamali, M.; Aminabhavi, T.M.; Appels, L.; Dewil, R. Efficient Adsorptive Removal of Ciprofloxacin and Carbamazepine Using Modified Pinewood Biochar—A Ki-

- netic, Mechanistic Study. *Chem. Eng. J.* **2022**, 450, 137896. [CrossRef]
- [12] Pan, Y.; Han, G.; Mao, Z.; Zhang, Y.; Duan, H.; Huang, J.; Qu, L. Structural Characteristics and Physical Properties of Lotus Fibers Obtained from *Nelumbo nucifera* Petioles. *Carbohydr. Polym.* **2011**, 85, 188–195. [CrossRef]
- [13] Feng, Z.; Chen, N.; Feng, C.; Gao, Y. Mechanisms of Cr(VI) Removal by FeCl₃-Modified Lotus Stem-Based Biochar (FeCl₃@LS-BC) Using Mass-Balance and Functional Group Expressions. *Colloids Surf. A Physicochem. Eng. Asp.* **2018**, 551, 17–24. [CrossRef]
- [14] Hou, Y.; Liang, Y.; Hu, H.; Tao, Y.; Zhou, J.; Cai, J. Facile Preparation of Multi-Porous Biochar from Lotus Biomass for Methyl Orange Removal: Kinetics, Isotherms, and Regeneration Studies. *Bioresour. Technol.* **2021**, 329, 124877. [CrossRef]
- [15] Li, X.; Wang, Y.; Chen, C.; Tian, C.; Yu, X.; Liu, J.; Li, Q.; Wang, S. Sustainable Biochar Derived from Waste Lotus Seedpod for Efficient Adsorption of Residual Carbamate Pesticides. *Heliyon* **2025**, 11, e42741. [CrossRef]
- [16] Wang, Y.; Lin, R.; Zhang, L.; Han, X.; Li, J.; Huang, C.; Dong, Q.; Chen, P.; Li, H.; Wang, X. ZrO₂-MoO₃/Modified Lotus Stem Biochar Catalysts for Catalytic Aquathermolysis of Heavy Oil at Low-Temperature. *Fuel* **2024**, 357, 129597. [CrossRef]
- [17] Bui, T.X.; Choi, H. Adsorptive Removal of Selected Pharmaceuticals by Mesoporous Silica SBA-15. *J. Hazard. Mater.* **2009**, 168, 602–608. [CrossRef]
- [18] Afzal, M.Z.; Sun, X.-F.; Liu, J.; Song, C.; Wang, S.-G.; Javed, A. Enhancement of Ciprofloxacin Sorption on Chitosan/Biochar Hydrogel Beads. *Sci. Total Environ.* **2018**, 639, 560–569. [CrossRef]
- [19] Zhao, J.; Liang, G.; Zhang, X.; Cai, X.; Li, R.; Xie, X.; Wang, Z. Coating Magnetic Biochar with Humic Acid for High Efficient Removal of Fluoroquinolone Antibiotics in Water. *Sci. Total Environ.* **2019**, 688, 1205–1215. [CrossRef]
- [20] Bhatia, S.; Wang, Y.; Yu, J.; Li, C. Iron-Modified Biochar for Enhanced Removal of Ciprofloxacin and Amoxicillin in Wastewater. *Environ. Chem. Lett.* **2025**, 23, 27–32. [CrossRef]
- [21] Guan, X.; Guo, J.; Zhang, H.; Tao, S.; Mailhot, G.; Wu, F.; Xu, J. Effect of Co-Existing Cations and Anions on the Adsorption of Antibiotics on Iron-Containing Minerals. *Molecules* **2022**, 27, 8037. [CrossRef]
- [22] Wang, J.; Li, X.; Lan, Y.; Wang, H.; Ma, X.; Wang, H.; Xu, H.; Liu, H. Study on the Adsorption Mechanism of Ciprofloxacin in Wastewater by Modified Fly Ash under the Coexistence of Copper. *J. Environ. Chem. Eng.* **2024**, 12, 114336. [CrossRef]
- [23] Chen, J.; Liu, Y.; Liu, J.; Duan, Q.; Wang, Z.; Song, J.; Ji, C.; Sun, J. Effects of Carbonization on the Structure and Sorption Properties of Coffee Grounds for Pb(II) and Ni(II) in Various Metal Systems. *Desalin. Water Treat.* **2024**, 320, 100623. [CrossRef]
- [24] Kumar, N.V.; Sawargaonkar, G.L.; Rani, C.S.; Singh, A.; Prakash, T.R.; Triveni, S.; Kamdi, P.J.; Pasumarthi, R.; Karthik, R.; Venkatesh, B. Comparative Analysis of Pigeonpea Stalk Biochar Characteristics and Energy Use under Different Biochar Production Methods. *Sustainability* **2023**, 15, 14394. [CrossRef]
- [25] Gutierrez-Martinez, J.; Martinez-Vargas, D.R.; Vences-Alvarez, E.; Arjona-Jaime, P.; López-Cázares, M.I.; Rios-Saldaña, L.E.; Isaacs-Páez, E.D.; Quijano-Meza, M.; Rocha-Medina, C.; Rangel-Mendez, R. Point of Zero Charge, Isoelectric Point, and Potential of Zero Charge on Activated Carbons: A Comprehensive Interpretation about Their Interrelation. *Curr. Opin. Solid State Mater. Sci.* **2026**, 40, 101247. [CrossRef]
- [26] Zhang, L.; Ren, Y.; Xue, Y.; Cui, Z.; Wei, Q.; Han, C.; He, J. Preparation of Biochar by Mango Peel and Its Adsorption Characteristics of Cd(II) in Solution. *RSC Adv.* **2020**, 10, 35878–35888. [CrossRef]
- [27] Czyrski, A. The Spectrophotometric Determination of Lipophilicity and Dissociation Constants of Ciprofloxacin and Levofloxacin. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* **2022**, 265, 120343. [CrossRef]
- [28] Thao, N.T.P.; Le Na, P.T.; Huynh, K.P.H.; Dang, B.T. Comparison of Porous and Non-Porous Biochar for Trimethoprim Removal: Quantifying Uncertainty in Sorption and Thermodynamic Parameters over Different pH and Temperature. *Case Stud. Chem. Environ. Eng.* **2025**, 12, 101264. [CrossRef]
- [29] Le Na, P.T.; Quang, N.L.T.; Thao, N.T.P.; Chi, H.T.K.; Dang, B.T. Harnessing Corn-cob-Derived Materials for the Elimination of Sulfamethoxazole from Water. *Bioresour. Technol. Rep.* **2025**, 29, 102050. [CrossRef]
- [30] Thao, N.T.P.; Quang, N.L.T.; Le Na, P.T.; Dang, B.-T. Bayesian and Unsupervised Learning Insights into pH- and Temperature-Driven Sorption of Fluoroquinolones and Sulfonamides on Marine Algal Biochar. *Chemosphere* **2025**, 392, 144753. [CrossRef]
- [31] Alawa, B.; Singh, S.; Chakma, S.; Kishor, R.; Vinu, R.; Lundborg, C.S.; Diwan, V. Mechanistic Investigations on Sorption of Ciprofloxacin from Water Using Groundnut Shell Derived Biochar. *Results Eng.* **2026**, 29, 108812. [CrossRef]
- [32] Wang, H.; Wang, H.; Shahab, S.; Cheng, H.; Atroshko, M.; Wang, X.; Ye, M. Enhanced Adsorption of Ciprofloxacin by Biochar with Acid and Alkali Modification: Performance Comparison and Mechanism Analysis. *Results Chem.* **2025**, 17, 102603. [CrossRef]
- [33] Rauch, R.; Lukács, É.; Molnár, M. Adsorptive Removal of 2,4-Dichlorophenol from Aqueous Solution Using Micronized Oil Shale. *Adsorption* **2025**, 31, 11. [CrossRef]
- [34] Lin, H.; Qiu, S.; Wu, Z.; Ye, X.; Liu, M. Fabrication of Lignin-Based Biochar Containing Multi-Metal Ferrite and Efficient Removal for Oxytetracycline

- cline Hydrochloride. *J. Clean. Prod.* **2022**, *331*, 129885. [[CrossRef](#)]
- [35] Ferreiro, E.A.; de Bussetti, S.G. Thermodynamic Parameters of Adsorption of 1,10-Phenanthroline and 2,2'-Bipyridyl on Hematite, Kaolinite and Montmorillonites. *Colloids Surf. A Physicochem. Eng. Asp.* **2007**, *301*, 117–128. [[CrossRef](#)]
- [36] Liu, X.; Lu, S.; Liu, Y.; Meng, W.; Zheng, B. Adsorption of Sulfamethoxazole (SMZ) and Ciprofloxacin (CIP) by Humic Acid (HA): Characteristics and Mechanism. *RSC Adv.* **2017**, *7*, 50449–50458. [[CrossRef](#)]
- [37] Falyouna, O.; Maamoun, I.; Idham, M.F.; Eljamal, O. Effect of water matrix on ligand-assisted adsorption of ciprofloxacin from aqueous solutions by zerovalent iron nanoparticles. In Proceedings of the 8th International Exchange and Innovation Conference on Engineering and Sciences, Fukuoka, Japan, 20–21 October 2022; pp. 62–67. [[CrossRef](#)]
- [38] Peng, X.; Hu, F.; Lam, F.L.Y.; Wang, Y.; Liu, Z.; Dai, H. Adsorption Behavior and Mechanisms of Ciprofloxacin from Aqueous Solution by Ordered Mesoporous Carbon and Bamboo-Based Carbon. *J. Colloid Interface Sci.* **2015**, *460*, 349–360. [[CrossRef](#)]
- [39] Pitman, S.K.; Hoang, U.T.P.; Wi, C.H.; Alsheikh, M.; Hiner, D.A.; Percival, K.M. Revisiting Oral Fluoroquinolone and Multivalent Cation Drug-Drug Interactions: Are They Still Relevant? *Antibiotics* **2019**, *8*, 108. [[CrossRef](#)]
- [40] Walden, D.M.; Khotimchenko, M.; Hou, H.; Chakravarty, K.; Varshney, J. Effects of Magnesium, Calcium, and Aluminum Chelation on Fluoroquinolone Absorption Rate and Bioavailability: A Computational Study. *Pharmaceutics* **2021**, *13*, 594. [[CrossRef](#)]
- [41] Zeng, Z.W.; Tan, X.F.; Liu, Y.G.; Tian, S.R.; Zeng, G.M.; Jiang, L.H.; Liu, S.-B.; Li, J.; Liu, N.; Yin, Z.-H. Comprehensive Adsorption Studies of Doxycycline and Ciprofloxacin Antibiotics by Biochars Prepared at Different Temperatures. *Front. Chem.* **2018**, *6*, 80. [[CrossRef](#)]
- [42] Dang, B.-T.; Gotore, O.; Ramaraj, R.; Unpaprom, Y.; Whangchai, N.; Bui, X.-T.; Maseda, H.; Itayama, T. Sustainability and Application of Corncob-Derived Biochar for Removal of Fluoroquinolones. *Biomass Convers. Biorefin.* **2022**, *12*, 913–923. [[CrossRef](#)]
- [43] Alawa, B.; Singh, S.; Chakma, S.; Kishor, R.; Stålsby Lundborg, C.; Diwan, V. Development of Novel Biochar Adsorbent Using Agricultural Waste Biomass for Enhanced Removal of Ciprofloxacin from Water: Insights into the Isotherm, Kinetics, and Thermodynamic Analysis. *Chemosphere* **2025**, *375*, 144252. [[CrossRef](#)]
- [44] do Nascimento, R.A.; Novaes, N.d.R.d.O.; Morilla, D.P.; da Luz, P.T.S.; Costa, C.M.L.; de Faria, L.J.G. Removal of Ciprofloxacin and Norfloxacin from Aqueous Solution with Activated Carbon from Cupuaçu (*Theobroma grandiflorum*) Bark. *Molecules* **2024**, *29*, 5853. [[CrossRef](#)]

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