

Sugarcane Bagasse Biochar as a Sustainable Adsorbent for Cadmium Removal from Wastewater

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Received: 22 December 2025, Revised: 29 July 2026, Accepted: 29 September 2026, Published: 01 October 2026

KEY WORDS

Sugarcane Bagasse
Bbiochar
Fourier Transform Infrared Spectroscopy (FTIR)
Adsorption
Wastewater treatment
Isotherms
Cadmium

ABSTRACT

With rapid industrial expansion, effective wastewater treatment has become an urgent environmental priority. Industrial effluents contain diverse pollutants, including toxic heavy metals, organic and inorganic contaminants, and microplastics. Among these, cadmium (Cd) is a persistent, non-biodegradable heavy metal released through electroplating, mining, and agricultural activities, posing severe ecological and human health risks. This study evaluates the efficacy of chemically unmodified sugarcane bagasse biochar as a sustainable adsorbent for removing Cd from aqueous solutions. Sugarcane bagasse biochar was prepared via slow pyrolysis in a muffle furnace at 550 °C at Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, and surface functional groups were characterized before and after adsorption using Fourier Transform Infrared Spectroscopy (FTIR). Batch adsorption experiments evaluated the effects of solution pH (2–12), initial Cd concentration (5–100 mg/L), adsorbent dosage (0.5–3.0 g/L), and contact time (10–180 min) on Cd removal efficiency and adsorption capacity. Optimal removal was achieved at pH 10, an initial Cd concentration of 25 mg/L, an adsorbent dose of 3.0 g, and a contact time of 90 min, yielding removal efficiencies of 98.6% (at pH 10) and up to 99.8% (at a 3.0 g dose). Equilibrium data were modeled using the Langmuir and Freundlich isotherms; the Langmuir isotherm provided the best fit ($R^2 = 0.999$), confirming monolayer chemisorption on a homogeneous surface with a maximum adsorption capacity ($q_{\max}$) of 24.45 mg/g. Desorption experiments using 0.1 M CaCl₂ and 0.1 M HCl demonstrated that CaCl₂ achieved higher desorption efficiency (67.98% vs. 60.46% at 100 mg/L) due to the stronger competitive displacement of divalent Ca²⁺ ions compared with monovalent H⁺ ions. These findings demonstrate that unmodified sugarcane bagasse biochar is a low-cost, chemical-free, and sustainable adsorbent for cadmium remediation.

1. Introduction

Heavy metals such as mercury (Hg), copper (Cu), cadmium (Cd), and lead (Pb) are pervasive industrial pollutants that pose severe environmental and public health risks. These metals enter aquatic ecosystems through industrial discharges, including electroplating, nickel-cadmium battery manufacturing, phosphate fertilizers, pesticides, ore mining, plastics, pigments, and dyes [1], as well as urban stormwater runoff, tire wear, and corroding water distribution networks [2]. Among heavy metals, Cd is of particular concern due to its high mobility, bioaccumulation potential, and acute toxicity to human organs [3]. Consequently, the World Health Organization (WHO) and the United States Environ-

mental Protection Agency (EPA) restrict the maximum permissible concentration of Cd in drinking water to 0.003 mg/L. Over 90% of ingested Cd can be absorbed and retained in the human body, and Cd frequently accumulates in edible leafy vegetables, creating a direct dietary exposure pathway [4]. In addition to well-documented renal and skeletal damage, epidemiological studies link chronic Cd exposure to elevated cardiovascular disease (CVD) risk [5, 6]. Furthermore, because agricultural crops readily uptake Cd from contaminated irrigation water and soil, source-level treatment of Cd-bearing wastewater is critical to safeguard agricultural food webs [7].

Conventional physicochemical treatment methods for removing heavy metals from aqueous effluents include

membrane separation, ion exchange, chemical precipitation, coagulation–flocculation, reverse osmosis, and adsorption [8]. Among these techniques, adsorption is widely favored due to its operational simplicity, low cost, rapid kinetics, and versatility across diverse wastewater matrices. An effective adsorbent requires high sorption capacity, rapid uptake and desorption kinetics, and low regeneration energy [8].

Recent studies have explored both nanomaterial-based sorbents [9] and biochars derived from agricultural and organic residues—including rice husk, wheat straw, herbal medicine residues, magnetic biochar, corn stover, coconut husk, and lemonwood—for water decontamination [10–13]. Biochar is a carbon-rich, porous, and environmentally benign material produced from forestry, municipal, or agricultural biomass via thermochemical conversion processes such as slow pyrolysis, gasification, hydrothermal carbonization (HTC), and torrefaction [14].

Sugarcane bagasse, an abundant fibrous byproduct of the sugar industry, is a promising lignocellulosic precursor for both bioenergy (ethanol and high-calorific fuel briquettes with low ash content) and biochar production for environmental remediation [15, 16]. Engineered biochars modified with zeolites, alginate, or magnetic nanoparticles have shown strong affinity for divalent metal cations such as Cu^{2+} , Cd^{2+} , and Zn^{2+} , retaining high sorption capacity across multiple regeneration cycles [10]. Similarly, Inyang et al. [17] evaluated biochar derived from anaerobically digested sugarcane bagasse (DBC) against commercial activated carbon (AC) and unmodified bagasse biochar (BC) for Pb^{2+} removal, reporting a maximum Pb sorption capacity of 653.9 mmol/kg for DBC compared with 395.3 mmol/kg for AC and 31.3 mmol/kg for BC. More recently, Bakr et al. [18] demonstrated high Cd removal efficiency using $\text{Al}(\text{OH})_3$ -activated sugarcane bagasse biochar optimized via response surface methodology.

Although chemically modified sugarcane bagasse biochars have been widely studied, comparatively limited attention has been given to the cadmium sorption performance, surface mechanism, and desorption behavior of chemically unmodified, non-activated sugarcane bagasse biochar. Eliminating chemical activation reagents reduces both production cost and secondary chemical waste. Accordingly, this study investigates the batch adsorption behavior, functional-group interactions, equilibrium isotherm modeling, and chemical regeneration of unmodified sugarcane bagasse biochar produced at 550 °C. Specifically, batch experiments evaluate the effects of solution pH, contact time, adsorbent dosage, and initial Cd concentration, complemented by pre- and post-adsorption FTIR spectroscopy and Langmuir and Freundlich isotherm modeling.

2. Materials and Methodology

2.1 Chemicals, Materials, and Equipment

Analytical-grade reagents—including cadmium chloride (CdCl_2), sodium hydroxide (NaOH), hydrochloric acid (HCl), and calcium chloride (CaCl_2)—were obtained from the Department of Environmental Sciences, University of Gujrat, Pakistan. All glassware and apparatus were thoroughly rinsed with deionized (DI) water prior to use. Batch adsorption experiments were conducted in 250 mL Erlenmeyer flasks agitated on an orbital shaker. Solution pH was adjusted using 0.1 M HCl or 0.1 M NaOH and monitored with a digital pH meter (Mettler Toledo). Residual Cd concentrations in the supernatant were quantified via atomic absorption spectroscopy (AAS) against calibrated standard curves.

2.2 Preparation of Synthetic Cadmium Solutions

A 1,000 mg/L (ppm) stock solution of $\text{Cd}(\text{II})$ was prepared by dissolving analytical-grade CdCl_2 in deionized water. Working solutions with initial concentrations ranging from 5 to 100 mg/L were subsequently prepared by serial dilution of the stock solution.

2.3 Biochar Preparation and Characterization

Sugarcane bagasse biomass was washed, dried, and pyrolyzed in a muffle furnace at 550 °C at Pir Mehr Ali Shah Arid Agriculture University, Rawalpindi, to produce unmodified sugarcane bagasse biochar. Surface functional groups before and after Cd adsorption were characterized by Fourier Transform Infrared Spectroscopy (FTIR; PerkinElmer) over the wavenumber range of 400–4,000 cm^{-1} using the KBr pellet method at a spectral resolution of 0.4 cm^{-1} . Biochar pH was measured using a 1% (w/w) aqueous suspension in deionized water heated to approximately 90 °C in a water bath and stirred for 20 min prior to cooling and measurement.

2.4 Batch Adsorption and Isotherm Modeling

Batch sorption experiments were conducted in 250 mL conical flasks containing 25 mL of synthetic Cd solution (at a baseline concentration of 50 mg/L unless varied) agitated at 100 rpm on an orbital shaker. Operational parameters were systematically varied across solution pH (2, 4, 6, 8, 10, and 12), initial Cd concentration (5–100 mg/L), adsorbent dosage (0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 g/L), and contact time (10, 30, 60, 90, 120, and 180 min). Following agitation, suspensions were centrifuged at 1,000 rpm for 10 min, and the supernatant was analyzed for residual Cd.

Cadmium removal efficiency ($\%R$) and equilibrium adsorption capacity (q_e , mg/g) were calculated using Eqs. (1) and (2):

$$\%R = \frac{C_i - C_e}{C_i} \times 100 \quad (1)$$

$$q_e = \frac{(C_i - C_e) \times V}{m} \quad (2)$$

where C_i and C_e denote the initial and equilibrium Cd concentrations (mg/L), V is the solution volume (L), and m is the dry mass of biochar adsorbent (g).

To elucidate the sorption mechanism and surface homogeneity of the sugarcane bagasse biochar, equilibrium data were fitted to the Langmuir and Freundlich isotherm models (Table 1). The linear and nonlinear forms of the Langmuir isotherm and the dimensionless separation factor (R_L) are given by Eqs. (3)–(5):

$$\frac{1}{q_e} = \frac{1}{K_L q_{\max}} \cdot \frac{1}{C_e} + \frac{1}{q_{\max}} \quad (3)$$

$$q_e = \frac{q_{\max} K_L C_e}{1 + K_L C_e} \quad (4)$$

$$R_L = \frac{1}{1 + K_L C_e} \quad (5)$$

The linear and nonlinear forms of the Freundlich isotherm are given by Eqs. (6) and (7):

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \quad (6)$$

$$q_e = K_F C_e^{1/n} \quad (7)$$

2.5 Statistical Analysis

Isotherm regression modeling, goodness-of-fit evaluation (R^2), and graphical analyses of the batch experimental data were performed using Microsoft Excel.

3. Results and Discussion

3.1 FTIR Characterization

To evaluate functional-group modifications on the sugarcane bagasse biochar surface, FTIR spectra recorded before and after Cd adsorption were compared across the 400–4,000 cm^{-1} region (Fig. 1). In the pre-adsorption spectrum (Fig. 1a), a broad absorption band at 3,409.40 cm^{-1} corresponds to O–H and N–H stretching vibrations of surface hydroxyl and amine groups. The peaks at 2,920.76 cm^{-1} and 2,853.85 cm^{-1} are attributed to symmetric and asymmetric aliphatic C–H stretching in alkane chains [19], while the band at 2,338.43 cm^{-1} reflects $\text{C}\equiv\text{N}$ or $\text{C}\equiv\text{C}$ stretching of nitrile or alkyne moieties. The prominent peak at 1,589.14 cm^{-1} corresponds to aromatic C=C ring stretching formed during pyrolysis [20], and the band at 1,438.64 cm^{-1} arises from asymmetric C–H bending deformation in $-\text{CH}_3$ and $-\text{CH}_2$ groups [21]. The strong band at 1,091.91 cm^{-1} is assigned to C–O stretching vibrations of carboxylic and alcoholic groups [22], whereas the low-frequency bands at 614.89 cm^{-1} and 471.56 cm^{-1} correspond to C–Cl stretching and Si–O–Si or metal–oxygen bending vibrations, respectively.

Following Cd adsorption (Fig. 1b), distinct wavenumber shifts and intensity changes were observed across key functional bands. The hydroxyl O–H/N–H stretching peak shifted from 3,409.40 cm^{-1} to 3,391.42 cm^{-1} , while the aliphatic C–H stretching bands shifted slightly to 2,919.92 cm^{-1} and 2,852.39 cm^{-1} . Similarly, the triple-bond band shifted to 2,333.60 cm^{-1} and the aromatic C=C vibration shifted to 1,588.99 cm^{-1} . Notably, new bands appeared at 1,374.79 cm^{-1} (methyl C–H bending) and 1,245.70 cm^{-1} (C–O stretching) [23], confirming coordination between oxygenated surface groups and Cd^{2+} ions [24]. Additional bands at 876.73 cm^{-1} and 817.86 cm^{-1} reflect out-of-plane aromatic C–H bending perturbations [25]. Collectively, these spectral shifts confirm that hydroxyl, carboxyl, and aromatic functional groups actively coordinate Cd^{2+} via chemisorption and surface complexation [26].

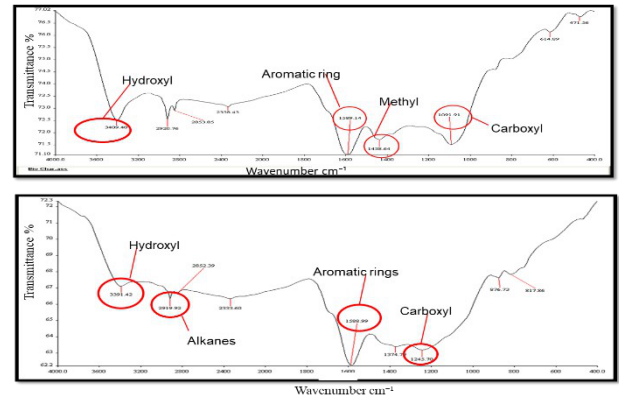


Fig. 1. FTIR spectra of sugarcane bagasse biochar: (a) before Cd adsorption and (b) after Cd adsorption

3.2 Biochar pH Analysis

Physicochemical evaluation indicated that the sugarcane bagasse biochar was moderately alkaline, with an aqueous suspension pH of 8.5. An alkaline surface environment promotes heavy-metal immobilization by deprotonating acidic oxygen-containing functional groups ($-\text{OH}$ and $-\text{COOH}$) and facilitating surface hydroxide precipitation [27]. Combined with the aromatic and oxygenated functional groups identified by FTIR, this inherent alkalinity makes unmodified sugarcane bagasse biochar well suited for aqueous Cd remediation.

3.3 Factors Affecting Cadmium Adsorption

3.3.1 Effect of Initial Cadmium Concentration

Initial metal concentration provides the driving force for overcoming mass-transfer resistance between the aqueous and solid phases. Batch trials were conducted across initial Cd concentrations of 5–100 mg/L at pH 8 (Fig. 2a). At a low initial concentration of 5 mg/L, Cd removal efficiency was 70.04% because the dilute metal ions interacted with only a fraction of the available sorption sites. As the initial concentration increased to 25 mg/L, removal efficiency rose sharply to 97.82% due to enhanced mass-transfer driving force and abundant active binding sites on the biochar surface. At higher concentrations (50 and 100 mg/L), removal efficiency

Table 1

Linear and nonlinear forms of adsorption isotherm models

Model	Linear Form	Nonlinear Form	Parameters
Langmuir	$\frac{1}{q_e} = \frac{1}{K_L q_{\max}} \cdot \frac{1}{C_e} + \frac{1}{q_{\max}}$	$q_e = \frac{q_{\max} K_L C_e}{1 + K_L C_e}$	$q_{\max}$ (mg/g), K_L (L/mg), R^2
Freundlich	$\log q_e = \log K_F + \frac{1}{n} \log C_e$	$q_e = K_F C_e^{1/n}$	K_F , $1/n$, R^2

plateaued at 97.74% and 97.08%, respectively, as metal ions competed for a finite number of surface attachment sites [28].

3.3.2 Effect of Solution pH

Solution pH governs both the surface charge of the biochar and the speciation of Cd in solution. The effect of pH on Cd removal was evaluated across pH 2, 4, 6, 8, 10, and 12 using an initial Cd concentration of 50 mg/L and an adsorbent dose of 0.5 g/L agitated at 100 rpm for 24 h (Fig. 2b). Under strongly acidic conditions (pH 2 and 4), removal efficiencies were relatively low (64.40% and 77.60%, respectively) because protonation of surface functional groups caused electrostatic repulsion and strong competition between H^+ and Cd^{2+} ions for active binding sites. As pH increased to the neutral-to-alkaline range (pH 6–10), surface deprotonation exposed negatively charged hydroxyl and carboxyl sites, increasing Cd removal to 97.00% at pH 6, 98.40% at pH 8, and a maximum of 98.60% at pH 10 [28,29]. At pH 12, sorption efficiency declined to 91.00% due to extensive precipitation of cadmium hydroxide, $Cd(OH)_2$, which passivates accessible pore surfaces [30].

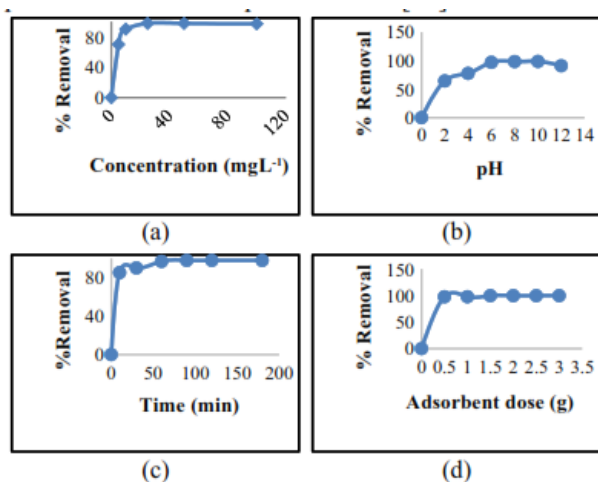


Fig. 2. Effect of operational parameters on Cd removal efficiency: (a) initial concentration, (b) pH, (c) contact time, and (d) adsorbent dosage

3.3.3 Effect of Contact Time

The effect of contact time on Cd removal was evaluated at 10, 30, 60, 90, 120, and 180 min at a constant initial Cd concentration of 50 mg/L (Fig. 2c). Within the first 10 min, the biochar achieved 85.40% Cd removal due to the abundance of vacant surface binding sites [28]. Removal efficiency increased to 90.26% at 30 min and 97.06% at 60 min, reflecting rapid initial uptake via physical adsorption and ion exchange. Peak removal efficiency was reached at 90 min (98.12%) and

remained virtually constant at 120 min (98.10%) and 180 min (98.06%), indicating that sorption equilibrium was established within 60–90 min as active surface sites became saturated [31].

3.3.4 Effect of Adsorbent Dosage

The influence of biochar dosage on Cd removal was investigated across dosages of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 g (Fig. 2d). Removal efficiency increased from 97.74% at 0.5 g and 97.80% at 1.0 g to 99.85% at 1.5 g and 99.80% at 3.0 g (reducing the residual Cd concentration to 0.1 mg/L). Higher adsorbent dosages provide a greater surface area and a larger number of hydroxyl and carboxyl binding sites; beyond 1.5–3.0 g, removal plateaued as the solution approached complete depletion and excess active sites remained unsaturated [28,32].

3.4 Adsorption Isotherm Modeling

Equilibrium sorption data for Cd onto sugarcane bagasse biochar were analyzed using the linear Langmuir and Freundlich isotherm models (Table 2 and Fig. 3). The Langmuir model—which assumes monolayer coverage over a homogeneous adsorbent surface with identical binding sites—exhibited an exceptional linear fit with a correlation coefficient of $R^2 = 0.999$ (Fig. 3a). From the Langmuir regression, the maximum monolayer adsorption capacity ($q_{\max}$) was determined to be 24.449 mg/g, with a Langmuir affinity constant (K_L) of 11.928 L/mg. The high correlation with the Langmuir model confirms that monolayer chemisorption is the dominant uptake mechanism [33]. The dimensionless separation factor ($R_L = 0.999$, falling within $0 < R_L < 1$) further confirms favorable adsorption under the studied conditions, where saturation of monolayer attachment sites prevents further uptake [31,34]. The Freundlich model, which describes multilayer sorption on heterogeneous surfaces, yielded a lower correlation coefficient of $R^2 = 0.952$ (Fig. 3b). Thus, while minor surface heterogeneity exists, monolayer sorption predominates, consistent with recent biochar sorption studies [35].

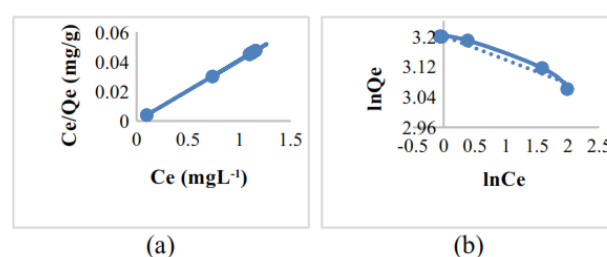


Fig. 3. Adsorption isotherm linear regressions for Cd uptake: (a) Langmuir isotherm and (b) Freundlich isotherm

Table 2

Linear isotherm model parameter values for Cd adsorption

Model	Parameter	Value (Cd)
Langmuir	$q_{\max}$ (mg/g)	24.449
Langmuir	K_L (L/mg)	11.928
Langmuir	R_L	0.999
Langmuir	R^2	0.999
Freundlich	K_F	1,588.071
Freundlich	$1/n$	-0.0629
Freundlich	R^2	0.952

3.4.1 Effect of Pyrolysis Conditions on Cadmium Adsorption

The sugarcane bagasse biochar evaluated in this study was produced at a slow pyrolysis temperature of 550 °C, a temperature widely reported to balance pore development with the retention of oxygen-containing functional groups for heavy-metal sorption [27]. Although only a single pyrolysis temperature was investigated here due to laboratory reactor constraints, biochar surface area, aromaticity, and functional-group density vary systematically with pyrolysis temperature; future studies across a broader temperature gradient will further optimize sorbent performance.

3.4.2 Proposed Adsorption Mechanism

Cadmium immobilization onto sugarcane bagasse biochar proceeds through a combination of surface complexation, ion exchange, electrostatic attraction, and surface precipitation. Pre- and post-adsorption FTIR spectra confirmed wavenumber shifts in hydroxyl (–OH), carboxyl (–COOH), and C–O stretching vibrations, demonstrating inner-sphere complexation with Cd^{2+} ions [24, 26]. At alkaline pH, deprotonation of these oxygenated groups increases negative surface charge density, strengthening electrostatic attraction toward divalent Cd^{2+} . Furthermore, the strong fit to the Langmuir isotherm ($R^2 = 0.999$) confirms uniform monolayer chemisorption, while the peak removal observed at pH 10 is additionally assisted by surface $\text{Cd}(\text{OH})_2$ precipitation.

3.4.3 Comparison with Previous Studies

Table 3 compares the maximum Cd adsorption capacity of unmodified sugarcane bagasse biochar (24.45 mg/g) with previously reported biochar adsorbents [10, 29, 33, 35]. Notably, the unmodified sugarcane bagasse biochar prepared in this study achieves a higher or comparable Cd sorption capacity relative to dairy manure biochar (17.5 mg/g) [33], wheat straw biochar (18.6 mg/g) [29], engineered magnetic biochar (22.8 mg/g) [10], and iron-enriched biochar (23.1 mg/g) [35]. These results confirm that unmodified sugarcane bagasse biochar provides high Cd uptake without requiring chemical activation, attributable to its porous pyrolytic carbon matrix and abundant oxygenated surface functional groups.

3.5 Desorption and Regeneration Study

Desorption of Cd from loaded sugarcane bagasse biochar was evaluated using 0.1 M calcium chloride (CaCl_2) and 0.1 M hydrochloric acid (HCl) at initial loading concentrations of 100 mg/L and 10 mg/L. As shown in Fig. 4, the mass of Cd desorbed using CaCl_2 was 3.066 mg/g at 100 mg/L and 1.291 mg/g at 10 mg/L, exceeding the desorption achieved using HCl (2.727 mg/g at 100 mg/L and 1.020 mg/g at 10 mg/L). Percentage desorption efficiency was calculated using Eq. (8):

$$\% \text{ Desorption} = \frac{\text{Amount of Cd desorbed}}{\text{Amount of Cd adsorbed}} \times 100 \quad (8)$$

Using 0.1 M CaCl_2 , Cd desorption efficiency reached 67.98% at 100 mg/L and 2.65% at 10 mg/L, whereas 0.1 M HCl yielded 60.46% desorption at 100 mg/L and 2.10% at 10 mg/L (Fig. 5). The superior desorbing performance of CaCl_2 compared with HCl is attributed to the higher charge density and stronger competitive ion-exchange displacement of divalent calcium cations (Ca^{2+}) relative to monovalent protons (H^+) on the biochar binding sites [3].

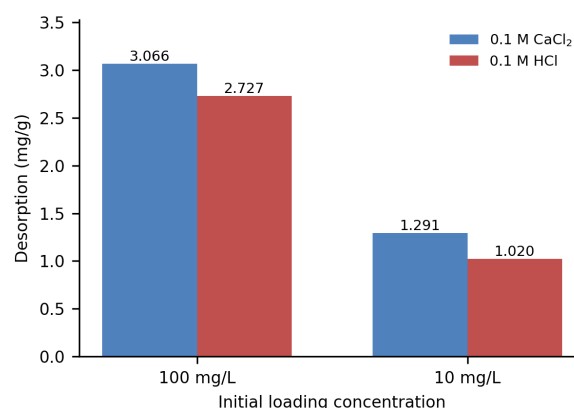


Fig. 4. Desorption of cadmium (mg/g) from sugarcane bagasse biochar using CaCl_2 and HCl

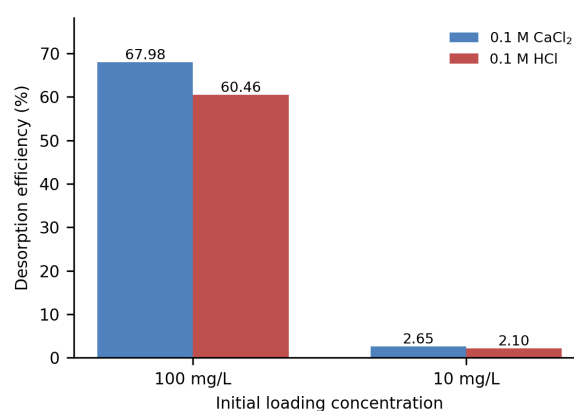


Fig. 5. Desorption efficiency (%) of cadmium from sugarcane bagasse biochar using CaCl_2 and HCl

Following regeneration and metal recovery, spent biochar with trace residual contaminant levels within regulatory thresholds may also be evaluated for secondary carbon sequestration or non-food soil condition-

Table 3

Comparison of sugarcane bagasse biochar with previously reported biochars for Cd adsorption

Sr. No.	Adsorbent	Feedstock	Heavy Metal	Adsorption Capacity (mg/g)	Reference
01	Dairy manure biochar	Dairy manure	Cd	17.5	Xu et al. [33]
02	Wheat straw biochar	Wheat straw	Cd	18.6	Naeem et al. [29]
03	Engineered magnetic biochar	Modified biochar	Cd	22.8	Azadian & Gilani [10]
04	Iron-enriched biochar	Iron-enriched biomass	Cd	23.1	Gameel et al. [35]
05	Sugarcane bagasse biochar	Sugarcane bagasse	Cd	24.45	Present study

ing applications in alignment with circular-economy principles.

4. Conclusion

This study demonstrated that chemically unmodified sugarcane bagasse biochar produced at 550 °C is a highly effective, low-cost adsorbent for removing toxic cadmium (Cd) from aqueous solutions. FTIR spectroscopy confirmed the presence of hydroxyl, aliphatic C–H, aromatic C=C, and carboxylic C–O functional groups that actively coordinate Cd²⁺ ions during sorption. Batch optimization showed that Cd removal reached 98.60% at pH 10, 97.82% at an initial Cd concentration of 25 mg/L, 98.12% at an equilibrium contact time of 90 min, and 99.80% at a 3.0 g adsorbent dose (reducing residual Cd to 0.1 mg/L). Equilibrium data conformed closely to the Langmuir isotherm ($R^2 = 0.999$), indicating homogeneous monolayer chemisorption with a maximum capacity ($q_{\max}$) of 24.45 mg/g, while 0.1 M CaCl₂ achieved 67.98% Cd desorption. Collectively, these results establish unmodified sugarcane bagasse biochar as a green, chemical-free, and scalable sorbent for heavy-metal wastewater remediation.

5. Limitations

The primary limitations of this study are as follows:

1. Batch sorption experiments were conducted using synthetic Cd solutions rather than complex multi-component industrial effluents.
2. Biochar production was evaluated at a single pyrolysis temperature (550 °C) rather than across a multi-temperature gradient.
3. Adsorbent regenerability was assessed over a single adsorption–desorption cycle.
4. Formal pseudo-first-order and pseudo-second-order kinetic modeling was not performed and should be addressed in future work.

Acknowledgments

The authors extend their gratitude to the University of Gujrat for providing laboratory facilities and technical support throughout this research.

Disclosure of Interest

The authors declare no competing financial or non-financial interests in relation to this work.

Author Contributions

Maham Nawaz: Investigation, Writing – original draft; Kiran Hina: Conceptualization, Supervision, Resources; Qaiser Hussain: Methodology, Formal analysis; Yousuf Jamal: Writing – review & editing, Project administration; Iram Gul: Data curation, Visualization.

Data Availability Statement

The datasets generated and analyzed during this study are available from the corresponding author (kiran.hina@uog.edu.pk) upon reasonable request.

Funding Source

This research received no external funding.

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