



Article

Removal of Copper and Zinc Using Biochar from Wild Sugarcane (*Saccharum spontaneum* L.): Sustainable Heavy Metal Removal from Aqueous Media

Joisleen Ramírez ^{1,2,3} , Josué Prens ^{2,4} , Zohre Kurt ^{5,6} and Arthur Mc Carty James ^{2,7,8,*}

¹ Doctorate Program in Biosciences and Biotechnology, Faculty of Sciences and Technology, Universidad Tecnológica de Panamá (UTP), Panama City 0819-07289, Panama; joisleen.ramirez@utp.ac.pa

² Research Group—Iniciativa de Integración de Tecnologías para el Desarrollo de Soluciones Ingenieriles (I2TEDSI), Universidad Tecnológica de Panamá, Panama City 0819-07289, Panama; josue.a.prens@gmail.com

³ Dipartimento Di Agraria, Università Degli Studi Di Napoli Federico II, 80055 Naples, Italy

⁴ Department of Hydraulics, Sanitary, and Environmental Sciences, Universidad Tecnológica de Panamá, Panama City 0819-07289, Panama

⁵ Energy Transition Center, Hanze University of Applied Science, 9747 AC Groningen, The Netherlands; z.g.kurt@pl.hanze.nl

⁶ Chemistry Department, Florida State University, Republic of Panama Campus, Panama City 0843-03081, Panama

⁷ Department of Mechanical Engineering, Universidad Tecnológica de Panamá, Panama City 0819-07289, Panama

⁸ Sistema Nacional de Investigación (SNI), Clayton, City of Knowledge Building 205, Panama City 0819-10280, Panama

* Correspondence: arthur.james@utp.ac.pa

Abstract

Water contamination by heavy metals is a major global concern resulting from anthropogenic activities and natural geological processes. Their removal and recovery are important for protecting water resources and addressing the depletion of critical metals. This study evaluated wild sugarcane (WSC) biochar as an adsorbent for Cu²⁺ and Zn²⁺ removal from aqueous media, providing a potential valorization pathway for this biomass. WSC biochars were produced at airflow rates of 8, 12, 16, and 20 L min^{−1} and characterized by Fourier-transform infrared spectroscopy, Raman spectroscopy, and X-ray diffraction. Cu²⁺ and Zn²⁺ adsorption data were analyzed using the Langmuir, Freundlich, and Temkin isotherm models. The characterization results indicated the presence of oxygen-, carbon-, and hydrogen-containing surface functional groups that may contribute to metal adsorption. Under the investigated batch conditions, BP12 achieved removal efficiencies of approximately 70–90% for Cu²⁺ and 83–94% for Zn²⁺. For BP12, the Langmuir expression yielded an apparent maximum Cu²⁺ adsorption capacity of 42.3 mg g^{−1}, while Zn²⁺ uptake reached 26.9 mg g^{−1} and was best described by the Freundlich expression among the models evaluated; the Langmuir model did not converge for Zn²⁺. These results demonstrate the potential of WSC biochar for Cu²⁺ and Zn²⁺ removal from aqueous media and support the valorization of wild-sugarcane biomass as a minimally processed adsorbent.

Keywords: *Saccharum spontaneum*; biochar; zinc; copper; adsorption; removal; heavy metals; Langmuir isotherms; Freundlich isotherms; Temkin isotherms



Academic Editors: Wei Du, Zhaofeng Chang and Yuanchen Chen

Received: 16 July 2026

Revised: 4 September 2026

Accepted: 14 September 2026

Published: 29 September 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](#)

[Attribution \(CC BY\)](#) license.

1. Introduction

One of the major challenges facing the world today is water stress resulting from the decline in available water resources, which can be caused by anthropogenic contamination [1]. A country's pollution level has been shown to be related to its degree of industrialization, strongly affecting the health of rural and urban communities alike [2]. Although many contaminants can be biologically degraded, heavy metals cannot be mineralized. Some of the most common heavy metals found in polluted areas include lead, copper, zinc, and cadmium [2].

Reports of pollution in drinking-water sources led this study to focus on zinc and copper removal. Both zinc (Zn) and copper (Cu) can originate from metallurgical and mining processes, while Zn can also be released as a waste product from galvanizing processes [3]. Although essential for life in small amounts, copper and zinc can bioaccumulate and enter the food chain. Because of their ability to bioaccumulate, the toxicity of heavy metals to living organisms can increase as they move through the food chain [4]. Zinc can have adverse effects on the nervous and gastrointestinal systems, while copper can cause gastrointestinal problems [5].

From a drinking-water perspective, the relevance of Cu and Zn removal should also be considered in relation to established water-quality guidelines. The World Health Organization recommends a health-based guideline value of 2 mg L^{-1} for Cu in drinking water. In contrast, no health-based guideline value has been established for Zn because the concentrations normally encountered in drinking water are generally not considered a health concern. Nevertheless, Zn concentrations above approximately 3 mg L^{-1} may reduce water acceptability by producing an astringent taste and opalescence [6]. These values provide a practical framework for assessing the removal of Cu(II) and Zn(II) from aqueous media.

Because of their potential biological hazards, processes such as reverse osmosis, precipitation, electrochemical removal, and adsorption have been proposed to remove Cu and Zn [5]. Adsorption has been proposed as a high-potential, low-cost method to remove these contaminants by retaining pollutants on the surface of the adsorbent [5]. The adsorption process can be employed with a wide range of materials, including nanomaterials. However, nanomaterials present disadvantages, such as agglomeration, high production costs and potential environmental risks [7], which has led to a search for alternatives. Biochar is presented as one of these alternatives because of its large surface area, which increases its adsorption capacity [8,9].

Biochar has been proposed as one of these alternatives. It is a carbonaceous material produced by the thermal decomposition of biomass. The structure of biochar varies depending on the biomass used and the production parameters, such as production temperature and method [10]. Biomass can be sourced from municipal, agricultural, or industrial wastes, which influence the properties of the resulting biochar. Because plant biomass has more volatile matter than animal biomass, plant-based biochars could exhibit a higher surface area but present fewer surface functional groups (SFGs). Functional groups are closely associated with adsorption, catalytic, and biodegradation mechanisms involved in contaminant removal [11]. Biochar can be produced at different temperatures, and the production temperature affects its physical and chemical properties. The surface area may increase with a temperature rise, but the hydrogen and oxygen SFGs tend to decrease [8].

The adsorption of dissolved heavy metals by biochar has been extensively investigated using materials derived from hardwood, crop residues, manure, sludge, and other lignocellulosic feedstocks [8,12–14]. In particular, Cu^{2+} and Zn^{2+} adsorption has been demonstrated using hardwood and corn-straw biochars, confirming that both feedstock composition and thermal conversion conditions strongly influence metal uptake [12,15].

The adsorption performance of biochar cannot therefore be generalized across different biomass sources. Feedstock composition and production conditions determine relevant physicochemical properties, including specific surface area, pore structure, mineral and ash composition, surface charge, ion-exchange capacity, and the abundance and nature of surface functional groups [8,13,14]. Accordingly, Cu^{2+} and Zn^{2+} removal may occur through different contributions from ion exchange, surface complexation with oxygen-containing functional groups, electrostatic interactions, physical adsorption, and mineral precipitation [8,13].

Despite the extensive investigation of biochar-based adsorption, several limitations remain. Conventional adsorbents such as activated carbon can provide high adsorption performance, but their production, activation, and regeneration may involve relatively high material and energy requirements [13,14]. Pristine biochar represents a renewable alternative, although its adsorption performance is highly heterogeneous and is strongly influenced by feedstock characteristics, thermochemical processing conditions, solution pH, ionic strength, initial metal concentration, and the presence of competing ions [8,13,14].

Surface modification and mineral or chemical functionalization can increase the number of available adsorption sites and improve affinity toward specific metal species. However, these treatments require additional reagents and processing steps that may reduce some of the economic and environmental advantages associated with unmodified biochar [13,14]. Furthermore, a substantial proportion of adsorption studies have been conducted under controlled batch conditions using synthetic aqueous solutions, and information regarding performance under complex water matrices and larger-scale operating conditions remains comparatively limited [8,14]. Consequently, the identification of minimally processed biochars with adequate adsorption performance remains relevant for the development of practical metal-removal technologies.

In this context, the valorization of unconventional lignocellulosic biomass as biochar feedstock represents an opportunity to produce adsorbent materials from locally available resources. *Saccharum spontaneum* is an herbaceous plant native to Asia that, due to its rapid and aggressive propagation, has become established in several countries, including France, Costa Rica, and Panama [16]. In Panama, it is commonly known as canal straw or wild sugarcane (WSC) and occupies approximately 3% of the Panama Canal Basin [16]. Given the challenges associated with the management and disposal of this biomass, alternative valorization strategies have been investigated. Previous studies have demonstrated that WSC can be successfully used as a feedstock for biochar production [1].

One of these processes used to produce biochar from lignocellulosic biomass is gasification. Several gasifier configurations can be employed for the thermochemical conversion of lignocellulosic biomass, among which the top-lit updraft (TLUD) gasifier is a relatively simple fixed-bed system. In this configuration, biomass is ignited at the top of the reactor, while a controlled upward airflow sustains the conversion process. Unlike conventional inert-atmosphere pyrolysis, TLUD operation uses limited air to sustain an autothermal conversion process and can simultaneously produce a carbonaceous solid and combustible gases. Its main advantages include relatively simple operation, low external energy requirements, and the possibility of controlling biochar properties through airflow conditions. However, the oxidative environment also represents a limitation because increasing airflow can intensify oxidation and gasification reactions, decrease biochar yield, and modify surface chemistry and pore development [17,18].

Previous studies have demonstrated the feasibility of producing wild sugarcane biochar using TLUD gasification and its potential as an adsorbent in aqueous systems. Prens et al. [1] produced *S. spontaneum* biochars at airflow rates ranging from 8 to 20 L min⁻¹ and evaluated their adsorption behavior toward atrazine. Subsequently, gasification-derived

wild sugarcane biochar was investigated for the removal of As(III) and malachite green from aqueous solutions [19]. These studies established the adsorptive potential of wild sugarcane biochar but did not systematically investigate Cu^{2+} and Zn^{2+} adsorption as a function of the airflow conditions applied during TLUD gasification. Therefore, a specific knowledge gap remains regarding the relationship between TLUD airflow rate, the resulting physicochemical characteristics of wild sugarcane biochar, and its adsorption behavior toward Cu^{2+} and Zn^{2+} .

The present study addresses this gap through the comparative evaluation of wild sugarcane biochars produced at 8, 12, 16, and 20 L min^{-1} , with an emphasis on the relationship between production conditions, physicochemical characteristics, and Cu^{2+} and Zn^{2+} adsorption performance. The objective of this study is to evaluate the removal of Cu^{2+} and Zn^{2+} from aqueous media using *S. spontaneum* biochar produced in a top-lit updraft gasifier (TLUD). Wild sugarcane biochars were generated at airflow rates of 8, 12, 16, and 20 L min^{-1} to determine how changes in airflow during gasification influence their physicochemical characteristics and adsorption performance.

The present study was designed to assess the Cu^{2+} and Zn^{2+} removal performance of TLUD-produced wild-sugarcane biochar under controlled batch conditions and to relate that performance cautiously to the pre-adsorption characteristics of the material. It was not designed to quantify the contributions of individual adsorption pathways. Consequently, the spectroscopic, diffraction, and model-fitting results are used to describe material properties and concentration-dependent uptake behavior rather than to provide direct proof of a molecular adsorption mechanism. Post-adsorption surface and phase characterization would be required to distinguish between surface complexation, ion exchange, electrostatic interaction, and mineral precipitation [12,20].

2. Materials and Methods

2.1. Materials and Reagents

Wild sugarcane (*Saccharum spontaneum* L.) biomass was used as a feedstock for biochar production. Copper(II) sulfate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) and zinc sulfate heptahydrate ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$) were used to prepare the Cu^{2+} and Zn^{2+} solutions, respectively. Deionized water was used for the preparation of all metal solutions.

2.2. Biomass Proximal Analysis and Characterization

The proximate analysis (see Table 1) showed that the WSC feedstock was primarily composed of volatile matter ($80.49 \pm 1.49\%$), followed by ash ($5.32 \pm 3.17\%$), fixed carbon ($4.72 \pm 1.62\%$), and moisture ($9.47 \pm 1.54\%$) [1]. These parameters are relevant because feedstock composition, together with thermochemical conversion conditions, influences the physicochemical characteristics of the resulting biochar, including its carbon content, mineral fraction, surface area, and pore development [15,21]. The biomass particle size ranged from 2 to 4.75 mm.

Table 1. Proximate analysis of *Saccharum spontaneum* L. feedstock. Data reported by Prens et al. [1].

Parameter	Unit	<i>S. spontaneum</i> Feedstock
Moisture	%	9.47 ± 1.54
Volatile Matter	%	80.49 ± 1.49
Fixed Carbon	%	4.72 ± 1.62
Ash	%	5.32 ± 3.17

2.3. Biochar Production

The methodology employed to produce WSC biochar was described in a previous study [17]. Briefly, the biochar was produced using a custom-built top-lit updraft TLUD gasifier fabricated at the Universidad Tecnológica de Panamá, Panama City, Panama. The TLUD reactor had dimensions of 1.52 m × 0.101 m. The experiment was conducted at airflow rates of 8, 12, 16, and 20 L min^{−1}. Air was used as the gasifying agent. The air was supplied using a Briggs & Stratton air compressor (Briggs & Stratton, Wauwatosa, WI, USA), while the airflow was controlled with a Bel-Art Riteflow flowmeter (Bel-Art Products, Wayne, NJ, USA). After igniting the biomass at the top of the reactor, the temperature was monitored using three K-type thermocouples (KMQIN-125U-4, OMEGA Engineering, Inc., Norwalk, CT, USA), shown in Figure 1 as TC-1, TC-2, and TC-3. Temperature data were recorded on an Onset HOBO UX120 (Onset Computer Corporation, Bourne, MA, USA) data logger (see Table 2). At the end of the carbonization process, the biochar was left to cool and stored for later use.

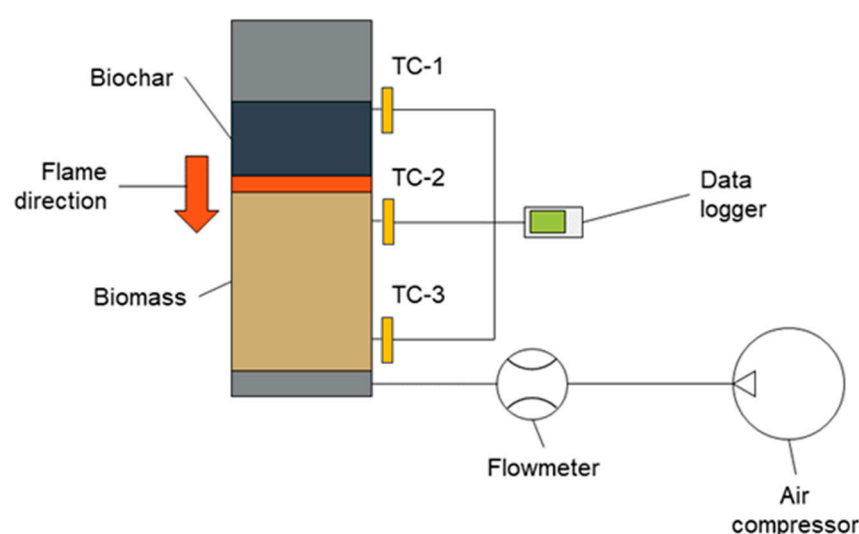


Figure 1. Gasification diagram of wild sugarcane biochar. The orange arrow indicates the downward propagation of the flame front, while the triangle within the air-compressor symbol indicates the compressed-air outlet toward the flowmeter and the TLUD reactor.

Table 2. Average and maximum temperatures, biochar yield, and surface area obtained during the carbonization of wild sugarcane.

Biochar	Airflow (lpm)	Average Temperature (°C)	Maximum Temperature (°C)	Biochar Yield (%)	Surface Area (m ² /g)
BP8	8	369.4	556.7	27.59 ± 1.88	3.11
BP12	12	406.3	589.3	26.18 ± 3.90	3.50
BP16	16	395.5	597.6	26.71 ± 1.24	4.86
BP20	20	441.7	642.0	22.96 ± 1.26	11.26

Biochar yield (see Table 2) varied according to the airflow rate applied during TLUD gasification. Mean biochar yields of 27.59 ± 1.88%, 26.18 ± 3.90%, 26.71 ± 1.24%, and 22.96 ± 1.26% were obtained at airflow rates of 8, 12, 16, and 20 L min^{−1}, respectively. Concurrently, the maximum gasification temperature increased from 556.70 °C at 8 L min^{−1} to 589.37, 597.65, and 642.04 °C at 12, 16, and 20 L min^{−1}, respectively. A strong inverse relationship was observed between maximum temperature and mean biochar yield ($R^2 = 0.901$), indicating that higher gasification temperatures were associated with lower

solid product recovery. This trend was particularly evident at 20 L min^{-1} , which resulted in the highest maximum temperature (642.04°C) and the lowest biochar yield ($22.96 \pm 1.26\%$). Higher gasification temperatures promote biomass devolatilization and the conversion of the solid carbonaceous fraction into gaseous and condensable products, thereby reducing biochar yield. Moreover, in TLUD gasification, increased airflow can intensify oxidation and gasification reactions, resulting in greater consumption of the carbonaceous solid phase. Similar behavior has been reported for TLUD systems, in which increasing airflow decreased biochar yield, while broader studies have also demonstrated an inverse relationship between conversion temperature and biochar yield [15,17].

The BET specific surface area increased from $3.11 \text{ m}^2 \text{ g}^{-1}$ for BP8 to $11.26 \text{ m}^2 \text{ g}^{-1}$ for BP20 as the maximum TLUD temperature increased. This trend indicates that the higher-airflow conditions increased the surface area accessible to nitrogen under the measurement conditions. Gas-physisorption analysis can provide complementary information on pore volume and pore-size distribution when the complete adsorption–desorption isotherm is available [17]. Because total pore volume and pore-size distribution were not determined for the present samples, the results do not establish how micro-, meso-, or macroporosity varied among BP8–BP20. The BET values are therefore interpreted as comparative textural descriptors and not as evidence that physical adsorption dominated Cu^{2+} or Zn^{2+} uptake.

2.4. Biochar Characterization

A Fourier Transform Infrared (FTIR) analysis of the feedstock and the biochar was performed using an Agilent Technologies Cary 600 spectrometer (Agilent Technologies, Santa Clara, CA, USA). The analyses were performed over a wavenumber range of 400 to 4500 cm^{-1} . Furthermore, a Raman spectroscopic analysis was conducted to determine the composition of the biochar. The Raman analysis was performed with a Thermo Raman DXR spectrophotometer (Thermo Fisher Scientific, Madison, WI, USA) featuring a laser with a wavelength of 532 nm . Peak deconvolution was performed using Fityk software (Fityk, version 1.3.1). X-ray diffraction (XRD) patterns were determined using a Rigaku Ultima III X-ray diffractometer (Rigaku Corporation, Akishima, Tokyo, Japan) with $\text{CuK}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$) and an angular region of $2\theta = 10\text{--}80^\circ$ and 0.05° step scanning [17].

2.5. Adsorption Experiments and Isotherms Modeling

Copper(II) sulfate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$; Supelco, Merck KGaA, Darmstadt, Germany) and zinc sulfate heptahydrate ($\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$; Supelco, Merck KGaA, Darmstadt, Germany) were used to prepare the Cu^{2+} and Zn^{2+} solutions, respectively. The corresponding salts were dissolved in 1.75 L of deionized water. Five initial metal concentrations, 1 , 5 , 10 , 20 , and 30 mg L^{-1} , were evaluated to investigate the adsorption behavior of Cu^{2+} and Zn^{2+} . All adsorption experiments were performed in triplicate to ensure experimental reproducibility and to assess the variability of the measurements. Cu^{2+} and Zn^{2+} adsorption experiments were conducted independently as single-solute systems. No binary Cu^{2+} and Zn^{2+} adsorption experiments were performed. For each batch adsorption experiment, 100 mL of metal solution was placed in a 200 mL polypropylene container, followed by the addition of 0.1 g of biochar. The suspensions were agitated at 300 rpm for a fixed contact time of 6 h . This contact period was selected as a conservative experimental condition based on previous biochar adsorption studies in which Cu^{2+} and Zn^{2+} uptake approached equilibrium within approximately $2\text{--}4 \text{ h}$, although the required contact time varied according to the physicochemical properties of the adsorbent [22–24]. Because independent kinetic experiments were not performed with the wild sugarcane biochars evaluated in this study, equilibrium attainment at 6 h could not be experimentally verified. Therefore,

the 6 h period should be interpreted as a standardized contact time used for comparison among treatments rather than an experimentally determined equilibrium time.

The pH was maintained within a narrow range of 6.3–6.5 to provide consistent experimental conditions among the adsorption treatments. Previous studies have demonstrated that solution pH significantly affects Cu^{2+} and Zn^{2+} adsorption by biochar through its influence on the protonation and deprotonation of surface functional groups, biochar surface charge, and aqueous metal speciation [22,23]. High adsorption of Cu(II) and Zn(II) has been reported within mildly acidic pH ranges, particularly around pH 5–6 [22,23]. However, because pH-dependent adsorption experiments were not conducted in the present study, the selected pH range should not be interpreted as an experimentally optimized condition. The influence of pH and associated changes in metal speciation were therefore considered limitations of the experimental design.

Following the 6 h contact period, the suspensions were gravity-filtered using cellulose filters with a pore size of 14–18 μm (Whatman International Ltd., Maidstone, UK). A second filtration step was subsequently performed using 0.45 μm nylon syringe filters. The final Cu^{2+} and Zn^{2+} concentrations were determined using a Shimadzu AA-7000 flame atomic absorption spectrophotometer equipped with an ASC-7000 autosampler (Shimadzu Corporation, Kyoto, Japan). For adsorption-model fitting, the metal concentration measured after the standardized 6 h contact period was operationally denoted as (C_e), and the corresponding adsorption capacity, (q_e) (mg g^{-1}), was calculated according to Equation (1).

$$q_e = \left(\frac{C_0 - C_e}{m} \right) V \quad (1)$$

where (C_0) is the initial metal concentration (mg L^{-1}), (C_e) is the metal concentration measured after the standardized 6 h contact period (mg L^{-1}), (V) is the solution volume (L), and (m) is the mass of biochar (g). The use of (C_e) and (q_e) follows conventional adsorption-isotherm notation. However, because equilibrium attainment was not independently verified by kinetic experiments, these variables represent the operational endpoint adopted for the present adsorption experiments.

The concentration-dependent adsorption data obtained after the standardized 6 h contact period were fitted using the Langmuir, Freundlich, and Temkin models to compare the adsorption behavior of the different biochars. Langmuir and Freundlich were selected to provide complementary descriptions of concentration-dependent adsorption behavior, while the Temkin expression was included as an additional empirical model that incorporates an adsorption-energy term varying with surface coverage. Temkin was therefore used for comparative model fitting rather than as independent evidence of a specific adsorption mechanism.

The Langmuir model was expressed according to Equation (2).

$$q_e = \left(\frac{q_m K_L C_e}{1 + (K_L C_e)} \right) \quad (2)$$

K_L is the Langmuir constant (L mg^{-1}), and q_m represents the apparent maximum adsorption capacity predicted by the model (mg g^{-1}). The dimensionless separation factor, (R_L), was calculated according to Equation (3).

R_L parameter:

$$R_L = \left(\frac{1}{1 + (K_L C_0)} \right) \quad (3)$$

The model proposed by Freundlich is shown in Equation (4).

$$q_e = \left(K_F C_e^{\left(\frac{1}{n}\right)} \right) \quad (4)$$

where K_F is the constant of the Freundlich ((mg g⁻¹)(L mg⁻¹) n⁻¹) and n is the Freundlich index.

Finally, Temkin's model, proposed by Temkin and Pyzhev, is shown in Equation (5).

$$q_e = \left(\frac{RT}{b_T} \right) \ln(A_T C_e) \quad (5)$$

where (b_T) is the Temkin constant associated with adsorption energy (J mol⁻¹), (A_T) is the Temkin binding constant (L mg⁻¹), (R) is the universal gas constant (8.314 J mol⁻¹ K⁻¹), and (T) is the absolute temperature of the solution (K). For reporting purposes, $B = \frac{RT}{b_T}$ was also calculated. Because adsorption equilibrium was not independently confirmed, the parameters derived from the Langmuir, Freundlich, and Temkin models were interpreted comparatively under the standardized 6 h experimental condition.

The efficiency E (%) of biochar was calculated using Equation (6).

$$E = \left(\frac{C_0 - C_e}{C_0} \right) \times 100 \quad (6)$$

2.6. Data Analysis

Statistical analyses were performed using InfoStat software (InfoStat, version 2020, Centro de Transferencia InfoStat, FCA, Universidad Nacional de Córdoba, Córdoba, Argentina). All adsorption experiments were performed in triplicate ($n = 3$). Differences among initial concentrations were evaluated using Tukey's test at a significance level of $p < 0.05$.

2.7. AI-Assisted Figure Preparation

ChatGPT (OpenAI) was used to generate the visual design of Figure 7 based on instructions provided by the authors. The authors reviewed the proposed mechanisms, labels, and visual elements for scientific accuracy and take full responsibility for the final figure.

3. Results and Discussion

3.1. FTIR Characterization

As shown in Figure 2, the feedstock exhibited a broad peak between 3000 and 3600 cm⁻¹, with its center at 3400 cm⁻¹. The broad peak in this range is associated with hydroxyl functional groups, which can be alcohols and phenols [25]. Wild sugarcane feedstock also exhibited peaks at 2856 and 2915 cm⁻¹, corresponding to stretching vibration of -CH groups [26]. Furthermore, the FTIR analysis showed small peaks between 900 and 1770 cm⁻¹ associated with stretching vibrations of various functional groups [27,28]. The FTIR spectrum of wild sugarcane is similar to those of other perennial grasses.

However, after carbonization, the peaks observed in the biochar differed from those in the feedstock. The four biochar samples (BP8, BP12, BP16, and BP20) showed a wide peak between 3150 and 3600 cm⁻¹, often attributed to the -OH functional groups. The absorbance of these peaks increased after carbonization, showing a higher absorbance in BP12, which may be caused by oxidation of the raw material. Furthermore, the decrease in BP16 and the subsequent increase in BP20 suggests a change in the hydrogen structure. Díez and Pérez reported a similar phenomenon when producing biochar in a TLUD gasifier. The carbonization process of WSC also caused a decrease in the peaks at 2856 and 2915 cm⁻¹,

suggesting the degradation of the aliphatic structure with increasing temperature [18]. These peaks are more noticeable in BP8, indicating a lower degree of carbonization [18,26].

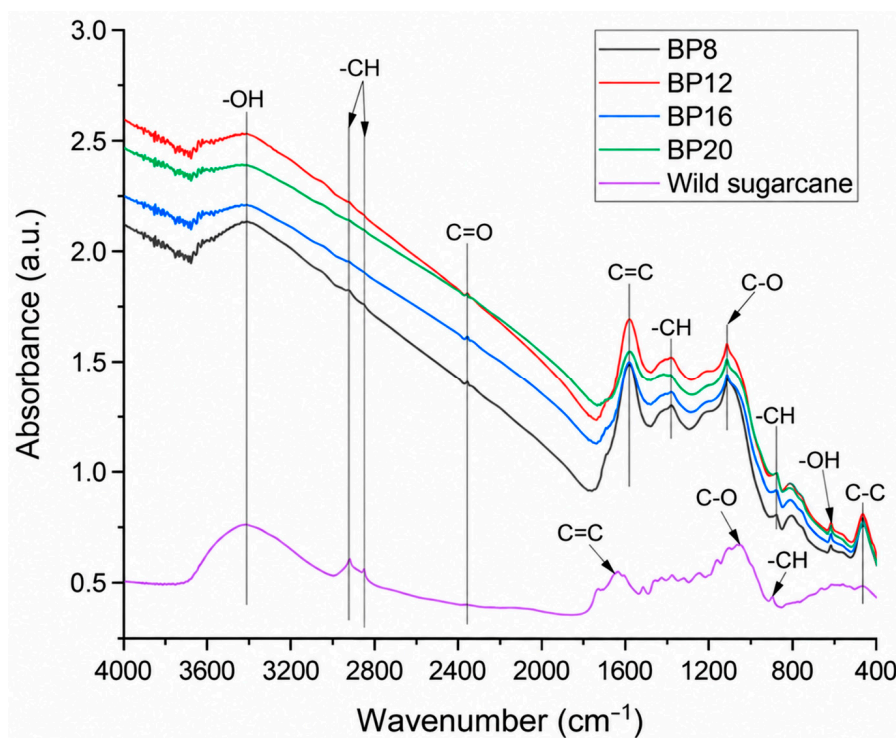


Figure 2. FTIR analysis for wild sugarcane biochar and feedstock samples.

A peak appeared at 2343 cm^{-1} in the biochar spectra, attributed to the stretching of ketone functional groups and CO_2 peaks [18,26]. The appearance of these peaks suggests successful oxidation of the biochar via the TLUD gasification method. Among the four biochars, BP12 and BP20 exhibited higher absorbance at 2343 cm^{-1} , indicating more prominent spectroscopic features associated with the corresponding functional groups.

The peak present at 1581 cm^{-1} corresponds to aromatic groups of -C=C and -C=O , attributed to the degree of aromatization in biochar. As noted above, BP12 exhibits a higher absorbance of this peak when compared to the other three WSC biochars, suggesting a higher degree of aromatization and oxidation. The carbonization process also increased the absorbance at 1378 cm^{-1} . An increase in this peak can be attributed to aliphatic groups [29] and carbonate [25]. The higher absorbance observed for BP12 suggests more prominent spectroscopic features associated with hydrogen- and oxygen-containing functional groups.

At the end of the carbonization process, the peak observed at 1024 cm^{-1} in the feedstock shifted to 1100 cm^{-1} . The shift may be associated with the thermal degradation of cellulose and hemicellulose and with the increasing relative contribution of inorganic mineral components in the biochar [29,30]. The WSC biochar exhibited small peaks at 609 and 871 cm^{-1} , attributed to -OH and -CH groups, respectively [31–33]. Oxygen-containing surface functional groups, particularly hydroxyl (-OH) and carboxyl (-COOH) groups, play a fundamental role in Cu(II) adsorption, as they can act as active coordination sites and form stable surface complexes with copper ions [34]. Additionally, the peak at 458 cm^{-1} is attributed to the stretching of -C-C groups due to increased aromaticity following degradation of organic material [35].

3.2. Raman Characterization

The deconvolution of the peaks in the Raman analysis was performed using the methodology proposed by Li et al. (2006) [36]. This methodology is applicable to biomass-

derived carbon. The Raman analysis showed that the WSC biochar exhibited -C=O, -C-C, -C-H functional groups [36]. Table 3 presents the Gaussian bands used for the analysis.

Table 3. Raman bands, according to Li et al. This method uses ten bands in the 800 to 1700 cm^{-1} range [36].

Wavenumber (cm^{-1})	Band Name	Characteristics
800–960	R	-C-C groups of alkanes and cyclic alkanes
1060	S _R	-C-H groups in aromatic rings
1185	S	-C-C groups in hydroaromatic Rings
1230	S _L	Aryl-alkyl ethers
1300	D	-C-C bonds between aromatics, with at least six rings
1380	V _R	Amorphous carbon structures
1465	V _L	Amorphous carbon structures
1540	G _R	Amorphous carbon structures
1590	G	Graphite E _{2g} vibration
1700	G _L	Carbonyl group -C=O

As can be seen in Figure 3, BP8 showed seven Gaussian bands, namely R, SR, S, D, VR, GR, and G. The R band present in BP8 suggests the presence of -C-C functional groups, such as alkanes and cyclic alkanes. Furthermore, the SR and S bands indicate the existence of hydroaromatic groups, while the D band suggests that the aromatics have at least six rings. The presence of VR and GR bands in BP8 suggests that the graphitization process was incomplete, as there were some amorphous structures on the surface of the biochar [37].

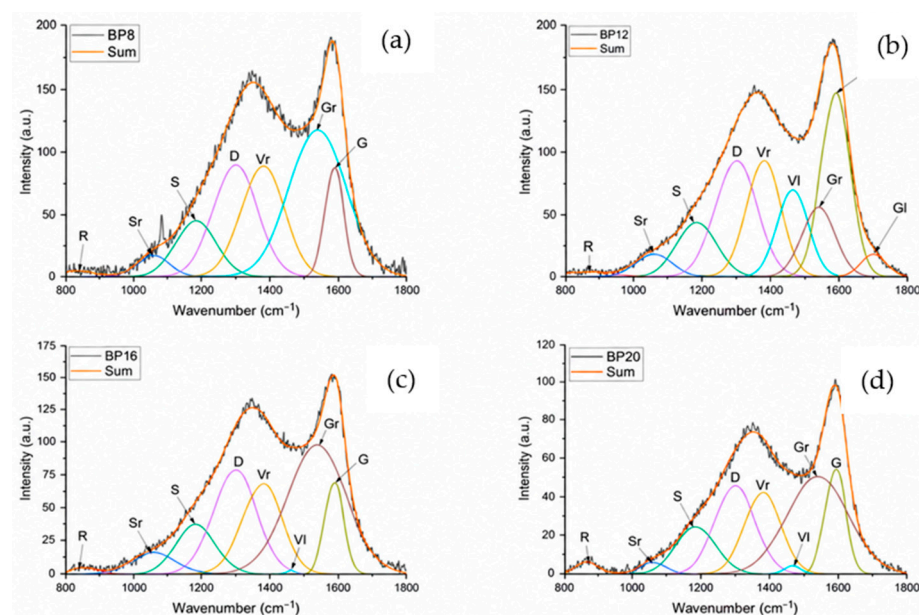


Figure 3. Raman analysis and Gaussian peak deconvolution of WSC biochar samples produced at airflow rates of (a) 8, (b) 12, (c) 16, and (d) 20 L min^{-1} . The black/gray line represents the experimental Raman spectrum, the orange line represents the sum of the fitted components, and the colored curves represent the individual Gaussian bands used for peak deconvolution. Increasing the airflow rate caused a decrease in overall intensity.

As the airflow rate increased, BP12 exhibited two more bands, VL and GL, at 1465 and 1700 cm^{-1} , respectively. On the one hand, the appearance of the VL band suggests the presence of more amorphous carbon structures. However, as shown in Figure 3, the intensity of GR decreased. The appearance of VL and the decrease in GR band intensity indicate the formation of a different type of amorphous structure, namely methylene functional groups [36]. On the other hand, the presence of the GL band indicates a more

prominent spectroscopic contribution associated with carbonyl functional groups, which can be attributed to the increased airflow rate. Furthermore, the intensity of the G band increased, suggesting that BP12 exhibited a higher degree of graphitization than BP8 [38].

A further increase in airflow rate caused a decrease in the overall intensity of the Raman bands. The reduction in intensity is often linked to the homogenization of the material's surface. Furthermore, BP16 lacked the GL band, which can be attributed to the degradation of -C=O bonds. The VL band also decreased, indicating a less prominent spectroscopic contribution associated with methylene-related features [37]. In addition, the GR band was higher than the G band, which can be attributed to a lower graphitization of the biochar. Lastly, BP20 exhibited the lowest overall intensity among the four WSC biochars, indicating an even higher degree of homogenization compared with the other biochars. In addition, the G band exhibited a higher peak intensity than the GR band, suggesting more graphitic structures as the airflow rate increased (see Table 4) [39].

Table 4. Intensity of Gaussian bands present in canal straw biochars. Based on the method proposed by Li and colleagues [36].

Biochar	Intensity									
	R	S _R	S	S _L	D	V _R	V _L	G _R	G	G _L
BP8	4.576	17.41	45.19	0	89.70	88.81	0	118.2	87.11	0
BP12	3.929	18.39	43.78	0	93.22	93.60	69.54	55.59	147.1	18.38
BP16	4.773	16.17	37.66	0	78.64	68.41	2.551	97.43	68.15	0
BP20	6.129	5.816	24.59	0	46.30	42.56	4.242	50.67	54.48	0

Raman analysis showed that WSC biochar exhibited behavior similar to that of other biochars (Table 5). Similarly, Zhang et al. produced seaweed biochar. They observed that carbon formation started at 400 °C, suggesting restructuring of the internal structure of the biochar. When the biochar was restructured, ID/IG and ID/I_(VR+VL+GR) ratios of 0.67 and 0.36, respectively, were observed. By increasing the temperature to 500 °C, the authors observed an increase in both ratios, to 0.72 and 0.56, respectively. They attributed this change to an increase in larger hydrocarbons, as part of the cross-condensation between small aromatics [40].

Table 5. Raman intensity ratio in WSC biochars.

Biochar	Maximum Temperature (°C)	ID/I _(VR+VL+GR)	ID/IG
BP8	556.7	0.4333	1.029
BP12	589.3	0.4261	0.6337
BP16	597.6	0.4670	1.153
BP20	642.0	0.4750	0.8498

In contrast, increasing the temperature to 600, 700, and 800 °C caused both ratios to decrease. Zhang et al. attributed the reduction to the downsizing of the biochar's hydrocarbon systems. Likewise, the total Raman area decreased with increasing temperature. This reduction was shown to be consistent with the decrease in oxygen in the biochar [40].

3.3. X-Ray Diffraction (XRD) Characterization

The XRD analysis provides information on the chemical and structural composition of the biochar, as shown in Figure 4. The results of the XRD analysis show that WSC biochars are amorphous, which is characteristic of organic materials with a high presence of cellulose, hemicellulose, and lignin [41]. The four biochar samples also exhibited a broad

peak in the 2θ range of 20° to 30° . This peak is attributed to amorphous carbon structures, with an indexed plane of (0 0 2) [40,42]. Goswami et al. reported that peak intensity may increase with increasing temperature. However, this study observed no change in the amorphous carbon peak. This may be due to the lack of significant differences among the biochar production temperatures [25].

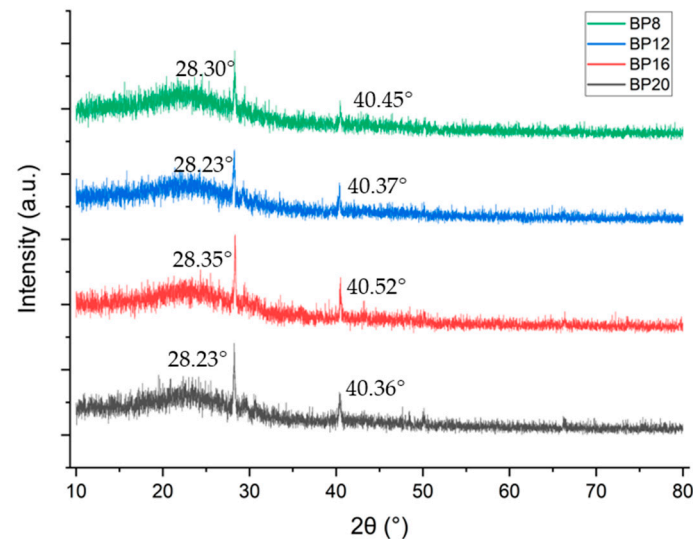


Figure 4. XRD analysis of WSC biochars produced at different airflow rates.

For BP8, strong peaks were observed at $2\theta = 28.30^\circ$ and 40.45° . The first peak (28.30°) can be attributed to the presence of potassium iodate (KIO_3) [43] and fluorite (CaF_2) [44]. Additionally, the peak at 40.45° is attributed to the presence of potassium [45] and sodium in analcime [46]. On the other hand, BP12 showed peaks at $2\theta = 28.23^\circ$ and 40.37° . The peak at 28.23° is attributed to silicon oxide (SiO_2) in its indexed plane (1 1 6) [47], as well as the presence of chitosan [48]. The peak at 40.37° suggests the presence of Fe_3O_4 and silicon (SiO_2) in its plane (2 0 0) [49,50].

In the case of BP16, two peaks were observed at 28.35° and 40.52° . The peak at 28.35° suggests the presence of calcium in the form of CaTiO_3 in its plane (2 2 0) [51] and in the form of montmorillonite [52]. In addition, it suggests the presence of silicates. The peak at 40.52° is attributed to the presence of potassium chloride (KCl) [53] and diffraction (1 1 3) of calcium carbonate (CaCO_3) [54]. BP20 also showed a peak at $2\theta = 28.23^\circ$, indicating the presence of SiO_2 [47]. In addition, it showed a peak at 40.36° , attributed to Gibbsite ($\text{Al}(\text{OH})_3$) [44] and the presence of silicon and aluminum [55].

The pre-adsorption FTIR and Raman results indicate the presence of oxygen-containing and carbonaceous surface functionalities in the WSC biochars, while XRD describes crystalline and amorphous features of the starting materials. These characteristics may influence metal uptake, but they do not demonstrate which surface groups reacted with Cu^{2+} and Zn^{2+} or whether new metal-bearing phases formed during adsorption. In addition, XRD identifies diffraction patterns associated with crystalline phases; it does not directly determine elemental composition. The phase assignments discussed here should therefore be considered tentative unless supported by validated database matching and complementary elemental analysis.

3.4. Contaminant Removal

Among the four WSC biochars, BP12 was selected for the Cu^{2+} and Zn^{2+} adsorption experiments based on its overall physicochemical profile rather than on specific surface area alone. Although BP20 exhibited the highest BET specific surface area, $11.26 \text{ m}^2 \text{ g}^{-1}$

compared with $3.50 \text{ m}^2 \text{ g}^{-1}$ for BP12, the spectroscopic characterization of BP12 showed more prominent features associated with oxygen-containing surface functionalities. FTIR analysis showed comparatively stronger signals assigned to oxygen-containing groups in BP12, while Raman analysis identified the GL band at approximately 1700 cm^{-1} only in BP12 among the evaluated biochars. This band is associated with carbonyl $\text{C}=\text{O}$ functionalities. This distinction is relevant because heavy-metal sorption by biochar is governed by both physical and chemical surface properties and is not determined by specific surface area alone. Oxygen-containing functionalities, including hydroxyl, carboxyl, and carbonyl groups, may contribute to metal uptake through surface complexation and ion-exchange processes [27,38,56–58]. Increasing thermal severity can promote surface area and pore development while simultaneously altering or reducing oxygen-containing surface functionalities [15,21,59,60]. Therefore, BP12 was selected as a characterization-based compromise between surface development and the preservation of oxygen-containing functionalities potentially relevant to Cu^{2+} and Zn^{2+} uptake.

3.4.1. Removal Efficiency

As shown in Figure 5, BP12 exhibited removal efficiencies of 70–90% for copper and 83–94% for zinc. No linear relationship was observed between initial metal concentration and removal efficiency. The greatest zinc removal occurred at a concentration of 1 mg/L and then decreased as C_0 increased to 5 mg/L . However, the removal efficiency increased as C_0 increased. This behavior may be related to concentration-dependent interactions involving Zn^{2+} ions and available adsorption sites. However, the present data do not allow a specific interaction mechanism to be established [61,62].

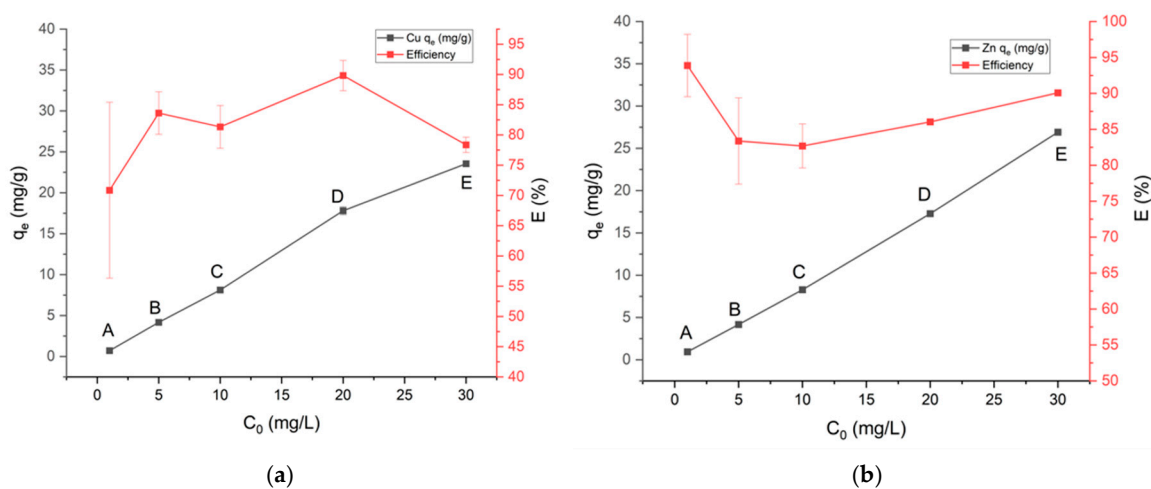


Figure 5. BP12 removal capacity and removal efficiency for (a) Cu^{2+} and (b) Zn^{2+} as a function of the initial concentration (C_0). Error bars represent the standard deviation of triplicate experiments ($n = 3$). Different letters indicate significant differences in adsorption capacity among initial concentrations according to Tukey's test ($p < 0.05$).

Adsorption capacity increased with increasing initial concentration for both copper and zinc. The experimental removal capacity of copper reached 23.5 mg/g , while zinc removal was higher at 26.9 mg/g . Although Zn^{2+} exhibited a higher experimental uptake, the adsorption-model results should be interpreted cautiously, as discussed in the following section. Significant differences in adsorption capacity were observed among the initial concentrations ($p < 0.05$).

3.4.2. Adsorption Isotherms

Figure 6 shows the fit of the experimental removal data using the Langmuir, Freundlich, and Temkin models. The Langmuir, Freundlich, and Temkin expressions were fitted to the concentration-dependent Cu^{2+} and Zn^{2+} uptake data obtained after the standardized 6 h contact period. For Cu^{2+} , all three models produced R^2 values greater than 0.83, with the Langmuir expression showing the highest R^2 and an apparent maximum adsorption capacity of 42.3 mg g^{-1} (Table 6). For Zn^{2+} , the Freundlich expression showed the highest R^2 , while the Langmuir model did not converge and the maximum observed uptake was 26.9 mg g^{-1} (Table 7).

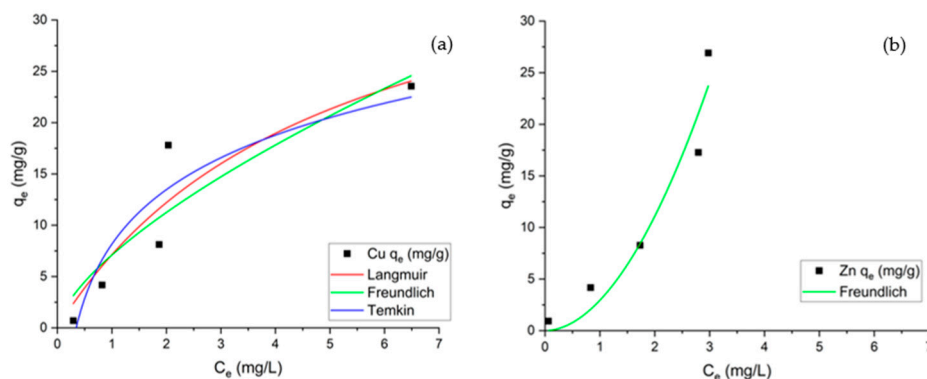


Figure 6. Adsorption isotherms for (a) copper and (b) zinc.

Table 6. Isotherm parameters for copper and zinc removal using BP12.

Metal	Langmuir				Freundlich			Temkin			
	$q_m (\text{mg} \cdot \text{g}^{-1})$	$K_L (\text{L} \cdot \text{mg}^{-1})$	R^2	R_L	n	K_F	R^2	$A_T (\text{L} \cdot \text{g}^{-1})$	B	$b_T (\text{J} \cdot \text{mol}^{-1})$	R^2
Cu^{2+}	42.387	0.202	0.867	0.141–0.831	1.506	7.097	0.837	2.89	7.66	323.2	0.857
Zn^{2+}	-	-	-	-	0.522	2.946	0.933	10.645	5.001	495.3	0.580

These models provide empirical descriptions of the dataset obtained in the present study. Preference for one model, or the non-convergence of another, does not uniquely establish monolayer adsorption, chemisorption, physical adsorption, surface heterogeneity, or adsorbate–adsorbate interactions. Mechanistic interpretation requires independent physicochemical evidence and careful consideration of the terminology and assumptions associated with adsorption models [63].

Because equilibrium was not independently verified through kinetic experiments, the fitted parameters are interpreted as parameters corresponding to the adopted operational endpoint rather than as confirmed equilibrium constants or capacities.

Metal uptake by biochar can involve several concurrent processes, including electrostatic interaction, ion exchange, complexation with oxygen-containing surface groups, and precipitation with mineral components (Figure 7) [12,20,64]. The pre-adsorption FTIR, Raman, BET, and XRD results show that BP12 possesses characteristics that are compatible with more than one of these pathways. However, compatibility alone does not demonstrate that a particular pathway occurred.

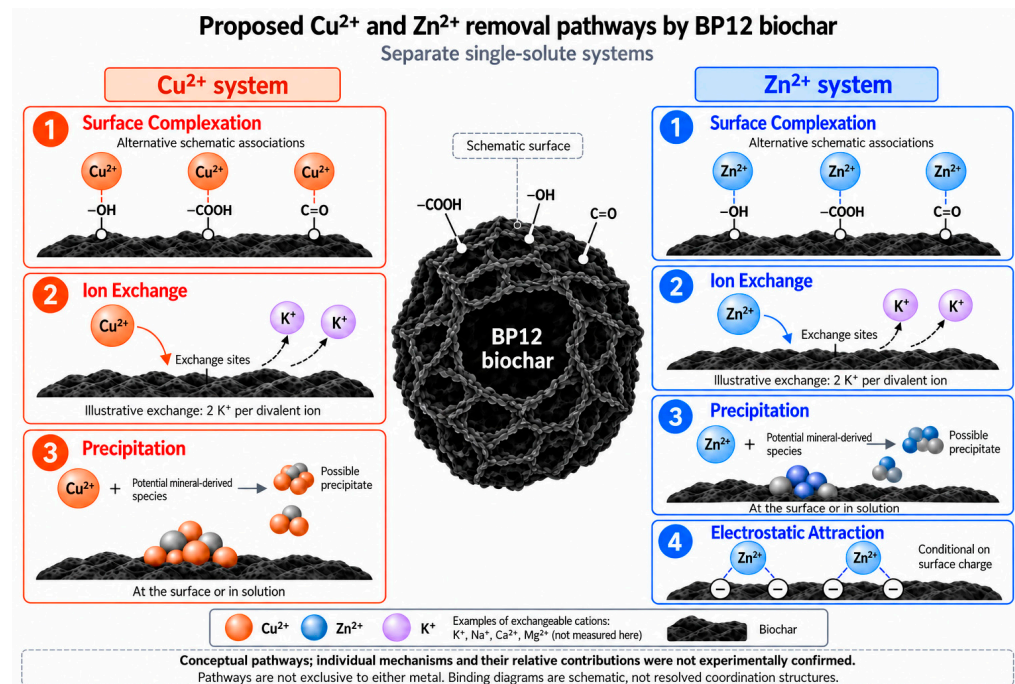


Figure 7. Proposed mechanisms for Cu^{2+} and Zn^{2+} removal by BP12 biochar under single-solute experimental conditions. This figure was generated with the assistance of ChatGPT (OpenAI) to create the visual design based on instructions provided by the authors. The authors reviewed the figure for scientific accuracy and take full responsibility for its content.

No post-adsorption XPS, FTIR, XRD, or SEM–EDS analyses were performed, and changes in dissolved counterions or mineral components were not quantified. Consequently, the present data demonstrate Cu^{2+} and Zn^{2+} uptake but do not identify the dominant pathway or verify the formation of Cu- or Zn-bearing phosphate or carbonate phases. These possibilities should be tested in future work using paired pre- and post-adsorption characterization. XPS could examine surface chemical states, FTIR could identify reproducible changes in functional-group bands, SEM–EDS could assess the presence and distribution of Cu and Zn on sampled surfaces, and post-adsorption XRD could test for newly formed crystalline phases. Because poorly crystalline, amorphous, low-abundance, or surface-limited products may not be detected by XRD alone, the results obtained from these techniques should be interpreted together rather than individually.

The adsorption experiments conducted in the present study were performed using single-solute systems. Therefore, the adsorption capacities obtained for Cu^{2+} and Zn^{2+} represent their individual interactions with WSC biochar in the absence of competition from the other metal ion. In multicomponent aqueous systems, coexisting metal ions can compete for available adsorption sites, including oxygen-containing functional groups, ion-exchange sites, and mineral-associated binding sites, thereby modifying both adsorption capacity and selectivity. Chen et al. reported competitive adsorption between Cu^{2+} and Zn^{2+} on hardwood- and corn-straw-derived biochars, particularly when both metal concentrations were equal to or greater than 1.0 mM. Cu^{2+} adsorption was only slightly affected by the presence of Zn^{2+} , whereas Cu^{2+} exerted a stronger competitive effect on Zn^{2+} adsorption [12]. Similarly, Soudani et al. observed antagonistic adsorption behavior for Cu^{2+} , Cd^{2+} , and Zn^{2+} in binary systems, demonstrating that adsorption capacities obtained under single-solute conditions cannot necessarily be extrapolated to multicomponent systems [65]. Preferential adsorption of Cu^{2+} over Zn^{2+} has also been reported and has been associated with stronger Cu–O interactions and more favorable adsorption energies at oxygen-containing binding sites [66]. However, because binary Cu^{2+} – Zn^{2+} experiments

were not performed in the present study, competitive adsorption and selectivity of WSC biochar toward these metals cannot be established from the present results. Further studies using binary and multicomponent systems are required to determine the behavior of WSC biochar under conditions more representative of complex aqueous matrices.

Under the investigated single-solute conditions, Zn^{2+} exhibited a slightly higher experimental adsorption capacity than Cu^{2+} . However, the differences observed between Cu^{2+} and Zn^{2+} uptake should not be attributed solely to electronegativity. Metal adsorption by biochar is governed by multiple ion-specific and adsorbent-specific factors, including metal speciation, hydrated ionic radius, hydration characteristics, affinity toward oxygen-containing surface functional groups, surface charge, mineral composition, and ion-exchange interactions [58,67]. Pan et al. reported stronger Cu–O interactions and more favorable adsorption energies for Cu^{2+} than for Zn^{2+} on a carboxylated biogas-residue adsorbent, where carboxyl groups were identified as the main adsorption sites [66]. Nevertheless, the relative adsorption behavior of Cu^{2+} and Zn^{2+} depends strongly on the physicochemical characteristics of the biochar, solution chemistry, metal concentration, and the presence of competing ions [12]. Therefore, the differences observed in the present study cannot be assigned to a single physicochemical property of the metal ions.

Regeneration and end-of-life management are important considerations for the practical application of biochar adsorbents. Previous studies have shown that metal-loaded biochars can be regenerated through chemical desorption, although regeneration efficiency depends on the adsorption mechanism, surface functional groups, pore structure, and strength of the adsorbate–adsorbent interactions [68,69]. For example, Lin et al. demonstrated that an oxidized biochar used for Cu^{2+} and Zn^{2+} removal could be regenerated using HCl while maintaining relatively consistent adsorption performance over ten adsorption–desorption cycles [70]. However, regeneration may also generate a secondary concentrated waste stream containing the desorbed metals, which requires appropriate treatment or recovery. In addition, inappropriate disposal of spent adsorbents may pose a risk of secondary contaminant release, making recovery, regeneration, and controlled management important components of adsorption-based wastewater treatment [71]. Regeneration, reusability, and the leaching stability of Cu^{2+} and Zn^{2+} loaded WSC biochar were not evaluated in the present study and therefore remain subjects for future investigation.

Table 7. Removal of copper and zinc with different biochars. NR indicates “not reported,” whereas NR * indicates “not explicitly reported”.

Biochar Feedstock	Metal	Adsorption Capacity (mg g^{-1})	pH	Initial Concentration (mg L^{-1})	Contact Time	Reference
Wild sugarcane	* Cu^{2+}	42.3	6.3–6.5	1–30	6 h	This study
	* Zn^{2+}	26.9	6.3–6.5	1–30	6 h	
Tobacco Stalk	Cu^{2+}	428	NR *	5–2000	12 h	[72]
<i>Jatropha curcas</i> seeds	Cu^{2+}	32.8	5.0	NR	NR	[73]
Rice straw	Zn^{2+}	38.6	5.0	100	4 h	[27]
	Cu^{2+}	56.5	5.0	100	4 h	
Oak fruit peel	Cu^{2+}	41.9	5.53	1–100	4 h	[65]
	Zn^{2+}	27.0	5.53	1–100	4 h	
<i>Chlorella</i> sp. residue	Zn^{2+}	21.3	6	50–400	0.13 h	[74]
Banana Peels	Cu^{2+}	20.6	NR	NR	NR	[3]
Marine macroalgae	Zn^{2+}	20.1	NR	NR	NR	
Apple Tree Branches	Cu^{2+}	11.4	5.0	6.4–384	24 h	[68]
	Zn^{2+}	10.2	5.0	6.5–390	24 h	

* For the present study, the Cu^{2+} value corresponds to the apparent Langmuir maximum capacity, whereas the Zn^{2+} value corresponds to the maximum observed uptake because the Langmuir model did not converge.

4. Conclusions

1. Wild sugarcane (*Saccharum spontaneum* L.) can be converted into biochar through TLUD gasification, providing a potential valorization pathway for this biomass.
2. Wild-sugarcane biochar demonstrated the ability to remove both Cu^{2+} and Zn^{2+} from synthetic aqueous media under the investigated batch conditions.
3. BP12 was selected for the adsorption experiments based on its overall physicochemical profile and the comparatively prominent spectroscopic features associated with oxygen-containing surface functionalities. This selection was based on pre-adsorption characterization and should not be interpreted as evidence that BP12 exhibited a higher adsorption capacity than BP8, BP16, or BP20, which were not evaluated in the metal adsorption experiments.
4. BP12 removed both Cu^{2+} and Zn^{2+} from synthetic aqueous solutions during the standardized 6 h contact period. The Langmuir expression yielded an apparent maximum Cu^{2+} capacity of 42.3 mg g^{-1} , whereas Zn^{2+} uptake reached 26.9 mg g^{-1} and was best described by the Freundlich expression among the tested models.
5. These findings support the potential of wild-sugarcane biochar as a minimally processed adsorbent and as a pathway for invasive-biomass valorization. However, the experiments did not establish adsorption equilibrium, compare Cu^{2+} and Zn^{2+} uptake across all four biochars, or determine a dominant adsorption mechanism. In addition, the non-convergence of the Langmuir model for Zn^{2+} prevented estimation of a model-derived maximum adsorption capacity, limiting the extrapolation and prediction of Zn^{2+} removal performance beyond the investigated experimental conditions.
6. Future work should include kinetic experiments, full gas-physisorption analysis, paired pre- and post-adsorption XPS and FTIR, SEM-EDS mapping, post-adsorption XRD, regeneration tests, and validation in complex water matrices.

Author Contributions: Conceptualization, J.P., Z.K. and A.M.C.J.; methodology, J.P., A.M.C.J. and Z.K.; data curation, J.P.; writing—original draft preparation, J.R. and J.P.; writing—review and editing, J.R., J.P., A.M.C.J. and Z.K.; funding acquisition, J.R. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Master of Science in Water Resources Program and the Doctoral Program in Biosciences and Biotechnology, both supported by the National Secretariat of Science, Technology, and Innovation (SENACYT) of Panama; the National Research System (SNI); and grant No. 66-2019-ITE18-R2-016, entitled “Carbonización de Biomasa: Aprovechamiento de Residuos Agrícolas para el Mejoramiento de las Propiedades Físico-químicas del Suelo en Áreas de Cultivo”.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors thank the National Secretariat of Science, Technology and Innovation (SENACYT) of the Republic of Panama for its commitment to and financial support of the project. The authors also acknowledge CEMCIT-AIP for its support in the financial and administrative management of the project. The authors also thank the Industrial Analysis and Environmental Sciences Laboratory (LABAICA) for the technical support during the FTIR analysis, particularly Javier Lloyd, Mario Altamirano, and Cecilio Hernández. The authors also thank Eduardo López from the National Institute of Water and Sewerage (IDAAN) for providing support with the adsorption analysis. Finally, the authors thank SENACYT for their financial support through the Master of Science program in Water Resources, and the Doctoral Program in Biosciences and Biotechnology

at the Universidad Tecnológica de Panamá. The corresponding author was partially funded by the National Research System (SNI, Spanish: Sistema Nacional de Investigación) from the Republic of Panama. The authors acknowledge the use of ChatGPT (OpenAI) to assist with the visual design of Figure 7 based on their instructions. The authors reviewed the final figure and take full responsibility for its content.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Prens, J.; Kurt, Z.; James Rivas, A.M.; Chen, J. Production and Characterization of Wild Sugarcane (*Saccharum spontaneum* L.) Biochar for Atrazine Adsorption in Aqueous Media. *Agronomy* **2022**, *13*, 27. [\[CrossRef\]](#)
2. Fisher, R.; Gupta, V. Heavy Metals. In *StatPearls [Internet]*; StatPearls Publishing: Treasure Island, FL, USA, 2026. Available online: <https://pubmed.ncbi.nlm.nih.gov/32491738/> (accessed on 23 August 2026).
3. Niedzbała, N.; Rutkowski, P.; Michalak, I. The Pyrolysis and Co-Pyrolysis Processes Used to Obtain Biochar from Waste as Potential Biosorbents for Cu(II) and Zn(II) Ions. *Biomass Bioenergy* **2027**, *216*, 109721. [\[CrossRef\]](#)
4. Briffa, J.; Sinagra, E.; Blundell, R. Heavy Metal Pollution in the Environment and Their Toxicological Effects on Humans. *Heliyon* **2020**, *6*, e04691. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Osman, A.I.; El-Monaem, E.M.A.; Elgarahy, A.M.; Aniagor, C.O.; Hosny, M.; Farghali, M.; Rashad, E.; Ejimofor, M.I.; López-Maldonado, E.A.; Ihara, I.; et al. Methods to Prepare Biosorbents and Magnetic Sorbents for Water Treatment: A Review. *Environ. Chem. Lett.* **2023**, *21*, 2337–2398. [\[CrossRef\]](#)
6. Al-Ansari, H.; Al-Qashouti, H.; Al-Neama, R.; Al-Moadhadi, A.; Nazzal, H.; Philip, N. Content of Cariostatic Trace Elements (F, Cu, and Zn) in the Commercially Packaged and Public Tap Waters of Qatar. *Saudi Dent. J.* **2024**, *36*, 1321–1325. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Yang, J.; Hou, B.; Wang, J.; Tian, B.; Bi, J.; Wang, N.; Li, X.; Huang, X. Nanomaterials for the Removal of Heavy Metals from Wastewater. *Nanomaterials* **2019**, *9*, 424. [\[CrossRef\]](#)
8. Qiu, B.; Tao, X.; Wang, H.; Li, W.; Ding, X.; Chu, H. Biochar as a Low-Cost Adsorbent for Aqueous Heavy Metal Removal: A Review. *J. Anal. Appl. Pyrolysis* **2021**, *155*, 105081. [\[CrossRef\]](#)
9. Wang, Y.; Kang, J.; Jiang, S.; Li, H.; Ren, Z.; Xu, Q.; Jiang, Q.; Liu, W.; Li, R.; Zhang, Y. A Composite of Ni-Fe-Zn Layered Double Hydroxides/Biochar for Atrazine Removal from Aqueous Solution. *Biochar* **2020**, *2*, 455–464. [\[CrossRef\]](#)
10. Gabhane, J.W.; Bhange, V.P.; Patil, P.D.; Bankar, S.T.; Kumar, S. Recent Trends in Biochar Production Methods and Its Application as a Soil Health Conditioner: A Review. *SN Appl. Sci.* **2020**, *2*, 1307. [\[CrossRef\]](#)
11. Yang, Y.; Piao, Y.; Wang, R.; Su, Y.; Liu, N.; Lei, Y. Nonmetal Function Groups of Biochar for Pollutants Removal: A Review. *J. Hazard. Mater. Adv.* **2022**, *8*, 100171. [\[CrossRef\]](#)
12. Chen, X.; Chen, G.; Chen, L.; Chen, Y.; Lehmann, J.; McBride, M.B.; Hay, A.G. Adsorption of Copper and Zinc by Biochars Produced from Pyrolysis of Hardwood and Corn Straw in Aqueous Solution. *Bioresour. Technol.* **2011**, *102*, 8877–8884. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Qiu, M.; Liu, L.; Ling, Q.; Cai, Y.; Yu, S.; Wang, S.; Fu, D.; Hu, B.; Wang, X. Biochar for the Removal of Contaminants from Soil and Water: A Review. *Biochar* **2022**, *4*, 19. [\[CrossRef\]](#)
14. Xiang, W.; Zhang, X.; Chen, J.; Zou, W.; He, F.; Hu, X.; Tsang, D.C.W.; Ok, Y.S.; Gao, B. Biochar Technology in Wastewater Treatment: A Critical Review. *Chemosphere* **2020**, *252*, 126539. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Hassan, M.; Liu, Y.; Naidu, R.; Parikh, S.J.; Du, J.; Qi, F.; Willett, I.R. Influences of Feedstock Sources and Pyrolysis Temperature on the Properties of Biochar and Functionality as Adsorbents: A Meta-Analysis. *Sci. Total Environ.* **2020**, *744*, 140714. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Saltonstall, K.; Bonnett, G.D.; Aitken, K.S. A Perfect Storm: Ploidy and Preadaptation Facilitate *Saccharum Spontaneum* Escape and Invasion in the Republic of Panama. *Biol. Invasions* **2021**, *23*, 1101–1115. [\[CrossRef\]](#)
17. James R, A.M.; Yuan, W.; Boyette, M.D.; Wang, D. Airflow and Insulation Effects on Simultaneous Syngas and Biochar Production in a Top-Lit Updraft Biomass Gasifier. *Renew. Energy* **2018**, *117*, 116–124. [\[CrossRef\]](#)
18. Díez, H.E.; Pérez, J.F. Effects of Wood Biomass Type and Airflow Rate on Fuel and Soil Amendment Properties of Biochar Produced in a Top-lit Updraft Gasifier. *Environ. Prog. Sustain. Energy* **2019**, *38*, 13105. [\[CrossRef\]](#)
19. Barría, Y.; Burbano, A.; James, A.; Gascó, G.; Méndez, A. Sorption Capacity of Biochars Obtained by Gasification of Rice Husks and Wild Sugarcane: Removal of Malachite Green and Arsenic from Water Solutions. *Biomass Convers. Biorefin.* **2023**, *15*, 2131–2143. [\[CrossRef\]](#)
20. Harvey, O.R.; Herbert, B.E.; Rhue, R.D.; Kuo, L.-J. Metal Interactions at the Biochar-Water Interface: Energetics and Structure-Sorption Relationships Elucidated by Flow Adsorption Microcalorimetry. *Environ. Sci. Technol.* **2011**, *45*, 5550–5556. [\[CrossRef\]](#) [\[PubMed\]](#)

21. Aller, D.; Bakshi, S.; Laird, D.A. Modified Method for Proximate Analysis of Biochars. *J. Anal. Appl. Pyrolysis* **2017**, *124*, 335–342. [[CrossRef](#)]
22. Kołodziejńska, D.; Wnętrzak, R.; Leahy, J.J.; Hayes, M.H.B.; Kwapiński, W.; Hubicki, Z. Kinetic and Adsorptive Characterization of Biochar in Metal Ions Removal. *Chem. Eng. J.* **2012**, *197*, 295–305. [[CrossRef](#)]
23. Pelleria, F.-M.; Giannis, A.; Kalderis, D.; Anastasiadou, K.; Stegmann, R.; Wang, J.-Y.; Gidarakos, E. Adsorption of Cu(II) Ions from Aqueous Solutions on Biochars Prepared from Agricultural by-Products. *J. Environ. Manag.* **2012**, *96*, 35–42. [[CrossRef](#)] [[PubMed](#)]
24. Van Hien, N.; Valsami-Jones, E.; Vinh, N.C.; Phu, T.T.; Tam, N.T.T.; Lynch, I. Effectiveness of Different Biochar in Aqueous Zinc Removal: Correlation with Physicochemical Characteristics. *Bioresour. Technol. Rep.* **2020**, *11*, 100466. [[CrossRef](#)]
25. Goswami, R.; Shim, J.; Deka, S.; Kumari, D.; Katak, R.; Kumar, M. Characterization of Cadmium Removal from Aqueous Solution by Biochar Produced from Ipomoea Fistulosa at Different Pyrolytic Temperatures. *Ecol. Eng.* **2016**, *97*, 444–451. [[CrossRef](#)]
26. Luo, M.; Lin, H.; Li, B.; Dong, Y.; He, Y.; Wang, L. A Novel Modification of Lignin on Corncob-Based Biochar to Enhance Removal of Cadmium from Water. *Bioresour. Technol.* **2018**, *259*, 312–318. [[CrossRef](#)] [[PubMed](#)]
27. Park, J.H.; Wang, J.J.; Kim, S.H.; Cho, J.S.; Kang, S.W.; Delaune, R.D.; Han, K.J.; Seo, D.C. Recycling of Rice Straw through Pyrolysis and Its Adsorption Behaviors for Cu and Zn Ions in Aqueous Solution. *Colloids Surf. A Physicochem. Eng. Asp.* **2017**, *533*, 330–337. [[CrossRef](#)]
28. Hernandez, P.T.; Franco, S.P.; Georgin, J.; Salau, N.P.G.; Dotto, G.L. Investigation of Biochar from Cedrella Fissilis Applied to the Adsorption of Atrazine Herbicide from an Aqueous Medium. *J. Environ. Chem. Eng.* **2022**, *10*, 107408. [[CrossRef](#)]
29. Kritikaki, A.; Karmali, V.; Vathi, D.; Bartzas, G.; Komnitsas, K. Advanced Characterization of Biochars Produced from Three Different Organic-Based Feedstocks and Their Potential Applications. *Circ. Econ. Sustain.* **2025**, *5*, 7465–7488. [[CrossRef](#)]
30. Binh, Q.A.; Nguyen, V.H.; Kajitvichyanukul, P. Influence of Pyrolysis Conditions of Modified Corn Cob Bio-Waste Sorbents on Adsorption Mechanism of Atrazine in Contaminated Water. *Environ. Technol. Innov.* **2022**, *26*, 102381. [[CrossRef](#)]
31. Zhou, N.; Wang, Y.; Yao, D.; Li, S.; Tang, J.; Shen, D.; Zhu, X.; Huang, L.; Zhong, M.E.; Zhou, Z. Novel Wet Pyrolysis Providing Simultaneous Conversion and Activation to Produce Surface-Functionalized Biochars for Cadmium Remediation. *J. Clean. Prod.* **2019**, *221*, 63–72. [[CrossRef](#)]
32. Wang, Z.; Shen, F.; Shen, D.; Jiang, Y.; Xiao, R. Immobilization of Cu²⁺ and Cd²⁺ by Earthworm Manure Derived Biochar in Acidic Circumstance. *J. Environ. Sci.* **2017**, *53*, 293–300. [[CrossRef](#)] [[PubMed](#)]
33. Yang, T.; Xu, Y.; Huang, Q.; Sun, Y.; Liang, X.; Wang, L.; Qin, X.; Zhao, L. Adsorption Characteristics and the Removal Mechanism of Two Novel Fe-Zn Composite Modified Biochar for Cd(II) in Water. *Bioresour. Technol.* **2021**, *333*, 125078. [[CrossRef](#)] [[PubMed](#)]
34. Liu, N.; Charrua, A.B.; Weng, C.H.; Yuan, X.; Ding, F. Characterization of Biochars Derived from Agriculture Wastes and Their Adsorptive Removal of Atrazine from Aqueous Solution: A Comparative Study. *Bioresour. Technol.* **2015**, *198*, 55–62. [[CrossRef](#)] [[PubMed](#)]
35. Guo, X.; Liu, C.; Lu, F.; Liu, B.; Zhang, Q.; Zhou, T. Preparation of a Novel N-Doped Biochar from Agricultural Waste for Cu(II) Removal: Insights into the Kinetic, Equilibrium, Adsorption Mechanisms and Economic Feasibility. *Water Air Soil Pollut.* **2026**, *237*, 910. [[CrossRef](#)]
36. Li, X.; Hayashi, J.I.; Li, C.Z. FT-Raman Spectroscopic Study of the Evolution of Char Structure during the Pyrolysis of a Victorian Brown Coal. *Fuel* **2006**, *85*, 1700–1707. [[CrossRef](#)]
37. Zhong, Z.; Chen, J.; Sun, M.; Li, Y. Efficient Adsorption of Cu(II) from Wastewater via Modified Biochars from Residues of Chinese Herbal Medicines *Pueraria lobata* and *Leonurus japonicus* and Direct Reuses for Electrode Materials. *J. Environ. Manag.* **2026**, *404*, 129511. [[CrossRef](#)] [[PubMed](#)]
38. Keown, D.M.; Li, X.; Hayashi, J.I.; Li, C.Z. Evolution of Biomass Char Structure during Oxidation in O₂ as Revealed with FT-Raman Spectroscopy. *Fuel Process. Technol.* **2008**, *89*, 1429–1435. [[CrossRef](#)]
39. Mohanty, P.; Nanda, S.; Pant, K.K.; Naik, S.; Kozinski, J.A.; Dalai, A.K. Evaluation of the Physiochemical Development of Biochars Obtained from Pyrolysis of Wheat Straw, Timothy Grass and Pinewood: Effects of Heating Rate. *J. Anal. Appl. Pyrolysis* **2013**, *104*, 485–493. [[CrossRef](#)]
40. Zhang, C.; Zhang, L.; Gao, J.; Zhang, S.; Liu, Q.; Duan, P.; Hu, X. Evolution of the Functional Groups/Structures of Biochar and Heteroatoms during the Pyrolysis of Seaweed. *Algal Res.* **2020**, *48*, 101900. [[CrossRef](#)]
41. Islam, M.S.; Kwak, J.-H.; Nzediegwu, C.; Wang, S.; Palansuriya, K.; Kwon, E.E.; Naeth, M.A.; El-Din, M.G.; Ok, Y.S.; Chang, S.X. Biochar Heavy Metal Removal in Aqueous Solution Depends on Feedstock Type and Pyrolysis Purging Gas. *Environ. Pollut.* **2021**, *281*, 117094. [[CrossRef](#)] [[PubMed](#)]
42. Saini, J.; Garg, V.K.; Gupta, R.K. Cadmium Removal from Water by Green Synthesized Nanobioadsorbent [SiO₂@DOPP]: Mechanism, Isotherms, Kinetics and Regeneration Studies. *Sustain. Chem. Pharm.* **2021**, *19*, 100350. [[CrossRef](#)]
43. Eleryan, A.; Aigbe, U.O.; Ukhurebor, K.E.; Onyancha, R.B.; Eldeeb, T.M.; El-Nemr, M.A.; Hassaan, M.A.; Ragab, S.; Osibote, O.A.; Kusuma, H.S.; et al. Copper(II) Ion Removal by Chemically and Physically Modified Sawdust Biochar. *Biomass Convers. Biorefin.* **2022**, *14*, 9283–9320. [[CrossRef](#)]

44. Shao, Q.; Li, Y.; Wang, Q.; Niu, T.; Li, S.; Shen, W. Preparation of Copper Doped Walnut Shell-Based Biochar for Efficiently Removal of Organic Dyes from Aqueous Solutions. *J. Mol. Liq.* **2021**, *336*, 116314. [[CrossRef](#)]
45. Akaangee Pam, A.; Oluseun Elemile, O.; Ephraim Musa, D.; Chijoke Okere, M.; Olusegun, A.; Ahmed Ameh, Y. Removal of Cu (II) via Chitosan-Conjugated Iodate Porous Adsorbent: Kinetics, Thermodynamics, and Exploration of Real Wastewater Sample. *Results Chem.* **2023**, *5*, 100851. [[CrossRef](#)]
46. Waqas, M.; Aburizaiza, A.S.; Miandad, R.; Rehan, M.; Barakat, M.A.; Nizami, A.S. Development of Biochar as Fuel and Catalyst in Energy Recovery Technologies. *J. Clean. Prod.* **2018**, *188*, 477–488. [[CrossRef](#)]
47. Peres, C.B.; Rosa, A.H.; de Moraes, L.C. CO₂ Adsorption of Bagasse Waste Feedstock Using Thermogravimetric Analyses. *J. Therm. Anal. Calorim.* **2022**, *147*, 5973–5984. [[CrossRef](#)]
48. Tsai, C.K.; Horng, J.J. Transformation of Glass Fiber Waste into Mesoporous Zeolite-like Nanomaterials with Efficient Adsorption of Methylene Blue. *Sustainability* **2021**, *13*, 6207. [[CrossRef](#)]
49. He, R.; Peng, Z.; Lyu, H.; Huang, H.; Nan, Q.; Tang, J. Synthesis and Characterization of an Iron-Impregnated Biochar for Aqueous Arsenic Removal. *Sci. Total Environ.* **2018**, *612*, 1177–1186. [[CrossRef](#)] [[PubMed](#)]
50. Saravanan, R.; Aviles, J.; Gracia, F.; Mosquera, E.; Gupta, V.K. Crystallinity and Lowering Band Gap Induced Visible Light Photocatalytic Activity of TiO₂/CS (Chitosan) Nanocomposites. *Int. J. Biol. Macromol.* **2018**, *109*, 1239–1245. [[CrossRef](#)] [[PubMed](#)]
51. Zhang, M.; Ma, X.; Li, J.; Huang, R.; Guo, L.; Zhang, X.; Fan, Y.; Xie, X.; Zeng, G. Enhanced Removal of As(III) and As(V) from Aqueous Solution Using Ionic Liquid-Modified Magnetic Graphene Oxide. *Chemosphere* **2019**, *234*, 196–203. [[CrossRef](#)] [[PubMed](#)]
52. Amjlef, A.; Farsad, S.; Chaoui, A.; Ben Hamou, A.; Ezzahery, M.; Et-Taleb, S.; El Alem, N. Effective Adsorption of Orange G Dye Using Chitosan Cross-Linked by Glutaraldehyde and Reinforced with Quartz Sand. *Int. J. Biol. Macromol.* **2023**, *239*, 124373. [[CrossRef](#)] [[PubMed](#)]
53. Pitchaiya, S.; Eswaramoorthy, N.; Natarajan, M.; Santhanam, A.; Asokan, V.; Madurai Ramakrishnan, V.; Rangasamy, B.; Sundaram, S.; Ravirajan, P.; Velauthapillai, D. Perovskite Solar Cells: A Porous Graphitic Carbon Based Hole Transporter/Counter Electrode Material Extracted from an Invasive Plant Species Eichhornia Crassipes. *Sci. Rep.* **2020**, *10*, 6835. [[CrossRef](#)] [[PubMed](#)]
54. Abukhadra, M.R.; Ali, S.M.; Nasr, E.A.; Mahmoud, H.A.A.; Awwad, E.M. Effective Sequestration of Phosphate and Ammonium Ions by the Bentonite/Zelite Na-P Composite as a Simple Technique to Control the Eutrophication Phenomenon: Realistic Studies. *ACS Omega* **2020**, *5*, 14656–14668. [[CrossRef](#)] [[PubMed](#)]
55. Mansooramaei, Z.; Mowla, D.; Esmailzadeh, F.; Dashtian, K. Sustainable Biodiesel Production from Waste Cooking Oil Using Banana Peel Biochar-Fe₂O₃/Fe₂K₆O₅ Magnetic Catalyst. *Fuel* **2024**, *357*, 129821. [[CrossRef](#)]
56. Mohan, D.; Preetiva, B.; Chaubey, A.K.; Singit, J.S.; Mina, U.; Pittman, C.U., Jr. Eggplant Growth in Wheat Straw-, Wheat Straw Biochar- and Compost-Amended Soils: A Field Study of CO₂ Emission Dynamics, Soil Physicochemical, Microbial, and Nutrient Effects. *Waste Manag. Bull.* **2024**, *1*, 143–157. [[CrossRef](#)]
57. Banerjee, S.; Barman, S.; Halder, G. Elucidation of Preferential Elimination of Cr(VI) via Bioinspired Adsorbents: A Comparative Assessment. *Environ. Earth Sci.* **2019**, *78*, 121. [[CrossRef](#)]
58. Gao, L.; Li, Z.; Yi, W.; Li, Y.; Zhang, P.; Zhang, A.; Wang, L. Impacts of Pyrolysis Temperature on Lead Adsorption by Cotton Stalk-Derived Biochar and Related Mechanisms. *J. Environ. Chem. Eng.* **2021**, *9*, 105602. [[CrossRef](#)]
59. Zhao, M.; Dai, Y.; Zhang, M.; Feng, C.; Qin, B.; Zhang, W.; Zhao, N.; Li, Y.; Ni, Z.; Xu, Z.; et al. Mechanisms of Pb and/or Zn Adsorption by Different Biochars: Biochar Characteristics, Stability, and Binding Energies. *Sci. Total Environ.* **2020**, *717*, 136894. [[CrossRef](#)] [[PubMed](#)]
60. Li, H.; Dong, X.; da Silva, E.B.; de Oliveira, L.M.; Chen, Y.; Ma, L.Q. Mechanisms of Metal Sorption by Biochars: Biochar Characteristics and Modifications. *Chemosphere* **2017**, *178*, 466–478. [[CrossRef](#)] [[PubMed](#)]
61. Yuan, H.; Lu, T.; Huang, H.; Zhao, D.; Kobayashi, N.; Chen, Y. Influence of Pyrolysis Temperature on Physical and Chemical Properties of Biochar Made from Sewage Sludge. *J. Anal. Appl. Pyrolysis* **2015**, *112*, 284–289. [[CrossRef](#)]
62. Fu, P.; Hu, S.; Xiang, J.; Sun, L.; Su, S.; Wang, J. Evaluation of the Porous Structure Development of Chars from Pyrolysis of Rice Straw: Effects of Pyrolysis Temperature and Heating Rate. *J. Anal. Appl. Pyrolysis* **2012**, *98*, 177–183. [[CrossRef](#)]
63. Tran, H.N.; You, S.-J.; Hosseini-Bandegharaei, A.; Chao, H.-P. Mistakes and Inconsistencies Regarding Adsorption of Contaminants from Aqueous Solutions: A Critical Review. *Water Res.* **2017**, *120*, 88–116. [[CrossRef](#)] [[PubMed](#)]
64. Liu, L.; Huang, Y.; Meng, Y.; Cao, J.; Hu, H.; Su, Y.; Dong, L.; Tao, S.; Ruan, R. Investigating the Adsorption Behavior and Quantitative Contribution of Pb²⁺ Adsorption Mechanisms on Biochars by Different Feedstocks from a Fluidized Bed Pyrolysis System. *Environ. Res.* **2020**, *187*, 109609. [[CrossRef](#)] [[PubMed](#)]
65. Soudani, A.; Youcef, L.; Bulgariu, L.; Youcef, S.; Toumi, K.; Soudani, N. Characterizing and Modeling of Oak Fruit Shells Biochar as an Adsorbent for the Removal of Cu, Cd, and Zn in Single and in Competitive Systems. *Chem. Eng. Res. Des.* **2022**, *188*, 972–987. [[CrossRef](#)]
66. Pan, J.; Gao, B.; Guo, K.; Gao, Y.; Xu, X.; Yue, Q. Insights into Selective Adsorption Mechanism of Copper and Zinc Ions onto Biogas Residue-Based Adsorbent: Theoretical Calculation and Electronegativity Difference. *Sci. Total Environ.* **2022**, *805*, 150413. [[CrossRef](#)] [[PubMed](#)]

67. Nazal, M.K. Marine Algae Bioadsorbents for Adsorptive Removal of Heavy Metals. In *Advanced Sorption Process Applications*; IntechOpen: Rijeka, Croatia, 2019.
68. Zhao, S.; Ta, N.; Wang, X. Absorption of Cu(II) and Zn(II) from Aqueous Solutions onto Biochars Derived from Apple Tree Branches. *Energies* **2020**, *13*, 3498. [[CrossRef](#)]
69. Alsawy, T.; Rashad, E.; El-Qelish, M.; Mohammed, R.H. A Comprehensive Review on the Chemical Regeneration of Biochar Adsorbent for Sustainable Wastewater Treatment. *npj Clean Water* **2022**, *5*, 29. [[CrossRef](#)]
70. Lin, S.; Huang, W.; Yang, H.; Sun, S.; Yu, J. Recycling Application of Waste Long-Root Eichhornia Crassipes in the Heavy Metal Removal Using Oxidized Biochar Derived as Adsorbents. *Bioresour. Technol.* **2020**, *314*, 123749. [[CrossRef](#)] [[PubMed](#)]
71. Baskar, A.V.; Bolan, N.; Hoang, S.A.; Sooriyakumar, P.; Kumar, M.; Singh, L.; Jasemizad, T.; Padhye, L.P.; Singh, G.; Vinu, A.; et al. Recovery, Regeneration and Sustainable Management of Spent Adsorbents from Wastewater Treatment Streams: A Review. *Sci. Total Environ.* **2022**, *822*, 153555. [[CrossRef](#)] [[PubMed](#)]
72. Zhou, Z.; Xu, Z.; Feng, Q.; Yao, D.; Yu, J.; Wang, D.; Lv, S.; Liu, Y.; Zhou, N.; Zhong, M.E. Effect of Pyrolysis Condition on the Adsorption Mechanism of Lead, Cadmium and Copper on Tobacco Stem Biochar. *J. Clean. Prod.* **2018**, *187*, 996–1005. [[CrossRef](#)]
73. Zuo, W.; Shi, B.; Chen, S.; Zhou, X.; Duan, Y.; Liao, A. Low-Cost and Efficient Adsorbent Derived from Pyrolysis of *Jatropha curcas* Seeds for the Removal of Cu²⁺ from Aqueous Solutions. *Chem. Ecol.* **2018**, *34*, 655–674. [[CrossRef](#)]
74. Amin, M.; Chetpattananondh, P. Biochar from Extracted Marine *Chlorella* Sp. Residue for High Efficiency Adsorption with Ultrasonication to Remove Cr(VI), Zn(II) and Ni(II). *Bioresour. Technol.* **2019**, *289*, 121578. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.