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Arsenic removal from aqueous solutions by biochar derived from *Guadua inermis* bamboo

Remoción de arsénico en soluciones acuosas mediante biocarbón derivado del bambú *Guadua inermis*

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ABSTRACT

Arsenic (As) contamination is a significant global issue that demands the development of sustainable technologies to remove As, particularly from water resources. One such technology is adsorption by biochar, which has been demonstrated to be effective for arsenate (As(V)) and arsenite (As(III)) removal. Due to its unique properties, bamboo species have emerged as a promising source for biochar production for remediation purposes. In this study, we determined the physicochemical properties of a biochar derived from the Mexican bamboo *Guadua inermis* and evaluated its As adsorption capacity in aqueous solutions contaminated with As(V). The evaluation included kinetic studies and solutions with varying initial concentrations of As(V). The results showed that the biochar has a surface area of 230 $m^2\ g^{-1}$ and an organic matter content of 86.9 %. Moreover, it reached equilibrium within approximately three hours, removing 68.9 % of the initial As. Additionally, it removed 37-68 % of As from solutions containing 5-50 mg L^{-1} of As(V). These findings contribute to the characterization of the As adsorption capacity of biochar derived from *G. inermis* bamboo, laying the groundwork for research and sustainable utilization of the species for biotechnological purposes, while also contributing to the development of technologies to ensure As-free water.

KEY WORDS: *Guadua inermis*, bamboo, arsenic, biochar, adsorption.

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RESUMEN

La contaminación con arsénico (As) es un gran problema a nivel mundial que requiere del desarrollo de tecnologías sustentables para remover As principalmente de los recursos hídricos. Una de estas tecnologías es la adsorción con biocarbón, la cual ha demostrado ser efectiva para remover arsenato (As(V)) y arsenito (As(III)) del agua. Debido a sus características, las especies leñosas de bambú son un cultivo que puede ser aprovechado para la elaboración de biocarbón con fines de adsorción de contaminantes. En el presente estudio, se determinaron parámetros fisicoquímicos de un biocarbón derivado del bambú mexicano *Guadua inermis,* y se evaluó la capacidad de adsorción de As en soluciones acuosas contaminadas con As(V), a través de un estudio cinético y con diferentes concentraciones de As(V). Los resultados demostraron que el biocarbón presenta un área superficial de 230 m^2 g^{-1} y un contenido de materia orgánica de 86.9 %. Además, alcanzó un tiempo de equilibrio de alrededor de tres horas, logrando remover el 68.9 % del As inicial, y puede remover 37-68 % de As en soluciones contaminadas con 5-50 mg As(V) L^{-1}. Estos hallazgos contribuyen a la caracterización de la capacidad de adsorción de As, del biocarbón elaborado con el bambú *G. inermis,* estableciendo las bases para la investigación y aprovechamiento sustentable de la especie con fines biotecnológicos, y contribuyendo al desarrollo de tecnologías para garantizar agua libre de As.

PALABLAS CLAVE: *Guadua inermis*, bambú, arsénico, biocarbón, adsorción.

Introduction

Rising arsenic (As) levels in drinking water are a major global concern, as As is a highly toxic metalloid for living organisms and a carcinogen for humans (Huang *et al*., 2015; IARC, 2012). Over 120 countries have reported As concentrations in water exceeding the permissible limit for ensuring good water quality (10 μg L^{-1}), as established by the World Health Organization (Alchouron *et al*., 2022; WHO, 2023). Among the most affected countries is Mexico, with regions reporting drinking water contaminated with As levels ranging from 14.7 to 1004 μg L^{-1} (Colín-Torres *et al*., 2014; 2008; Monroy-Torres *et al*., 2009; Osuna-Martínez *et al*., 2021).

Currently, many methods are being developed to remove As from water. One of these is As removal through the use of different types of adsorbents, such as biochar, which is produced via the pyrolysis of organic materials in an oxygen-free or low-oxygen environment at temperatures below 800 °C (Amen *et al*., 2020). In general, biochar is characterized by a large specific surface area, abundant adsorption sites, charged organic functional groups, aromatic groups, neutral to

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alkaline pH, and a relatively high cation exchange capacity (Ahmad *et al*., 2016; Duwiejuah *et al*., 2020; Zhang *et al*., 2016), which contribute to its ability to adsorb a variety of contaminants, including metals, metalloids, methylene blue, nitrogenous compounds, phosphates, and aromatic compounds, among others (Alchouron *et al*., 2022; Yang *et al*., 2016; Zhang & Gao, 2013). In addition, biochar production is a cost-effective, environmentally friendly, and often sustainable technology, as it can be derived from crop residues, thereby preventing their disposal as waste.

In the last decade, bamboo has been considered a suitable plant for biochar production due to its wide distribution, economic importance, and morphological characteristics. Its cultivation offers several advantages, including rapid growth—ranging from 30 to 60 cm per day—annual harvesting without the need for replanting, and fast-growing and maturing culms (stems), which enable a continuous supply of material for various purposes, including biochar production (Bian *et al*., 2020; Chaturvedi *et al*., 2023). Recently, the potential of some bamboo-derived biochars to remove the most common ionic forms of As in aqueous systems, arsenate (As(V)) and arsenite (As(III)), has been demonstrated (Alchouron *et al*., 2021; Pinisakul *et al*., 2023; Zheng *et al*., 2023). For example, biochar produced from *Guadua chacoensis* bamboo has been shown to remove over 90 % of As(V) in solution (Alchouron *et al*., 2021). However, compared to other biochar sources like rice husk and other inorganic elements like lead, research on As removal using bamboo-derived biochar remains scarce. Given that bamboo species exhibit morphological and cellular composition differences, it is essential to individually characterize the As adsorption capacity of each biochar to assess its potential for specific applications (Alfei & Pandoli, 2024; Vithanage *et al*., 2017).

Guadua, belonging to the Bambusoideae subfamily, is a crop of ecological and economic importance in several American countries, with species distributed from Mexico to Argentina, and is considered woody due to its culms with thick cell walls resulting from high lignin content (Gutiérrez & De Lira Fuentes, 2020; Pérez-Alquicira *et al*., 2021). *Guadua inermis* is a native Mexican species found in the states of Campeche, Chiapas, Oaxaca, Tabasco, and Veracruz. It is used in construction, as a fuel source, and for crafting, among other uses. It is a caespitose bamboo, without spines or with poorly developed spines, featuring solid, cylindrical internodes 11 to 23 centimeters long. Its whitish-green culms reach heights of 4 to 12 meters and diameters of 2 to 10 centimeters. They are characterized by being strongly asymmetrical, densely pubescent, and solid (not hollow). This last feature could be advantageous for biochar production, as it is associated with higher lignin content (Orozco-Gutiérrez *et al*., 2022; Pérez-Alquicira *et al*., 2021; Ramírez-Ojeda *et al*., 2023). Solid waste generated from the *G. inermis* industry could be used for biochar production, contributing to the sustainable use of this species in the regions where it is cultivated and to the development of technologies for cleaning water contaminated with As or other pollutants. Therefore, the objective of this study was to evaluate the As removal capacity of biochar produced from *G. inermis* in an aqueous system, through an adsorption study as a function of time (kinetics) and different initial As(V) concentrations.

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Material and Methods

Reagents and Equipment

For the As adsorption experiments, the reagents used were sodium arsenate ($Na_2HAsO_4 \cdot 7H_2O$), concentrated nitric acid (HNO_3, 69 %, ACS), and a concentrated solution of 1000 µg As mL^{-1} (Instra-Analyzed®). All reagents were analytical grade and obtained from J.T. Baker. As quantification was performed using an atomic absorption spectrometer (AA-6300, Shimadzu, Kyoto, Japan). Deionized water (18 MΩ) was obtained using a PureLab-Q system (Elga).

Biochar Production and Chemical Characterization

The *G. inermis*-derived biochar was produced from culms of five-year-old, overmature plants of the woody bamboo species. Plants were sourced from the Tecomán experimental field of the National Institute for Forestry, Agricultural, and Livestock Research (INIFAP-Mexico) in Colima, Mexico. The biochar was generated through slow pyrolysis using a vertical pyrolysis furnace measuring 85 cm in height and 56 cm in diameter. This furnace was designed for small-batch production (less than 20 kg), making it suitable for use in rural communities and enabling the utilization of biomass derived from pruning activities.

For the process, approximately 16 kg of culm biomass with a moisture content of 10-12 %, determined according to the ASTM D1762-84 method (ASTM, 2021), were weighed. The culms, with diameters between 1 and 1.5 inches, were cut into 20 cm segments and placed in an 83 L internal cylindrical metal container within the pyrolysis furnace. A stepped heating ramp was then applied, reaching temperatures of 100, 180, 250, 350, and finally 550 °C, which was maintained for three hours. The temperature was monitored with a pyrometer, recording values between 500 and 560 °C during the maintenance period. Bamboo was used as fuel at the base of a larger external metal container. After the process, approximately 4.8 kg of biochar, designated as BG, were obtained and stored at room temperature (Gutiérrez & De Lira Fuentes, 2020).

The BG biochar was physicochemically characterized according to the following measurement standards. The pH value was determined using the ASTM D1293-18 method (ASTM, 2018), while the carbon content was determined with the ASTM D6866 method (ASTM, 2022). The surface area was measured based on the ASTM D-4607-14 method (ASTM, 2021), and the organic matter (OM) content was calculated according to the UNE 103204 method (Campillo & Rodriguez, 2004). The concentration of inorganic elements was determined in accordance with the specifications of the Mexican Official Standard NOM-021-RECNAT-2000. Inorganic nitrogen (N), extractable phosphorus (P), and potassium (K) were quantified using the AS-08 (micro-Kjeldahl procedure), AS-10, and AS-13 methods, respectively (NOM, 2002). Electrical conductivity (EC) was measured with a multiparameter meter (PCSTestr35, Oaklon), following the manufacturer's specifications.

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Arsenic Adsorption Experiments

Small pieces of biochar (<1 cm) were crushed and filtered through No. 20 and No. 12 sieves to recover particles sized between 0.8 and 1.7 mm. To remove impurities, the recovered particles were submerged in deionized water, and those that precipitated were selected and dried at 60 °C for 72 hours. Once dry, 50 to 100 mg of BG was used for the adsorption experiments (Wang *et al*., 2013).

To evaluate the As adsorption capacity of BG, two experiments were conducted: 1) Adsorption as a function of time (a kinetic study) and 2) Adsorption as a function of initial As(V) concentration. As(V) was supplied as $Na_2HAsO_4 \cdot 7H_2O$.

Kinetic Study

The kinetic study was conducted using the following method. 25 mL of a solution with 10 mg L^{-1} of As(V) and a pH adjusted to 7 was added to 50 mL low-density polypropylene tubes (Falcon) to equilibrate 50 mg of adsorbent for 5, 15, 30, 60, 120, 180, 240, or 360 minutes in a shaker at 200 rpm and 25 °C (Alchouron *et al*., 2020). After each exposure time, the solutions were filtered with Whatman paper (No. 2) and stored at room temperature until As quantification. A minimum of 3 independent replicates and 2 control samples, consisting of 25 mL of As(V)-free solution with 50 mg of adsorbent, were included for each time evaluated. The experimental As adsorption data were analyzed and fitted with the pseudo-second-order model.

Adsorption as a Function of As(V) Concentration

The As adsorption capacity of BG was evaluated in solutions contaminated with 5, 10, 25, or 50 mg L^{-1} of As(V) and a pH adjusted to 7. Fifty mL of the As(V)-added solutions were placed in 200 mL flasks with 100 mg of biochar (adsorbent) and subjected to shaking at 300 rpm and 25 °C for 60 minutes (Alchouron *et al*., 2020). After the exposure time, the solutions were filtered with Whatman paper (No. 2) and stored at room temperature until As quantification. A minimum of 3 independent replicates per As(V) concentration evaluated and 2 control samples, consisting of 50 mL of As(V)-free solution and 100 mg of adsorbent, were analyzed. The experimental As adsorption data were analyzed and plotted to obtain the best-fit model.

Arsenic Adsorption Analysis

Arsenic Quantification

The solutions recovered after the shaking time were filtered with nitrocellulose membranes (0.45 μm, Whatman) prior to quantifying the As concentration in the solution by flame atomic absorption spectrometry (EAA) using a wavelength of 193.7 nm, an air-acetylene mixture (3.7 L min^{-1}), and a burner slit of 0.2 nm. For each reading and calculation of As concentration, a standard As curve (0, 5, 10, 20, 30, 50, and 60 μg As mL^{-1}) was used, prepared from a concentrated As solution (1000 μg As mL^{-1}). All glassware used for sample and standard curve

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preparation was previously soaked in a 10 % (v/v) HNO_3 solution for 12 hours (Alcántara, 2013; Alcántara-Martínez *et al*., 2016).

Estimation of Arsenic Adsorption and Removal

Based on the As concentration results (mg L⁻¹) in the solutions, the adsorption and percentage of As removal for each treatment (different times and concentrations evaluated) were estimated using Equations 1 and 2, respectively:

$$q = \frac{(c_0 - c_f) x V}{P} \quad (1)$$

$$\%\ As\ removal = \frac{(c_0 - c_f)}{c_0} x\ 100 \quad (2)$$

Where adsorption (q) is the amount of As adsorbed by the adsorbent (mg g^{-1}) as a function of As concentration (q_e) or exposure times (q_t), C_0 and C_f are the initial and final concentrations of As(V) (mg L^{-1}), respectively, while V is the total volume (L) of the solution, and P is the weight (g) of the biochar. The percentage of As removal is an estimate of the amount of As removed by the adsorbent relative to the initial amount of As(V) in the solution (Lyu *et al*., 2022; Rahman *et al*., 2022).

Kinetic Model

To estimate the equilibrium time for As adsorption and obtain kinetic parameters, the data were fitted to the pseudo-second-order model using the following Equation 3 (Mamtimin *et al*., 2023):

$$\frac{t}{q_t} = \frac{1}{(K_2\ q_{e-cal}{}^2)} + \frac{t}{q_{e-cal}} \quad (3)$$

Where K_2 is the pseudo-second-order rate constant (g/mg·min), q_{e-cal} represents the maximum amount of As that the biochar can adsorb when equilibrium is reached in the adsorption system (mg g^{-1}), t is the contact time (minutes), and q_t is the amount of As adsorbed by the

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absorbent at each sampling time (mg g^{-1}), calculated according to Equation 1. The linear Equation 3 was plotted as t/q_t versus t. From the values of the slope and y-intercept, the kinetic parameters (K_2 and q_{e-cal}) were estimated (Ho *et al*., 2001; Mamtimin *et al*., 2023).

Results and Discussion

Bamboo-derived biochar has shown potential for removing inorganic elements from water, such as copper (Cu), lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), zinc (Zn), fluoride (F), and As, as well as molecules like methylene blue, N-nitrosodimethylamine, tetracycline, nitrate, ammonium, phosphate (PO_4^{3-}), and aromatic compounds, among others (Alchouron *et al*., 2022; Chen *et al*., 2022; Tan *et al*., 2012; Wendimu *et al*., 2017; Yang *et al*., 2016; Zhou *et al*., 2014). Among inorganic contaminants, As has been one of the least studied. In this study, biochar produced from *G. inermis* (BG) demonstrated high As removal in solutions contaminated with As(V).

Biochar Characterization

The yield obtained from the production of *G. inermis* biochar was 27–30 %, similar to that reported for biochars derived from *Guadua angustifolia* (27–40 %) (Gutiérrez & De Lira Fuentes, 2020; Hernández-Mena *et al*., 2014), and within the range observed for other plant sources (Amen *et al*., 2020). Compared with biochars derived from other biomass sources, bamboo biochar has been reported to provide competitive yields and a high carbon content, likely attributable to its elevated lignin content. Moreover, the pyrolysis temperature employed in this study (<700 °C) may have contributed to the relatively high yield obtained (Kim *et al*., 2020; Odega *et al*., 2023).

Among its characteristics, BG biochar exhibits a high content of organic matter OM, C, and a large surface area (Table 1). The OM originates from the thermal decomposition of cellulose, hemicellulose, and lignin during pyrolysis, compounds abundant in *Guadua* culms (Kim *et al*., 2020). The biomass composition, along with the pyrolysis temperature, also determines other physical properties, such as the biochar's surface area. In the case of BG, this surface area is higher than that reported for other pristine bamboo-derived biochars, such as *Bambusa beecheyana* (191.9 $m^2\ g^{-1}$) and *G. chacoensis* (6.7 $m^2\ g^{-1}$), as well as for biochars from other plant sources, including woody species like pine or oak, with values between 2.04 and 6.6 $m^2\ g^{-1}$ (Alchouron *et al*., 2021; Pinisakul *et al*., 2023; Vithanage *et al*., 2017).

The C content falls within the range reported for bamboo biochars, between 33–82 % (Alchouron *et al*., 2020; Gutiérrez & De Lira Fuentes, 2020; Hernandez-Mena *et al*., 2014), whereas the P and K content, which are part of the biochar's mineral residue, may originate from the high silica levels characteristic of bamboo culms (Alchouron *et al*., 2021; Alfei & Pandoli, 2024).Taken together, these findings suggest that BG biochar exhibits favorable properties for As adsorption. However, further studies focusing on the characterization of surface functional

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groups are recommended to better understand their influence on the adsorption process and on the structure of BG biochar.

Guadua inermis biochar shows rapid adsorption

The adsorption of As by BG was evaluated in a kinetic study. The results fitted well to the pseudo-second-order model, suggesting that As adsorption is primarily influenced by chemical interactions between As(V) and the biochar surface (Rahman *et al*., 2022). The fit with the linearized model, where q_t (mg g^{-1}) is the amount of As adsorbed at time (*t*), showed a high correlation value ($R^2 \geq 0.99$) (Figure 1). The calculated $q_{e\text{-}cal}$ value is 3.856 mg g^{-1}, representing the maximum amount of As the biochar can adsorb at equilibrium, aligning with the experimental value when the adsorbed As concentration no longer increases after three hours (3.55 ± 0.6 mg g^{-1}), corresponding to 68.9 % As removal (Figure 1).

BG biochar exhibited adsorption kinetics that could be considered rapid, reaching equilibrium within the first eight hours, specifically at three hours (Alchouron *et al*., 2022). This result suggests efficient As removal in a short time, a common characteristic among biochars derived from woody plants such as pine, Japanese oak, and bamboo (Alchouron *et al*., 2020; Lyu *et al*., 2022). Short equilibrium times, between one and five hours, have been reported for other pristine bamboo-derived biochars in the removal of As(V) or As(III) in aqueous solutions (Alchouron *et al*., 2020; Lyu *et al*., 2022; Pinisakul *et al*., 2023). In general, these biochars have exhibited short equilibrium times despite the wide range of experimental conditions employed (Table 2). For example, biochar produced from *G. chacoensis* reached equilibrium within one hour when exposed to a 10 mg L^{-1} As(V) solution (Alchouron *et al*., 2020), whereas biochar derived from *B. beecheyana* required five hours to reach equilibrium in a solution containing 0.05 mg L^{-1} As(V) (Pinisakul *et al*., 2023).

Nevertheless, the differences observed in removal percentages among different biochars may be attributed not only to the diversity of experimental factors but also to the specific morphological characteristics of each bamboo species. For instance, although *G. inermis* and *G. chacoensis* belong to the same genus and both are considered woody bamboo species, the solid culms characteristic of *G. inermis* could significantly contribute to the development of a large surface area (Table 1), as well as other structural properties that enhance As adsorption (Pérez-Alquicira *et al*., 2021; Ramírez-Ojeda *et al*., 2023).

In this study, BG not only demonstrated the ability to remove As in a relatively short time (Figure 1B) but also showed a remarkable 54 % removal in the first 30 minutes, reaching 67.2 % after one hour (Figure 1A). Although BG reaches equilibrium at approximately three hours, As removal did not show a significant increase after the first hour. Consequently, tests with different As(V) concentrations were conducted for one hour.

Several kinetic studies report a significant effect of the incorporation of compounds into the biochar structure on its As adsorption capacity and rate (Benis *et al*., 2020; Rahman *et al*., 2022; Van *et al*., 2015). In particular, the addition of Fe-based compounds, combinations of Ca, Mg, and Al, or chitosan can substantially enhance the As removal rate of bamboo-derived biochar (Alchouron *et al*., 2020; Lyu *et al*., 2022; Pinisakul *et al*., 2023). For a more accurate characterization of As removal time by BG, it is recommended to study the effect of various experimental parameters, including structural modification with primarily Fe-based compounds.

Guadua inermis biochar removes a high percentage of As

As removal by BG was evaluated in solutions with different As(V) concentrations ranging from 5 to 50 mg L^{-1} over a period of 1 hour. The results show a linear fit of adsorption data (q_e) as a function of initial As(V) concentration (Figure 2B), indicating that the amount of As adsorbed increases proportionally with the initial As concentration in the solution (C_0). This suggests that the data do not fit the Langmuir isotherm model, typically used to estimate the maximum As adsorption capacity under equilibrium conditions, i.e., when the amount of As adsorbed by the biochar remains constant (Vithanage *et al*., 2017). The observed linearity aligns with reports for other bamboo-derived and source-derived biochars, which exhibit an apparent linear trend at initial concentrations below 50 mg L^{-1} of As(V). However, these same studies indicate that adsorption reaches equilibrium at concentrations above this value (Alchouron *et al*., 2020; Rahman *et al*., 2022). Therefore, it is necessary to study BG adsorption in solutions with initial As(V) concentrations higher than 50 mg L^{-1} to find the best non-linear fit for the isotherm model and estimate BG's maximum adsorption capacity.

Nevertheless, the results obtained in this study demonstrate that BG biochar adsorbs As concentrations within the range reported for other biochars tested in As(V) solutions (2.59–868 mg g^{-1}). Specifically, BG showed a maximum adsorption value of 16.0 ± 1.2 mg g^{-1}, very similar to those reported for some surface-enhanced biochars, such as rice husk-Fe biochar (17 mg g^{-1}), poplar-AlOOH biochar (17 mg g^{-1}), wheat residue-Bi_2O_3 biochar (16.21 mg g^{-1}), and red oak-Fe^0 biochar (15.58 mg g^{-1}), among others (Bakshi *et al*., 2018; Samsuri *et al*., 2013; Zhang & Gao, 2013; Zhu *et al*., 2016).

The notable As adsorption capacity of pristine BG biochar could be attributed to the structural properties conferred by bamboo. Primarily, a high content of lignocellulosic compounds (lignin, cellulose, and hemicellulose) is related to the generation of a large surface area due to numerous micropores and a high percentage of OM (Chaturvedi *et al*., 2023; Dong *et al*., 2014). In particular, the high OM content in BG could participate in redox processes that modulate the oxidation state of As (e.g., oxidation of As(III) to As(V)) by acting as an electron donor and acceptor, thereby influencing interactions between As and chemical groups on the surface (Dong *et al*., 2014; Kim *et al*., 2020). Additionally, compared to other plant sources such as woody plants or plant residues, bamboo contains a higher amount of lignin with more phenolic hydroxyl groups and more silica in the culms, which persists after pyrolysis and may positively influence As adsorption (Alchouron *et al*., 2020; Chaturvedi *et al*., 2023; Liu *et al*., 2014; Sharma *et al*., 2018; Pinisakul *et al*., 2023). These characteristics may explain the high As removal by BG, which reached 68 % when exposed to a solution with 50 mg L^{-1} of As(V) (Figure 2A), indicating a higher removal rate than reported for pristine biochars produced from other sources, such as poplar (*Populus* genus), rice husk, and municipal solid waste, with removal percentages of less than 10.5 %, 25 %, and 55 %, respectively (Agrafioti *et al*., 2014; Xu *et al*., 2020).

In contrast, some pristine bamboo-derived biochars have shown As removal percentages below 50 %. For example, a biochar produced from bamboo biomass removed 5 % of As(V) in a complex solution with Pb(II), Cr(VI), PO_4^{3-}, methylene blue, and 21 mg L^{-1} of As(V) (Zhou *et al*., 2014), while another bamboo-derived biochar removed approximately 25 % of As(III) in a mixed solution with 80 mg L^{-1} of As(III)-Cd(II) (Lyu *et al*., 2022). As bamboo is the source of the biochar, distinctive characteristics such as porous surface, lignin, and silica content may be similar to BG. However, various experimental factors could significantly influence the adsorption process, such as As concentration in the solution, the chemical form of the metalloid, temperature, pH, contact time, and the presence of additional ions besides As in the solution, among others (Amen *et al*., 2020; Srivastav *et al*., 2022; Vithanage *et al*., 2017). For instance, a high phosphorus content has been reported to reduce As(V) removal by more than 50 %, as As(V) and PO_4^{3-} compete for the same adsorption sites (Alchouron *et al*., 2021).

Other key factors influencing adsorption efficiency include the conditions under which pyrolysis is performed to produce the biochar, such as temperature. Biochars produced via slow pyrolysis at low temperatures (300–600 °C), as in the case of BG, generally exhibit low hydrophobicity and aromaticity and a high content of C=O and C-H functional groups that facilitate contaminant adsorption (Amen *et al*., 2020; Vithanage *et al*., 2017). Temperature also influences properties such as surface area and carbon content, which are high in BG and may further contribute to its performance as an adsorbent. For example, pristine biochar made from *G. chacoensis* with a lower surface area (6.7 m^2 g^{-1}) and carbon content (33 %) removed about 30 % less As than BG after two hours under similar experimental conditions (Alchouron *et al*., 2020).

Taken together, the results of this study demonstrate BG's potential to remove at least 37 % of the metalloid present in water under the experimental conditions applied, without the addition of compounds to its structure, thereby reducing production costs and complexity.

To further characterize the As adsorption capacity of BG, it is recommended to conduct a more in-depth investigation of the experimental factors influencing its adsorption performance. For example, modifying the temperature during the adsorption process could be beneficial. It has been reported that increasing the temperature can significantly improve the adsorption of various types of biochars. For instance, biochar derived from *G. chacoensis* increased its As adsorption capacity (mg g^{-1}) by 3.5 times when the temperature was raised from 25 °C to 40 °C in a solution with 600 mg L^{-1} of As(V) (Alchouron *et al*., 2020). In addition, modifying the surface of BG with specific compounds may enhance its adsorption capacity, as observed in bamboo-derived biochars that achieved As removal increases ranging from 19.7 % to 236 % (Alchouron *et al*., 2020; Lyu *et al*., 2022; Pinisakul *et al*., 2023; Zheng *et al*., 2023; Zhou *et al*., 2014).

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Limitations and Perspectives

To our knowledge, this is the first study to evaluate As adsorption by biochar derived from *G. inermis*, a native Mexican bamboo, obtained through slow pyrolysis using an accessible method adaptable to rural communities. However, it is important to consider that biochar properties may vary depending on the plant batch, which could affect its efficacy. Therefore, it is recommended that future research evaluate the influence of these variations and establish ranges of effectiveness for adsorption.

Regarding As quantification, the technique used in this study (EAA) may have limitations in sensitivity, which could affect the precise detection of very low contaminant concentrations. Thus, incorporating more sensitive complementary analytical methods, such as inductively coupled plasma mass spectrometry (ICP-MS), would be beneficial to expand the range of evaluated conditions. Despite these limitations, the obtained results demonstrate significant adsorption potential, highlighting the importance of understanding the involved mechanisms. To achieve this, structural studies of the biochar are required using techniques such as Fourier-transform infrared spectroscopy (FTIR) or X-ray photoelectron spectroscopy (XPS) to identify functional groups. In addition, isotherm and kinetic analyses under varying experimental conditions (e.g., pH, temperature, high and low As concentrations, presence of other metals, or surface modifications of the material) are required, along with the evaluation of potential byproduct release during the adsorption process. These studies would enable projections of biochar performance under varied environmental or contamination conditions. Once characterized, its application could be scaled up to practical systems, such as reusable biofilters operated in continuous flow columns, in which the treated volume is estimated prior to requiring regeneration. Finally, to validate the use of *G. inermis* biochar as a sustainable alternative for remediating As-contaminated water bodies, it will be essential to integrate technical, economic, and social research.

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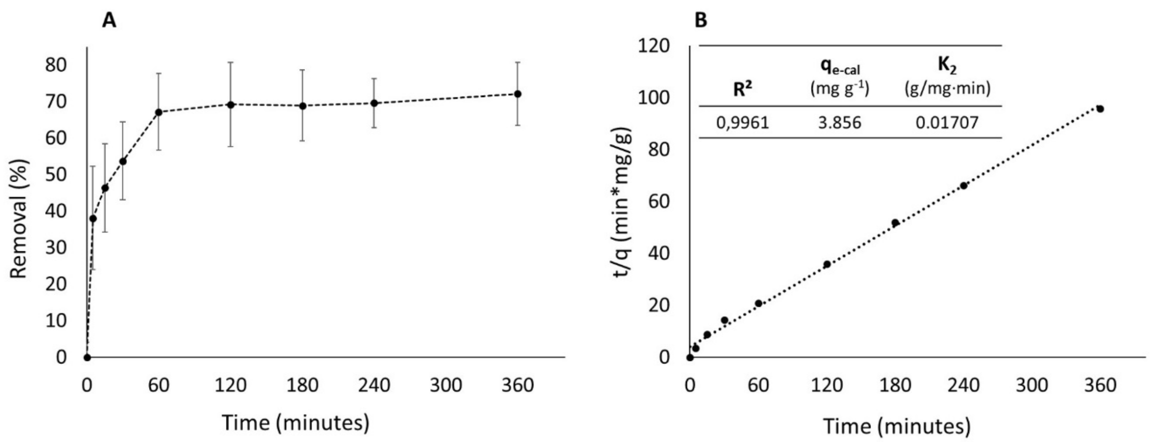

Figure 1. Arsenic adsorption by BG as a function of time.

(A) Arsenic removal percentage over time. (B) Linear fit of the pseudo-second-order kinetic model for adsorption at different time points. The calculated kinetic parameters are presented. R^2: correlation coefficient; $\boldsymbol{q_{e\text{-}cal}}$: maximum amount of As that the biochar can adsorb at equilibrium; K_2: pseudo-second-order rate constant.

Source: Own elaboration based on results.

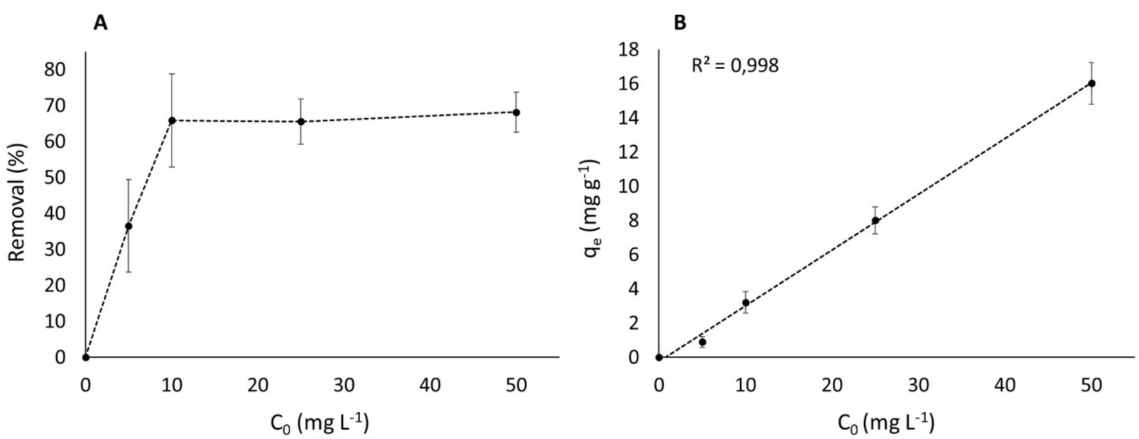

Figure 2. Arsenic adsorption by BG as a function of the initial As(V) concentration.

(A) Arsenic removal percentage at each evaluated initial As(V) concentration ($\boldsymbol{C_0}$). (B) Increase in adsorption capacity ($\boldsymbol{q_e}$) as a function of the initial As(V) concentration ($\boldsymbol{C_0}$).

Source: Own elaboration based on results.

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Table 1. Physicochemical parameter values of BG.

pH	EC	N	C	C:N	Surface area	OM	P	K
	dS/m	%			$m^2 g^{-1}$	%	mg kg^{-1}	
6.41	2.35	0.66	50.54	76.34	230	86.94	8532.8	312.60

EC = electrical conductivity; N = nitrogen; C = carbon; C:N = carbon-to-nitrogen ratio; OM = organic matter; P = phosphorus; K = potassium.

Source: Own elaboration based on results.

Table 2. Comparison of experimental variables and As adsorption parameters among studies using pristine bamboo-derived biochars in As-contaminated solutions.

Ionic species of As	Initial As concentration (mg L^{-1})	Initial pH	Maximum As adsorption (mg g^{-1})	Maximum As removal (%)	Equilibrium time	Bamboo species	Reference
As(V)	10	7	3.86	68.9	3 h	*G. inermis*	This study
As(V)	10	7	~2.2	~45	1 hr	*G. chacoensis*	Alchouron *et al*., 2020
As(V)	21	ND	ND	<5	ND	ND (bamboo biomass)	Zhou *et al*., 2014
As(V)	0.05	7	<0.001	ND	5 hr	*Bambusa beecheyana*	Pinisakul *et al*., 2023
As(III)	ND	4.5 y 5	~15	~20	100 min	ND (bamboo biomass)	Lyu *et al.*, 2022

ND: Not define.

Source: Own elaboration based on results and published papers.

Conclusions

Rapid kinetics and high adsorption capacities are two key characteristics for biochar characterization. This study demonstrates the ability of biochar derived from *G. inermis* to remove a high percentage of As from water in a relatively short time, contributing to the understanding of this biochar's As adsorption capacity in an aqueous system. For a comprehensive understanding of the efficacy and mechanisms involved in As removal by BG, it is suggested to estimate the maximum adsorption capacity for As(V) and As(III) under different experimental conditions and to characterize the chemical composition of its structure. Taken together, these studies could lay the foundation for developing water purification systems at both household and potentially industrial scales, based on bamboo-derived biochar.

Author Contributions

Work conceptualization, NAM and GOG; methodology development, NAM and GOG; experimental validation, NAM, GOG, and TVS; result analysis, NAM; data management, NAM; manuscript writing and preparation, NAM and GOG; writing, review, and editing, NAM, GOG, TVS, and CMO; project administration, GOG and TVS; funding acquisition, NAM, GOG, and TVS.

All authors of this manuscript have read and approved the published version.

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Conflict of Interest

The authors declare no conflict of interest.

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