CHEMICAL ENGINEERING TRANSACTIONS
VOL. 121, 2025

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov

ISBN 979-12-81206-22-9; **ISSN** 2283-9216

DOI: 10.3303/CET25121032

A Comparative Study of Bamboo Biochar and Hydrochar for Pollutant Removal

Sebastian Ponce[a], Mateo Paucar[a], Margaret Stern[b], David Egas[a], Herman A. Murillo[a,*]

[a]Department of Chemical Engineering, Universidad San Francisco de Quito USFQ, Diego de Robles s/n y Av. Interoceánica, Quito 170901, Ecuador
[b]EcoDecision, Edif. Zyra. Av. Portugal, Quito, Ecuador
hmurillor@usfq.edu.ec

Biochar and hydrochar produced from the culms (woody stems) of two South American bamboo species were tested for pollutant removal. *Guadua angustifolia* is a large and locally well-known commercial bamboo species native to Colombia, Ecuador, and Peru, whereas G. weberbaueri is smaller and strictly found in the Amazon region. The thermochemical conversion of their woody fibers was conducted through (a) pyrolysis at 400°C for biochar, and (b) hydrothermal carbonization (HTC) at 240°C for hydrochar production. Both biochar and hydrochar were tested as adsorbent materials to remove methylene blue (MB) dye and heavy metals (lead Pb^{2+}, cadmium Cd^{2+}, copper Cu^{2+}, and chromium Cr^{2+}) in aqueous medium. Laboratory results demonstrated that bamboo hydrochar exhibited a significant adsorption capacity for MB, whereas biochar showed better performance in removing heavy metals. A composite material made by combining both adsorbent materials improved the overall pollutant removal efficiency (MB and heavy metals). Characterization studies (e.g., SEM/EDS, XRD, and FTIR) revealed structural and compositional differences between these closely-related bamboo species that affected their adsorption efficiency. These findings demonstrate the potential of bamboo-derived biochar and hydrochar adsorbent materials for wastewater decontamination.

1. Introduction

Ecuador's Amazon region covers approximately one-third of the nation's area, and the escalating industrial activity in the region has led to a concerning rise in contamination of both surface and groundwater (Cabrera et al., 2023). Heavy metals in the environment (e.g., soils, sediments, water, fish, trees, air) often exceed the limits established by environmental regulations and are particularly dangerous as their accumulation can cause chronic illnesses in humans and pose a severe threat to aquatic ecosystems (Wang et al., 2022).
The need for effective wastewater treatment is particularly pressing in regions like the Amazon, where a significant share of wastewater remains untreated. According to Arcentales-Ríos et al (2022), only 25% of the wastewater in the Amazon is treated, with approximately 56% discharged directly into rivers without any prior treatment. Traditional wastewater treatment techniques, although effective, often rely on resource-intensive processes and harsh chemicals, raising concerns about environmental sustainability and operational costs. In recent years, biochar and hydrochar, both carbonaceous materials derived from biomass through thermochemical conversion processes, have emerged as promising alternatives for wastewater treatment.
Biochar is produced through a process called pyrolysis, where biomass is subjected to high temperatures (typically 300-700°C) in an oxygen-limited environment (An et al., 2024). This controlled heating triggers the breakdown of complex organic compounds into simpler molecules, releasing volatile gases while leaving behind a carbon-rich solid residue known as biochar. Inert conditions promote the formation of a stable, highly porous structure with various applications, including adsorbent, antibacterial material, and soil remediation (Moreno et al., 2024). Hydrochar, on the other hand, is obtained via hydrothermal carbonization (HTC). This process involves treating wet biomass with elevated temperatures (typically ≤ 250°C) and pressures in a water-rich environment. Simulating natural geological processes over a shorter timeframe, HTC triggers the breakdown of

Paper Received: 26 August 2025; Revised: 14 October 2025; Accepted: 08 December 2025
Please cite this article as: Ponce S., Paucar M., Stern M., Egas D., Murillo H.A., 2025, A Comparative Study of Bamboo Biochar and Hydrochar for Pollutant Removal, Chemical Engineering Transactions, 121, 187-192 DOI:10.3303/CET25121032

complex organic compounds within the biomass, resulting in the formation of a hydrophobic (water-repelling) carbon-rich material called hydrochar (Heidari et al., 2019). The HTC process involves a combination of chemical reactions and dehydration, ultimately converting wet biomass into a solid substance with a distinct porous nature and a hydrophobic surface (Murillo et al., 2021). Despite the promising potential of both biochar and hydrochar, existing research primarily focuses on utilizing readily available biomass sources, such as wood chips and agricultural residues. Ecuador's diverse native bamboos have only recently been considered for biochar and hydrochar production. Notably, *Guadua angustifolia*, a commercially valuable bamboo species, has shown promise in removing cadmium from contaminated water (Navas-Cárdenas et al. 2023). However, a closely related bamboo species, *G. weberbaueri*, that grows only in the Amazon region, has not been explored for its biochar and hydrochar potential.
This research aims to address this knowledge gap by investigating the potential of biochar and hydrochar derived from these two bamboo species for wastewater treatment applications. However, this approach extends beyond simply evaluating individual materials, as it also aims to explore the synergistic effects of combining biochar and hydrochar in composite materials. By leveraging the unique adsorption properties of both biochar and hydrochar, the objective is to develop a more efficient and targeted approach to wastewater remediation, particularly for the removal of heavy metals. This study seeks to contribute valuable insights into the feasibility and efficacy of utilizing Amazonian bamboo as a sustainable and cost-effective solution for wastewater remediation in the region.

2. Materials and methods

The methodology for the thermochemical conversion of bamboo fibers and their application as adsorbent materials is detailed in the following subsections.

2.1. Materials

Small samples (1-2 stems) of each bamboo species were collected from their natural environment in Pichincha Province (*G. angustifolia*) and Zamora-Chinchipe Province (*G. weberbaueri*) in Ecuador. Since bamboos are fast-growing clonal plants, it is non-destructive and straightforward to use a machete to remove a few above-ground mature stems from a single stand of bamboo, as was done to procure material for these experimental trials.

2.2. Thermochemical conversion of bamboo material

Bamboo stems were cut with a disc saw into sections of approximately 15 cm (Figure 1a). These small sections underwent physical pretreatment by hitting them with a hammer to break their structure and soften the fibers which were subsequently cut with scissors into 2 x 3 cm rectangular pieces (Figure 1b). These pieces of bamboo fiber were used for the thermochemical treatments of hydrothermal carbonization and pyrolysis.

2.2.1. Hydrothermal carbonization (HTC)

Bamboo pieces (15 g) were placed in a high-pressure reactor (500 mL capacity; model TGYF-B-500ML) with 300 mL of distilled water (i.e., a biomass-to-water ratio=1:20) with magnetic stirring at 1000 rpm. This equipment was set to a reaction temperature of 240°C and a reaction time of 60 min. Following the hydrothermal treatment, the reactor was allowed to cool to room temperature, at which point the hydrochar and process water mixture was vacuum-filtered. The process water was discarded, and the hydrochar solid was washed three times with distilled water and dried overnight at 105°C before further processing.

2.2.2. Pyrolysis

Bamboo pieces (10 g) were loaded into a graphite container inserted in the tubular reactor. Once securely in place, the reactor was covered, and safety devices were reinstalled. Gaseous nitrogen was introduced continuously to ensure an oxygen-free atmosphere. The reactor was configured to a heating rate of 5°C/min until reaching 400°C, with a dwell time of 1 hour at this temperature.

2.3. Adsorption experiments

The prepared hydro and biochar materials (Table 1) were individually subjected to adsorption experiments with methylene blue (MB) and heavy metals to evaluate their respective adsorption capacities. A graphical description of experiments is summarized in Figure 1c.

Table 1: Synthesized hydrochars and biochars

Materials	Nomenclature
Hydrochar from *G. angustifolia*	H-GA
Hydrochar from *G. weberbaueri*	H-GW
Biochar from *G. angustifolia*	B-GA
Biochar from *G. weberbaueri*	B-GW

Methylene Blue (MB) adsorption experiments: A 50 mL MB solution of 0.05 mM was placed with 2 g/L of adsorbent (i.e., hydrochar or biochar) in a 100 mL beaker at room temperature and mixed at 1000 rpm using magnetic stirring. Aliquots were taken regularly and filtered with syringe filters to remove adsorbent particles. MB concentration was determined by measuring the maximum absorbance at a wavelength of 668 nm with a Cecil CE204 UV-Visible spectrophotometer (Buck Scientific, USA). The adsorption efficiency was calculated as the percentage of adsorption at equilibrium.

Heavy metal adsorption experiments: Target pollutants (Pb^{2+}, Cd^{2+}, Cu^{2+} , and Cr^{2+}) were measured using a 230ATS Atomic Absorption Spectrometer (Buck Scientific, Ansonia, CT, USA). Calibration curves were generated using diluted standard solutions, following the guidelines and detection limit of the equipment. Five standards were used for each calibration curve, and measurements were taken in triplicate. A typical experiment used 500 mg of adsorbent material (i.e., hydrochar or biochar) and 20 mL of the metal solution, placed together in a 50 mL Falcon tube, and mixed for 1 min using a Fisher Scientific 945410 Vortex Mixer (USA). The initial concentration of the metal solution reflected the maximum detection limit of the equipment. After that, the Falcon tube was centrifuged at 3500 rpm (rotor diameter: 29 cm) for 10 min to separate the adsorbent material from the metal solution. These readings were used to determine the percentage of metal removed based on a calibration curve.

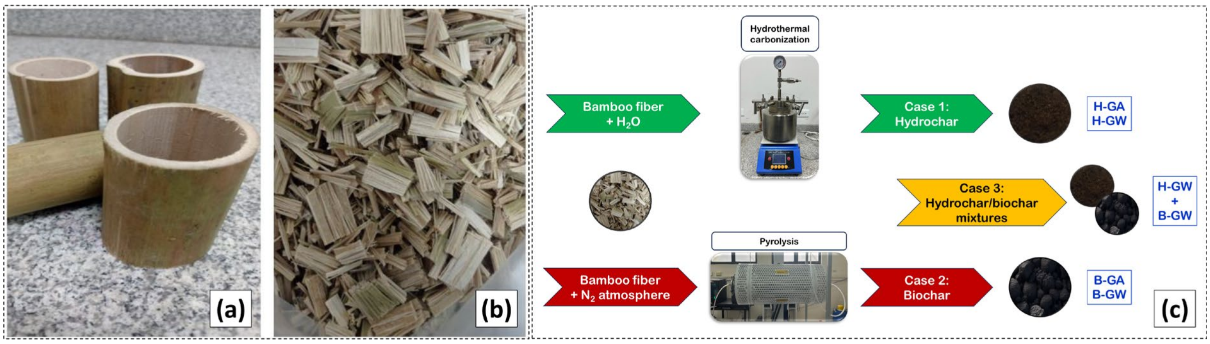

Figure 1: Woody bamboo stems were reduced (a) to small sections, and then (b) softened into smaller fibrous pieces that were subjected to thermochemical conversion. (c) Diagram of experimental process

2.4. Characterization studies

The morphology of the raw bamboo material from each species was examined using a Mira 3 microscope (Tescan, Brno-Kohoutovice, Czech Republic) equipped with a Schottky Field Emission Gun (FEG-SEM). For imaging, samples were mounted on SEM stubs and coated with a 20 nm layer of 99.99% pure gold using a sputter coater. Energy-dispersive spectroscopy (EDS) analysis was performed using a Bruker X-Flash 6|30 detector. X-ray diffraction (XRD) patterns were obtained using a MiniFlex II diffractometer (Rigaku, Japan). The samples were scanned over a 2θ angular range of 10-90° with 0.02° steps. FTIR spectroscopy was conducted using a Cary 630 FTIR Spectrometer (Agilent Technologies, Santa Clara, CA, USA) covering a wavenumber range of 600 to 4000 cm^{-1}.

3. Results and discussion

Results and corresponding discussions for the adsorption performance of the synthesized materials, along with their characterization, are detailed in the following subsections.

3.1. Adsorption performance

Hydrochars (H-GA and H-GW) exhibited the highest removal efficiency of MB, exceeding 75% removal (Figure 2a). In contrast, biochar's MB removal was lower (B-GA and B-GW) compared to hydrochars, with B-GW adsorbing the least MB. The removal capacities of all materials for four key heavy metals, lead, cadmium, copper, and chromium, demonstrated the opposite behavior: hydrochars showed almost negligible removal capacity for Pb, Cd, and limited capacity for Cu, and Cr, while both biochars exhibited excellent adsorption for heavy metals (Figure 2b). The latter can be confirmed by the main effects plot (Figure 2c), where both biochars were better at heavy-metal adsorption irrespective of the metal type. The limited surface area of hydrochar and low-volume pore restricts its potential to remove metals. Therefore, an additional activation process (physical or chemical) may be required to boost the adsorption capacity of hydrochar (Khanzada et al., 2024). In this study, the incorporation of biochar aims to eliminate the use of harsh chemicals, such as strong acids or alkaline solutions. These findings are exciting as combining both hydrochar and biochar might enable the removal of different pollutants without further material modification.

To showcase the potential applications of *G. weberbaueri* in water treatment, the following experiment utilized only H-GW and B-GW. Figure 3 shows the adsorption capabilities of materials when exposed to synthetic water containing a mix of contaminants, i.e., a heavy metal and MB. As expected, hydrochar (H-GW) used alone tended to selectively adsorb the dye, leaving the heavy metal in the solution. Interestingly, B-GW, while highly effective in single-contaminant tests for removing heavy metals, exhibited a significant reduction (four times lower) in its adsorption capacity when both contaminants were present. This result suggests that the dye molecules may restrict the pores of the biochar, thereby limiting its ability to capture heavy metal ions. A scenario of improved adsorption emerged when both H-GW and B-GW were used together in the mixture. Hydrochar still preferentially adsorbed the dye, which appeared to enhance the biochar capacity to capture heavy metal ions, particularly Pb and Cd. This highlights the potential of combined biochar-hydrochar materials for effective removal of a broad spectrum of contaminants from wastewater. One approach to operationalize this novel finding would be to create pellets that incorporate both biochar and hydrochar in specific ratios to optimize contaminant removal. Alternatively, adsorption columns could be designed with a layered approach, placing hydrochar first to capture dyes and then biochar to target heavy metals.

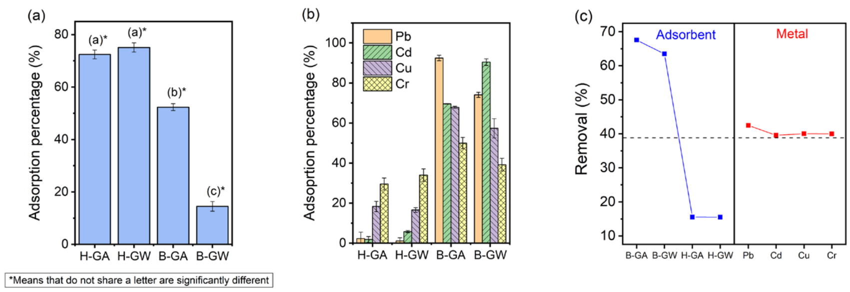

Figure 2: Adsorption by synthesized materials of (a) methylene blue and (b) heavy metals. (c) Main effects plot for heavy-metal adsorption

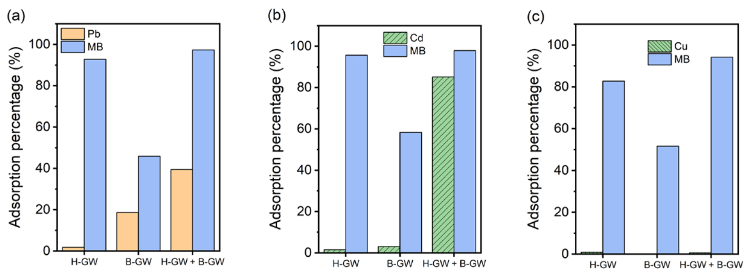

Figure 3: Adsorption percentage of a mixture of heavy metals and methylene blue (a) Pb^{2+}/MB, (b) Cd^{2+}/MB, and (c) Cu^{2+}/MB using H-GW, B-GW, and H-GW+B-GW

3.2. Material characterization

A characterization of the bamboo-derived materials was conducted to establish a direct relationship between adsorption performance and the physicochemical properties of hydrochar and biochar. SEM images (Figure 4) revealed that both materials exhibit an amorphous morphology due to the thermochemical process. Biochar

showed a higher degree of organic matter degradation, evidenced by the presence of well-defined pores on its surface. Generally, enhanced porosity is advantageous for the adsorption of heavy metal ions, as confirmed by the adsorption experiments. Further differences between hydrochar and biochar were observed in the elemental composition determined by EDS analysis. Biochar contained a higher concentration of inorganic ash components, which correlates with more extensive degradation of organic matter.
The XRD pattern of hydrochar retained characteristic peaks of crystalline cellulose at 2θ = 15°, 22.5°, and 35° (Luo et al., 2025), indicating a partially preserved biomass structure. In contrast, biochar exhibited no distinct crystalline peaks, confirming its higher degree of degradation (Figure 5). The broad peak at around 22° suggests the presence of amorphous silica, which aligns with the EDS results. FTIR spectra reinforced these observations. Hydrochar displayed absorption bands at 3400 cm^{-1} and 2930 cm^{-1}, corresponding to hydroxyl (-OH) and methylene (-CH_2) functional groups, typical of organic biomass. As expected, biochar exhibited distinct bands in the 2000–2500 cm^{-1} range, characteristic of amorphous carbon structures. These spectral differences further explain the improved adsorption capacity of biochar, as the loss of organic matter and the development of a porous, carbonaceous structure enhance metal-ion interactions.

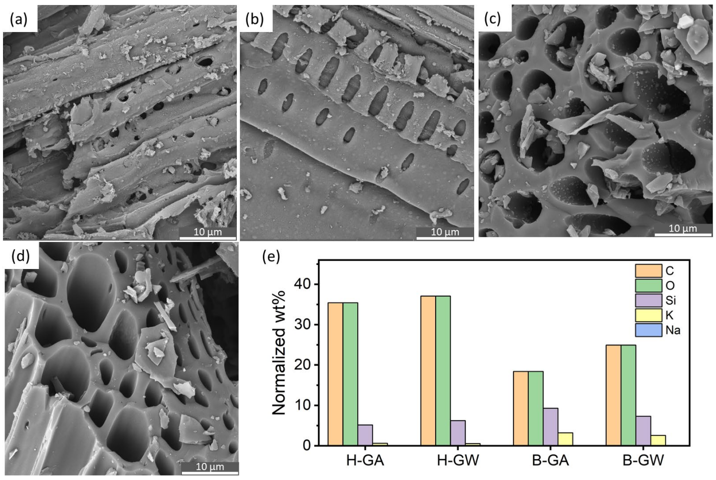

Figure 4: SEM images of (a) H-GA, (b) H-GW, (c) B-GA, (d) B-GW, and (e) normalized weight percentage of elements determined by EDS

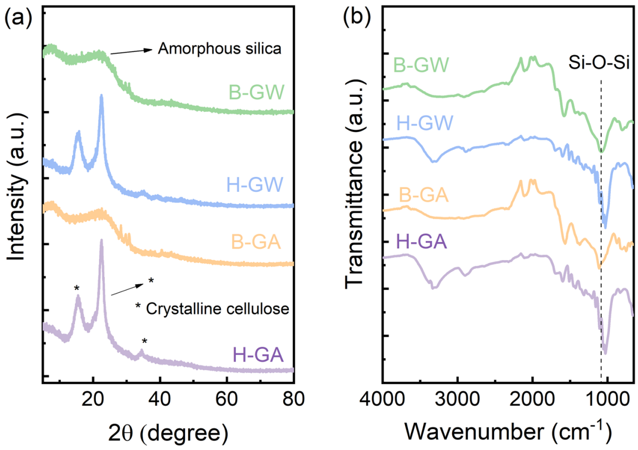

Figure 5: (a) XRD and (b) FTIR spectra of materials synthesized in this study

4. Conclusions

These results demonstrate the effectiveness of biochar and hydrochar materials derived from native woody bamboos for wastewater treatment applications. Our comparative results indicated that both hydrochars exhibited better removal capacity for MB (>75% removal). At the same time, both biochars were more effective in adsorbing the selected heavy metals, with up to 90% removal. Both hydrochars showed negligible removal for most metals. Interestingly, a synergistic effect was observed when hydrochar and biochar were combined into a composite material, as both MB and heavy metals were removed simultaneously. The latter led to ~85% removal of Pb^{2+} and Cd^{2+}, while maintaining high MB adsorption. The material characterization study indicated a highly porous structure for biochar, which was crucial for metal adsorption. On the other hand, hydrochar retained more functional groups, favouring cationic dye removal. These results indicate that adsorptive materials derived from local bamboos effectively removed the tested contaminants from water under laboratory conditions. Therefore, conducting field experiments in real-world scenarios of water pollution is the obvious next step. The potential development of an innovative biochar/hydrochar composite is particularly interesting due to the demonstrated efficacy of their combined use in removing different types of pollutants by harnessing the diverse characteristics of these thermochemically treated materials.

Acknowledgments

This research was financially supported by a grant from the Universidad San Francisco de Quito (USFQ), and MS received support from Conservation X Labs' Artisanal Mining Grand Challenge to mitigate the negative impacts of gold mining in the Amazon region.

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