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# Bamboo biochar as a sustainable technology to address arsenic pollution: A review

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**ABSTRACT**

The rising levels of arsenic (As) concentration in water and soil pose a global concern for human health and for the environment. One potential cost-effective and environmentally friendly approach to mitigate this toxic metalloid is to use the adsorption properties of biochar derived from plant biomass. Over the past decade, different studies on the use of bamboo biochar for As removal have gained traction due to its sustainable attributes. However, to date, no review has specifically focused on analyzing the potential of bamboo as a biochar for remediating As-polluted soil and water. This work provides a comprehensive review of articles published during the last decade on the potential of bamboo biochar as an efficient technology for As removal from water and soil. Different groups have shown As(III) and As(V) adsorption by bamboo biochar, revealing high rates of As removal, particularly in aqueous systems. Moreover, due to its cellular composition, bamboo offers significant As adsorption qualities, including short equilibrium times. We also discuss key factors influencing the performance of bamboo biochar As removal, such as surface modification, among others. We hope that this comprehensive review will help to identify challenges in the field and overcome research gaps that could position bamboo biochar as a viable and environmentally friendly alternative for achieving As-free water and soil.

## 1. INTRODUCTION

Arsenic (As) is a chemical element with metalloid properties, released into the environment through natural processes such as rock erosion and volcanic emissions, or via human activities, primarily mining. The increase in As levels in soil and water is a global concern due to its high toxicity to living organisms and its carcinogenic risk to humans [1,2]. Soil contamination with As has been reported in several countries, with concentrations ranging from 1,500 mg/Kg to 208,000 mg/Kg in regions of Iran, Great Britain, India, and Mexico [3-5]. In Mexico, for example, environmental regulations (NOM-147) set a maximum allowable As concentration of 22 mg/Kg for agricultural and commercial soils, nearly 10,000 times lower than the concentrations found in heavily contaminated areas [5].

As in water is also a significant concern in several countries due to the consumption of contaminated water [6]. In most countries, the limit for As concentration in drinking water is <10 μg/L, according to the World Health Organization (WHO) and the Environmental Protection Agency (EPA) [7,8]. However, groundwater concentrations exceeding this limit have been reported in more than 120 countries, with the highest levels found in Argentina, Bangladesh, Chile, China, Hungary, India, Mexico, Nepal, Romania, Taiwan, Vietnam, and the United States [1]. For instance, elevated levels of As have been detected in drinking water in at least 12 states of Mexico, with concentrations ranging from 50 μg/L to 2410 μg/L [9-11], greatly exceeding the permissible limits for water quality set by the Official Mexican Standard (NOM-127), as well as by the WHO and EPA [7,8,12].

Contamination of soil and water with As leads to its accumulation in the human body, primarily through the consumption of contaminated water and, to a lesser extent, vegetables that contain As in their tissues [11]. Because As is an inorganic, non-degradable element that is highly toxic, chronic exposure to As can cause various health issues, including skin conditions, cancer, diabetes, cardiovascular diseases, and neurological disorders, including autism [3,11,13].

In order to mitigate the risk of diseases associated with As poisoning, various methods have been developed to decrease As levels in soil and water in agreement with the international limits set by the WHO and EPA [7,8]. Emerging methods in recent decades using plant biomass adsorption properties present a low-cost and environmentally friendly alternative. One such method involves using biochar produced

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through the pyrolysis of biomass, a process that confers a structure and surface area with specific features for effectively adsorbing As [14]. Biochar is considered a sustainable technology because it avoids introducing unwanted by-products into the environment, is reusable, and can be derived from plant residues after harvesting, enabling the complete utilization of crops [15]. These characteristics align with the United Nations Sustainable Development Goals (UNSDGs), by promoting sustainable water management and reducing environmental pollution.

Bamboo is an ideal feedstock for biochar production due to its wide geographic distribution and significant economic importance in countries such as Mexico, China, and Brazil. Its unique cellular composition endows bamboo-derived biochar with properties particularly suited for adsorption processes [16,17]. After nearly a decade of research demonstrating its potential for As removal, these advantageous characteristics have positioned bamboo biochar as a promising material for the remediation of As-contaminated soil and water through adsorption performance. Despite its potential, studies on bamboo biochar for As adsorption remain relatively limited, with notable gaps in understanding the underlying mechanisms and factors influencing its adsorption efficiency. These gaps arise from the high dependency on specific experimental conditions, such as temperature, pH, competing ions, the ionic form of As, the bamboo species, and biochar production methods. A deeper understanding of these variables is essential to optimize its performance and facilitate the translation of laboratory findings into scalable, real-world applications. This review aims to summarize and critically evaluate the current state of knowledge in the field, providing guidance for future studies to address existing gaps and develop efficient methods for As removal. While the biotechnological applications of bamboo biochar and its role as an adsorbent for various contaminants have been discussed in some articles [16,18], no comprehensive review to date specifically focuses on the current research and future challenges related to bamboo biochar for As removal.

Therefore, this review provides a comprehensive overview of the recent advancements in the research of bamboo biochar for the removal of As from water and soils, contributing to the growing body of literature on biochar-based As remediation technologies. We highlight the efficacy of bamboo biochar in adsorbing both arsenite (As(III)) and arsenate (As(V)), examine the influence of various experimental factors on its performance, compares its adsorption capacity with that of other biochar sources, emphasize the potential of bamboo biochar as a sustainable technology for obtaining As-free resources, and address the challenges and research opportunities in the field.

## 2. METHODS

The literature between 2014 and 2024 on bamboo biochar for soil and water remediation was reviewed, focusing on two main aspects: (1) Biochar for As removal and (2) specifically bamboo biochar for As removal in water and soil. The first section aims provide an overview and summary of biochar technology use for remediation of systems contaminated with As, giving a general context for studies on bamboo biochar. Thus, only articles addressing biochar, and not other types of adsorbents, were included. The second section focuses exclusively on recent studies of bamboo biochar for As removal in soil and water. It compares its performance with biochar from other sources and highlights the advantages of using bamboo for remediating As-contaminated matrices. Both sections include original research studies and review articles, sourced from various databases such as Web of Science, National Center for Biotechnology Information, Elsevier (Scopus and ScienceDirect), Springer (SpringerLink), SciELO, and Google Scholar. The search was conducted using various combinations of keywords, including “bamboo biochar,” “bamboo biochar arsenic,” “biochar arsenic water,” and “biochar arsenic soil”.

## 3. RESULTS AND DISCUSSION

### 3.1. Biochar as a Solution for As Removal

#### *3.1.1. Characteristics of biochar*

Biochar has been widely studied as an adsorbent material with high potential for cleaning water and soils contaminated with metals and metalloids [19-21]. It is also effective in removing other contaminants, such as fluoride, pharmaceuticals, and phenols [1] and also serves as a soil amendment [22].

Biochar is produced through the carbonization of biomass. When generated through pyrolysis in an oxygen-free or low-oxygen environment at temperatures below 800°C, it retains a high carbon content, making it suitable for use as an adsorbent [23]. Unlike activated carbon, biochar does not require physical or chemical activation before pyrolysis, making it a low-cost product that does not depend on numerous reagents for its synthesis [23].

In general, the composition of biochar is highly heterogeneous, containing not only the main elements of carbonaceous adsorbents (carbon, hydrogen, and oxygen) but also nutrients such as nitrogen (N), phosphorus (P), and potassium (K), and occasionally some heavy metals [24]. Biochar’s chemical structure comprises abundant active organic functional groups and aromatic carbon molecules, with a neutral to alkaline pH. Overall, this material presents a relatively high cation exchange capacity, large specific surface area, and negative surface charge. However, the type of raw material used for its production significantly influences many of the surface properties of biochar. For example, biochar produced from plant biomass typically contains a higher carbon content compared with biochar derived from animal biomass or waste [25].

The effectiveness of biochar in reducing the bioavailability of As depends on various factors, including those related to: i) biochar production, such as carbon content, organic matter, pH value, type of biomass, pyrolysis temperature and time, and heating rate; and ii) biochar performance during adsorption, mainly the ion content, amount of biochar (adsorbent), initial concentration of the adsorbed element (adsorbate), pH and temperature values, and exposure time. Overall, the mechanisms of interaction between biochar and inorganic elements include complexation reactions, reduction, cation exchange, electrostatic attraction, and precipitation [26].

The pyrolysis temperature is particularly important, as it significantly affects the final physicochemical properties that define biochar’s capacity to remove inorganic elements. Higher temperatures (600–800°C) result in the elimination of greater amounts of volatile compounds, promoting structures more like graphite and creating larger pore volumes, pore distribution, and surface areas compared to processes carried out at lower temperatures (300–500°C) [1]. An example of the effect of pyrolysis temperature on biochar efficacy is reported by Ahmad *et al.* [25], who observed that biochar derived from soybean stubble and pine needles pyrolyzed at high temperature (700°C) induced a higher content of exchangeable As, likely due to its greater surface area and fixed carbon content, compared to biochar pyrolyzed at low temperature (300°C). Therefore, pyrolysis temperature is a key factor in biochar production that can limit or enhance its ability to remove As.

In order to enhance the sorption efficacy of biochar, composites aim to generate new functional groups on biochar surfaces. These composites are typically prepared by immersing raw biomass or produced biochar in solutions of metal oxides or salts (such as chloride or nitrate), along with various other pre- and post-processing steps. The metal impregnation agents used to modify the biochar surface often include metal nanoparticles or metal oxides/hydroxides [27]. Both pristine biochars and those modified with composites have demonstrated effectiveness in adsorbing a wide variety of contaminants. This versatility provides multiple alternatives, allowing for the use of low-cost pristine biochar or its modified forms, which, although more expensive to produce, may offer improved performance.

#### *3.1.2. Adsorption of As by biochar*

Biochar used for As removal has been produced from various agricultural residues, including bamboo fibers, Japanese oak wood, red oak, switchgrass, corn straw, banana pulp, rice straw, white birch, used coffee grounds, and rice and wheat husks [1,28,29]. Among the mechanisms of interaction between biochar and inorganic elements, the predominant methods by which biochar immobilizes As include complex formation, co-precipitation, and electrostatic interactions with the positively or negatively charged surfaces [Figure 1] [20,28,30]. Additionally, factors such as oxygen functional groups, zeta potential, O/C ratios, (O + N)/C ratios, and polarity indices also play significant roles in defining As adsorption [31].

The diverse composition of chemical elements and functional groups distributed on the surface of biochar can significantly influence the process of As adsorption. For instance, organic and inorganic hydroxyl groups promote the uptake of As(III) on the biochar surface. Furthermore, biochar may disperse iron oxides, such as $Fe_3O_4$, whose hydroxyl groups can react with As(III) [31]. However, ions present in the solution can interfere with the adsorption of As(V). For example, a high concentration of phosphorus can reduce As(V) removal by more than 50%, as As(V) and phosphate ($PO_4^{3-}$) compete for the same adsorption sites on the biochar [32].

Since chemical adsorption on the biochar surface and interaction with the contaminant may be the limiting steps in the As removal process, various biochar composites have been tested to enhance biochar's As adsorption capacity, including impregnation with zinc (Zn), manganese (Mn), titanium (Ti), calcium (Ca), aluminum (Al), and iron (Fe) [1]. These composites have been shown to promote a wide range of increased sorption capacities for both As(III) and As(V), which can be attributed to the production of compounds that co-precipitate with As. An interesting example is rice husk biochar modified with calcium ions ($Ca^{2+}$) and different forms of iron ($Fe^0$ and $Fe^{3+}$), showing higher As removal capacities (>95%) through As precipitation [33]. Moreover, composites offer increased surface area, pore volume, and more active sites for binding metal ions with varying electrochemical potentials, thereby facilitating the diffusion of As into the biochar pores [28].

The adsorption of As by various plant-based biochars is well described by a pseudo-second-order kinetic model, indicating that the rate of As sorption is dependent on the availability of binding sites on the adsorbent surface. From kinetic studies, the equilibrium time can be estimated as the point at which the concentrations of As adsorbed onto biochar and remaining in the solution stabilize, indicating maximum adsorption. Short equilibration times are particularly desirable as they minimize time-dependent requirements and resources in adsorption systems [6,28]. In addition, the Langmuir isotherm model is frequently used to describe the adsorption isotherms of As(III) and As(V), suggesting that electrostatic interactions or Van der Waals forces are involved in ion adsorption on the biochar surface, while providing the estimated maximum adsorption capacity for As [6,28]. Given the importance of fast kinetics and high adsorption capacities in biochar characterization, research efforts have primarily focused on improving As removal efficiency and optimizing equilibrium times for biochars derived from various sources.

### 3.2. Bamboo Biochar for As Removal in Water and Soil

#### *3.2.1. Versatility and sustainability of bamboo*

Bamboo belongs to a taxonomic group of large woody grasses in the subfamily Bambusoideae, which includes 1439 described species across 116 genera [17]. Native to tropical and subtropical climates, bamboo is characterized by its exceptionally rapid growth. Various studies report bamboo's growth rate ranges from 30 cm/day to 60 cm/day, reaching heights of approximately 36 m during the growing season, producing more biomass than other lignocellulosic crops [16]. In addition to its rapid growth, bamboo has several other notable characteristics. It is cost-effective, strong, lightweight, flexible, and durable. Bamboo can be harvested annually and regenerates without the need for replanting. Furthermore, it produces approximately 30% more oxygen than trees and helps reduce carbon dioxide levels,

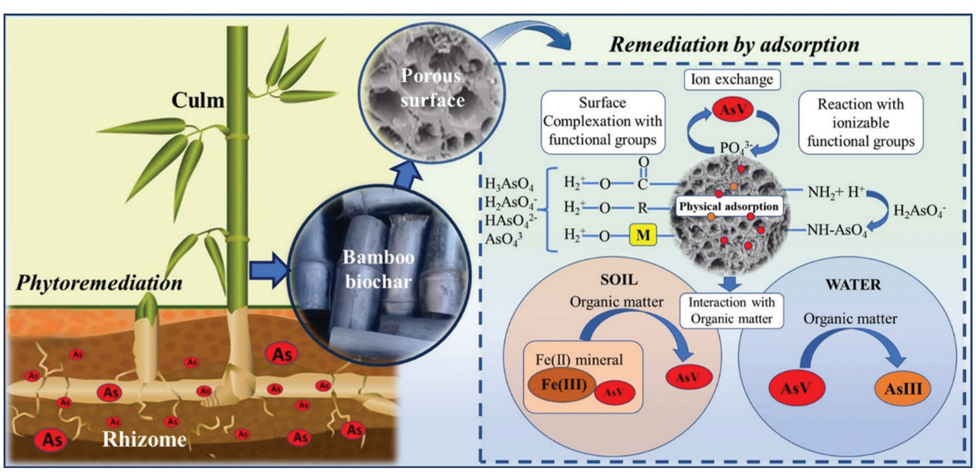


**Figure 1:** Scheme illustrating the potential uses of the bamboo plant for remediation technology, including phytoremediation and adsorption by biochar. The interactions of bamboo biochar in soil and water for adsorbing arsenic.

among other environmental benefits [16]. Although bamboos are not strictly woody, the Bambusoideae family comprises both woody and herbaceous species. Woody bamboos are distinguished by their culm leaves, which protect and support young shoots, as well as their complex vegetative branching [34]. The structure of bamboo culms consists of an epidermis, parenchyma cells, and vascular bundles, all encased by supporting fibers. The unique mechanical properties of bamboo fibers are attributed to their composite structure, in which cellulose fibrils are embedded in a matrix predominantly composed of lignin and hemicellulose [35]. Bamboo culms grow and mature rapidly, allowing for a continuous supply of fibers, which provides a significant advantage over trees in the production of high-quality products [34,36].

Bamboo is an exceptionally versatile species, with certain genera, such as *Otatea*, having been widely cultivated and used as a construction material and production of household items since ancient times in various countries, including Mexico, China, India, and Indonesia [17]. The modern bamboo industry generates significant volumes of solid lignocellulosic waste. For example, in the manufacturing of slats (also known as laths), approximately 80% of the waste comprises sawdust and wood shavings, which are typically discarded [37]. Production of bamboo biochar offers an excellent solution for managing residual lignocellulosic biomass, enabling its recovery and fostering a circular economy within production areas, while also contributing to the removal of various contaminants from water and soil matrices.

In addition, bamboo is a promising plant not only for biochar production but also for phytoremediation [Figure 1]. Bamboo species offer several advantages for remediating soils contaminated with heavy metals, including high biomass accumulation capacity, resistance to heavy metal-contaminated soils, ease of cultivation, high regeneration potential, rapid growth, and short rotation cycles [17,38]. These characteristics endow bamboo plants with a remarkable ability to extract heavy metals from the soil, primarily accumulating them in the root system. Bamboo rhizome and culm tissues can accumulate substantial amounts of heavy metals, particularly in the cell wall, vacuole, and cytoplasm [17]. The accumulation of As in bamboo shoots has also been documented; for instance, *Phyllostachys edulis* (Moso) bamboo can contain organic As compounds in its shoots [17]. Furthermore, certain bamboo species, such as *P. edulis, Phyllostachys praecox, Isopogon latifolius, Pleioblastus kongosanensis, Sasa fortunei*, and *Pleioblastus fortunei*, have the ability to grow under heavy metal stress in both soil and hydroponic conditions [17]. Nevertheless, the tolerance and accumulation capacity of As in bamboo plants remain relatively understudied. Bamboo, whether used as a source of biochar or in phytoremediation, has shown considerable potential for remediating As-contaminated water and soil. Particularly, its role in biochar production adds a sustainable dimension to bamboo harvesting by utilizing residual biomass. Furthermore, the production of pristine bamboo biochar does not require chemical additives, making it a cost-effective and feasible option for small communities to convert pruning residues into valuable remediation materials.

### *3.2.2. Bamboo biochar*

Over the last decade, there has been a growing interest in using bamboo as a material for producing various adsorbents, such as bamboo-activated carbon, bamboo biochar, and bamboo aerogel, among others [35,39]. According to a recent review by Alfei and Pandoli [40], approximately 351 publications from 2013 to February 2024 have addressed the application of bamboo-derived biochar for various purposes. The emerging interest in bamboo can be attributed to its primary composition of hemicelluloses, cellulose, and lignin [Figure 2], which can yield to higher value-added products through pyrolysis processes [22]. The lignocellulosic composition of bamboo biochar results in an exceptionally large surface area due to the abundance of micropores, as well as a high percentage of organic matter [16,41]. In addition, compared to other sources such as woody plants or agricultural residues, bamboo-derived biochar contains a higher lignin content with more phenolic hydroxyl groups and greater silica content in the culms, which remains after pyrolysis, enhancing the adsorption performance of bamboo biochar [6,16,24,42].

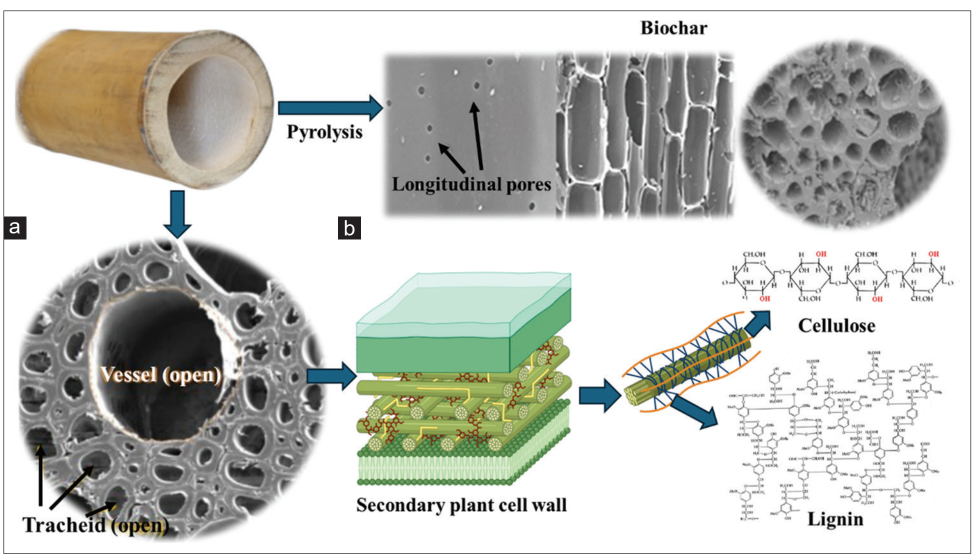


**Figure 2:** Scheme illustrating some morphological characteristics of bamboo. (a) A cross-section of a bamboo branch showing vascular bundles, tracheid, and sclerenchyma cells with thick secondary walls due to high lignin content. (b) Longitudinal and cross-sectional views of bamboo biochar resulting from pyrolysis. When pyrolysis temperatures exceed 400°C, cellulose and lignin decompose, altering the characteristics and morphology of the resulting biochar. The scanning electron microscope images of bamboo and bamboo biochar are adapted from Li *et al.*, 2022 [72], Pinisakul *et al.,* 2023 [24], and Alchouron *et al.,* 2020 [6], respectively.

Biochar from various bamboo species, including *Dendrocalamus giganteus*, *Dendrocalamus asper*, *Dendro latiflorus* Munro, *Phyllostachys viridiglaucescens*, *P. edulis*, *P. pubescens* Mazel, *Guadua chacoensis*, and *Bambusa beecheyana*, among others, have been produced and studied since 2011 for biotechnology applications such as environmental remediation [1,16,18,24,40-44]. The main bamboo residues reported in the literature as biochar precursors include stems or culms, chopsticks, sawdust, and shoots [29,40,45,46].

Similar to other types of biochar, bamboo-derived biochar has been utilized as a soil amendment and fertilizer due to its ability to enhance soil physicochemical and biological properties, including a higher water retention capacity, an increased microbial population and activity, and improved nutrient mobility [22,40,47]. Soil fertilization with bamboo biochar can improve plant growth and fruit quality. Moreover, as a porous carbonaceous material with a high surface area, bamboo biochar has also been used for biomass fuel and carbon capture [40].

The potential of bamboo biochar as an adsorbent for soil and water remediation has been previously studied. Studies have demonstrated high efficacy in removing various contaminants, including metals, metalloids, nitrate, ammonium, $PO_4^{3-}$, organic molecules such as methylene blue, N-nitrosodimethylamine, atrazine, and aromatic compounds [1,29,48,49]. Bamboo biochar has been shown to influence the bioavailability of not only As but other inorganic elements such as copper (Cu), lead (Pb), cadmium (Cd), chromium (Cr), mercury (Hg), zinc (Zn), and fluorine (F) [29,43,48,50].

The heterogeneous nature of biochar surfaces complicates the understanding of As adsorption mechanisms [6]. It is well established that bamboo biochar, compared to other biomass-derived biochars, has a higher particle density and porosity, with longitudinal pores originating from its vascular bundles and cellulose content. In addition, bamboo biochar exhibits a higher biochar yield and fixed carbonization index due to its greater lignin content and low volatile matter content [24,36].

The chemical composition of bamboo biochar is influenced by pyrolytic temperature and typically includes a range of functional groups such as O-H, $CH_3$, $CH_2$, C=C, C=O, aromatics, methylene, phenol, ethers, and alcohols. Fourier transform infrared (FTIR) spectroscopy analyses have confirmed the presence of hydroxyl groups (derived from phenols and alcohols) and carboxylic acids on the bamboo biochar surface. These functional groups are essential in determining the adsorption capacity of bamboo biochar by interacting with As ions and facilitating the formation of As complexes [28,36,51].

In addition, Fe oxides, metal ions, and ionizable functional groups containing N, generated under pyrolysis conditions, contribute to As binding on the biochar surface. For example, $Fe^{3+}$ can co-precipitate with As(III), while Fe oxides form Fe(As)OOH complexes. Surface chemical groups containing P also play a role, exchanging with As(V) due to their chemical similarity. Beyond surface interactions, intraparticle diffusion of As into mineral-enriched regions within the biochar structure is critical, further enhancing the overall adsorption process [Figure 1] [1,28,32,52].

Different neutral and anionic forms of As, including As(V) and As(III), can be adsorbed on the surface of biochar. Moreover, both As(V) reduction and As(III) oxidation reactions have been reported during As adsorption [32]. These redox reactions are influenced by factors such as pH, minerals, metal ions, various functional groups attached to the biochar surface, and organic matter interacting with As. For instance, Fe oxides like FeO(OH) can transform As(III) into As(V) species, whereas organic matter can act as electron donors, promoting the reduction of As(V) to As(III) [28]. However, the redox transformation of As and its bonding chemistry remain of both theoretical and practical interest and continue to be a subject of research. Nevertheless, it is well established that modifying the biochar surface with composites, primarily containing Fe, can enhance the efficacy of As adsorption or immobilization [43,51,53,54]. Compared to other ions, Fe exhibits a strong binding affinity for As(V), a characteristic attributed to its ability to form Fe-O and Fe-O-H functional groups. These groups can act as electron acceptors, facilitating the strong complexation of As on the biochar surface through electrostatic and chemical interactions [1,32,47,52].

While the removal of As by bamboo biochar has been less extensively studied compared to metals, increasing interest in developing new adsorbents for As remediation has spurred research on bamboo biochar as a promising option over the last decade [Table 1]. Overall, studies indicate that the effect of bamboo biochar varies depending on the specific soil or water matrix, influencing As bioavailability either through adsorption or the mobilization of As bound to minerals. Recent research has focused on enhancing the As adsorption or removal capacity of bamboo biochar, building on studies that have demonstrated its ability to alter As concentrations in these treated matrices.

**Table 1:** Summary of studies on bamboo biochar for as removal in water and soil.

| Water/Soil system | Ionic species of As tested | Initial pH | Langmuir maximum adsorption capacity | Maximum As removal | Equilibrium time | References |
|---|---|---|---|---|---|---|
| Water | As (III) | 4.5 and 5 | ~265.3 mg/g | ~99% | 100 min | Lyu *et al*., 2022 [54] |
| Water | As (V) | 5-9 | 90 mg/g | 98% | 1 hr | Alchouron *et al*., 2021 [53] |
| Water | As (V) | 7 | 868 mg/g | 100% | 1 hr | Alchouron *et al*., 2020 [6] |
| Water | As (V) | ND | ND | 95% | ND | Zhou *et al*., 2014 [43] |
| Water | As (III) | 5 | 223.7 mg/g | ~90% | ND | Zheng *et al*., 2023 [30] |
| Water | As (V) | 7 | 2.2568 mg/g | ND | 2-12 h | Pinisakul *et al*., 2023 [24] |
| Soil | Total As (III) and As (V) | 7.4 | ND | ND | ND | Lv *et al*., 2020 [57] |
| Soil | As (V) | 6.4 | ND | ~27% | ND | Zhang *et al*., 2020 [51] |
| Soil | ND | ND | ND | ~84% | ND | Tang *et al*., 2023 [63] |
| Soil | Total As | 7.46 | ND | ~22% | ND | Zhang *et al*., 2023 [47] |

### *3.2.3. Adsorption of As in soil by bamboo biochar*

Given the risk of As leaching from soil into drinking water or being absorbed by crop plants, studies investigating the efficacy of bamboo-derived biochar for remediating As-contaminated soil have emerged in recent years. Research with this adsorbent has demonstrated its influence on soil, affecting not only the concentration of As but also its bioavailability to plants. Bamboo biochar effect on the As-soil-plant system depends on different factors such as soil type, biochar dosage, dissolved organic matter, and biochar surface modification.

Considering that As is often leached from polluted farmlands and mining areas into paddy soils [51], bamboo biochar has been mostly tested for removing As from this type of soil. However, similar to other biochar sources (e.g., soybean stover biomass, pine needles, rice straw, corn stalks), the application of bamboo biochar tends to increase As mobilization in paddy soils [25,40,55-57]. High bamboo biochar doses (1–5%, w/w) promote a greater increase in As mobility compared to lower doses (0.5% w/w) [57]. This increased As mobility by bamboo biochar has also been observed in soil from an abandoned tailings pond after 30 days of incubation with biochar at 1% w/w [47]. Similar effects have been observed with other plant-derived biochars, such as powdered pine biochar, which increased the initial As concentration in agricultural soil after 60 days of incubation [54]. In the case of bamboo, this phenomenon may be attributed to the influence of organic matter, which can oxidize As(III) to As(V) and facilitate As desorption through increased pH levels. Another cause could be the reduction and dissolution of Fe(III) minerals, thereby increasing the release of As contained in these minerals [41,57-59]. This increase in As bioavailability in soil due to bamboo biochar application may be undesirable in commercial crop soils, as plants could potentially uptake the released As. In fact, an increase in As uptake by rice plants was observed with exposure to bamboo biochar [57], similar to what was observed in the same plant species exposed to maize biochar [60]. Hence, a recommended strategy for remediating As-contaminated soils is to combine biochar application with phytoremediation. In this approach, plants are expected to absorb the As released due to the influence of biochar [61,62].

In contrast, recent studies demonstrate that bamboo biochar also exhibits As remediation properties in paddy soils under flooded conditions, where its application for 60 days reduced As availability by around 84%. This remarkable reduction was achieved through the formation of amorphous Fe oxides with a large specific surface area and abundant complexation sites capable of binding and immobilizing released As. The amorphous Fe oxides facilitated the formation of a highly stable ternary complex of As, Fe, and dissolved organic matter, which is known to serve as both an electron donor and acceptor during redox reactions in soils [41,63]. This As remediation capacity is comparable to previous reports using other types of biochar, such as wheat biochar (83.7% maximum As removal) [64], and even higher than rice straw biochar combined with oyster shell waste (50% and 53% removal of As(III) and As(V), respectively) in highly contaminated soils [65]. However, it is necessary to consider the differences in the experimental conditions, including the As measurement system, making it difficult to compare biochar As mobility or immobilization capacities directly.

Despite the above, it is well known that the proper management of As-polluted soils with unmodified biochar remains challenging. This limitation might be overcome by adding composites [56]. Bamboo biochar modified with P, Fe, and Mn on their surfaces has demonstrated enhanced As remediation properties in soil [32]. For example, bamboo biochar produced by pyrolyzing bamboo biomass pre-impregnated with potassium phosphate ($K_3PO_4$) increased As(V) mobility in paddy soil by around 12% compared to untreated biochar [51]. Meanwhile, using Fe modification in bamboo biochar showed an enhanced remediation ability in abandoned tailing soil by reducing bioavailable As for plants by 65% compared to untreated soil [47]. The combination of composites, such as an Fe-Mn complex, promotes higher remediation performance by bamboo biochar, reducing bioavailable As by 88.65% through the formation of Fe–As complexes, adsorption sites, and an increased number of functional groups on the surface, such as Mn–O/As and Fe–O/As [47].

According to the reviewed studies, both pristine and modified versions of bamboo biochar exhibit remarkable potential for soil remediation, particularly in influencing As mobilization, making them especially suitable for use alongside phytoremediation processes. Although bamboo biochar can also remove As, further studies on the factors influencing As removal performance – such as soil type, pH, temperature, As concentration (isotherms), exposure time (kinetics), among others – are still needed.

### *3.2.4. Adsorption of As in water by bamboo biochar*

In contrast to soil (where As ions are retained in particles), in aqueous systems, As ions primarily exist as dissolved inorganic forms. This state is influenced by a complex interplay of solid-liquid interactions with minerals and, in many cases, dissolved organic matter, which acts as an electron donor and acceptor during redox reactions [1].

The effectiveness of biochar in adsorbing both As(V) and As(III) has been extensively studied in aqueous systems; similar to soil, the amount of As adsorbed largely depends on initial experimental conditions, including As concentration, the chemical form of As, temperature, and exposure time. This variability results in a wide range of As adsorption values, from 0.006 mg/g to 868 mg/g, across different biochar types, including those derived from woody plants, sewage sludge (biosolids), and food waste [23,28,33,66,67]. Among these, isotherm studies of bamboo-derived biochar have shown a Langmuir adsorption capacity exceeding 10 mg/g (up to 868 mg/g for As(V) and 224 mg/g for As(III)) [6,30], which can be considered a high adsorption capacity for As [1]. Potential As sorption mechanisms have been suggested through X-ray photoelectron spectroscopy analyses, indicating that As interactions with bamboo biochar in aqueous systems may occur via electrostatic attractions, hydrogen bonding, and weak chemisorption to biochar phenolics [53]. Furthermore, bamboo biochar has a remarkable capacity to remove As under varying experimental conditions, including pH, temperature, composite additions, and water composition [23,28,66].

The pH of the solution notably influences the surface properties of bamboo biochar, with optimal As removal efficiencies close to 100% observed at pH values not exceeding 8 [Table 1] [23,28,66]. This pH effect is consistent with findings from other biochar sources, such as sewage sludge, food waste, pineapple, and Japanese oak biochar, which achieved high As removal capacities of 56%–95% at pH values ranging from 2 to 7 [33,66,68,69].

Pristine bamboo biochar has shown an optimal pH range for As removal between 4.5 and 7. Specifically, As(III) adsorption in aqueous systems is favored at an acidic pH close to 5 [54], while As(V) adsorption is more efficient at a pH of 7 [6]. Below these pH values, As adsorption decreases. This pH dependency can be attributed to the different functional groups on the biochar surface, such as amine, alcohol, and carboxyl groups, which tend to protonate depending on the pH, thus altering the As adsorption capacity [23].

Conversely, some studies have shown that modified bamboo biochar can exhibit a pH-independent ability to remove As. For example, biochar made from the bamboo species *G. chacoensis* treated with $Fe_3O_4$ achieved nearly 100% of As(V) removal without significant impact from pH changes in the range between 5 and 9 when tested in As solution and a fixed-bed column [6,53]. A similar phenomenon was observed with hybrid biochar made from rice husk and wheat husk with added Fe oxide, which adsorbed As(III) with approximately 100% removal efficiency at pH values ranging from 3 to 10 [31]. In fact, it is not uncommon for modified biochar with added compounds to exhibit maximum As adsorption capacity in solutions with basic pH values between 8 and 9.3. Examples include biochar derived from rice husk and paper mill sludge modified with Fe compounds (23.1 mg/g As) and wheat straw modified with $Bi_2O_3$ (16.21 mg/g As) [67], indicating that the addition of composites can regulate As adsorption in response to pH.

In addition to influencing the response to pH variation, modifying the structure of bamboo biochar with metals or binary metal oxides can also increase As removal efficacy in water by up to 236% [Table 2]. Among these, Fe-based composites are the most extensively studied for bamboo biochar. Since 2014, various studies have demonstrated that adding Fe to the surface notably enhances As removal. For example, a recent study found that bamboo biochar modified with $Fe_3O_4$ achieved As(V) adsorption capacities ranging from 39 mg/g to 868 mg/g, indicating nearly complete removal of As approximately 57% more than its unmodified counterpart, this Fe effect could be explained by the Fe strong binding affinities to As(V) and their influence on surface reduction of As(V) to As(III) with $Fe^{3+}$ co-precipitating with As(III) to form Fe(As)-oxyhydroxides [1,32,52,53]. In addition to Fe ions, zero-valent iron (ZVI) modification can also improve As removal capacity. Higher amounts of ZVI added to the surface result in higher removal rates of As(V) (70–95%) compared to untreated surfaces, which show little to no adsorption [43]. Such a strong removal of As(V) can be attributed to the electrostatic attractions between the anions and the ZVI particles on the composites' surface [43]. ZVI based composite also promote remotion of As(III), where $Fe^0$ and H+ are proposed to react to produce Fe (II) and $H_2O_2$, and the formed Fe(II) could further react with $H_2O_2$ to produce reactive hydroxyl radicals (•OH), which could contribute to the oxidation of As(III) via reacting with $HAsO_2$ to generate $HAsO_4^{2}$ [30].

Another compound studied for its effect on bamboo biochar's performance is chitosan, which, when impregnated on the biochar surface, resulted in approximately a 66% increase in As(V) removal [24]. This composite, in combination with ZVI, also promoted almost 95% As removal by bamboo biochar in a complex solution containing As(V), Pb(II), Cr(VI), $PO_4^{3-}$, and methylene blue [43].

These As removal capacities are competitive among those of different modified biochars. For instance, biochar made from pine modified with $Zn(NO_3)2$ showed 87.62% As(III) removal [68], while biochar from rice husk impregnated with $Fe^0$ reached a 58% As(V) removal capacity [66]. Furthermore, bamboo biochar has demonstrated effectiveness in addressing As contamination in aqueous systems containing multiple pollutants. Since As is frequently found in water alongside other inorganic contaminants, such as Cd, recent studies have explored the performance of bamboo biochar in binary and ternary As-metal aqueous systems. Notably, a pre-magnetic bamboo biochar modified with Fe bound with a double-stranded hydroxide compound CaMgAl achieved a maximum As adsorption capacity of approximately 265.3 mg/g in an As(III)-Cd(II) contaminated solution [54]. In the same binary system, another bamboo biochar with ZVI-sulfide nanoparticles added showed high As adsorption of 276.133 mg/g, affected by the concentration ratio of Cd(II) to As(III) [30]. Remarkably, bamboo biochar can also remove As in a ternary system of As-Fe-Mn. An example is provided by the biochar made from B. beecheyana bamboo stem, which showed high As(V) removal efficacy. Both the raw biochar and the composites with Fe or chitosan completely removed As(V) in the presence of Fe and Mn [24].

In addition to high adsorption capacities, rapid kinetics are crucial for biochar characterization. Similar to other biochars derived from woody plants, such as pine or oak, bamboo-derived biochar has demonstrated rapid kinetics, reaching equilibrium within the first 8 h, particularly between one and 5 h [1,6,24,54]. This performance is notably faster compared to the equilibrium times reported in several kinetic studies, which often exceed 24 h [1]. For example, modified biochars like Fe-Hickory and ZVI-red oak show equilibrium times of 24 and 48 h, respectively [52,70]. Unlike other types of biochar, the high As removal capacity demonstrated by bamboo biochar may be influenced by its characteristic high lignin and silica content. Lignin can constitute more than 90% of the total bamboo dry mass and is richer in phenolic hydroxyl groups than wood lignin, while silica may enhance the content of surface chemical groups [6,16,24,71]. In addition, scanning electron microscope images confirm that raw bamboo biochar possesses high porosity, with longitudinal pores originating from the plant's vascular bundles [Figure 2] [24]. This, along with the effects of high temperatures during the biochar production process or

**Table 2:** Approximate enhancement of As removal by bamboo biochar with added composites, compared to unmodified biochar controls.

| Biochar Name | Composites | Ionic species of As tested | Increase in removal (%) | References |
|---|---|---|---|---|
| BBC, BBCF | Chitosan and Zero-valent Iron compositions | As (V) | ~ 23–95 | Zhou *et al*., 2014 [43] |
| nZVI@BC | Zero-valent Iron nanoparticles | As (III) | ~ 19.7 | Zheng *et al*., 2023 [30] |
| S-nZVI@BC | Zero-valent Iron sulfide nanoparticles | As (III) | ~ 38.1 | |
| BC -Fe | $Fe_3O_4$ nanoparticles | As (V) | ~ 57 | Alchouron *et al*., 2020 [6] |
| Fe-BC | $Fe^{3+}$and $Fe^{2+}$ | As (III) | ~ 108 | Lyu *et al*., 2022 [54] |
| Fe-BC@LDH | Layered double hydroxide compound CaMgAl | As (III) | ~ 155 | |
| BC | Chitosan | As (V) | 66 | Pinisakul *et al*., 2023 [24] |
| BFe | $FeCl_3 \cdot 6H_2O$ | As (V) | 236 | |
| m-BBC | $K_3PO_4$ | As (V) | ~ 12 | Zhang *et al*., 2020 [51] |
| F-BC<br>FM-BC | Fe and Mn | Total As | ~ 65-88 | Zhang *et al*., 2023 [47] |

the addition of composites, can enhance the diffusion of As onto the biochar surface [1,28].

In summary, the high adsorption efficiency for As, rapid equilibrium times, ability to remove As from complex matrices, and the performance enhancement through structural modifications or parameter optimization underscore the value of bamboo biochar as a promising material for advancing sustainable technologies in water As remediation.

### 3.3. Challenges in the Implementation of Bamboo Biochar

The successful implementation of bamboo biochar for the remediation of As-contaminated water or soil requires a comprehensive understanding of key factors influencing its performance. This includes the biochar's maximum adsorption capacity for As under varying environmental conditions and potential adverse effects, including the release of by-products, such as heavy metals, during its application. While the release of heavy metals from bamboo biochar remains largely undocumented, it has been found to contain approximately 0.70% Mn. In addition, biochars derived from other sources as coconut residues and rice straw, have been reported to contain trace metals such as Zn and Al [24].

In addition to the biochar's intrinsic properties, the environmental and contamination conditions at the application site must be carefully considered for bamboo biochar implementation. Adsorption performance is highly dependent on parameters such as temperature, pH, initial As concentration, the adsorbent-to-adsorbate ratio, and other site-specific factors. Evaluating the effectiveness of bamboo biochar under these conditions requires experimental studies focusing on adsorption isotherms and kinetics to provide a predictive framework for its behavior in real-world scenarios. A notable example is a study involving sulfide-modified nZVI bamboo biochar, which was assessed for the simultaneous removal of Cd(II) and As(III) from simulated lake water. The study examined key parameters such as pH, dissolved oxygen levels, and the Cd-As concentration ratio, reporting a remarkable As(III) removal efficiency of over 95.7% within 90 min [30].

The efficacy of bamboo biochar is further influenced by both the species of bamboo used and the pyrolysis conditions, with variations in cellular composition between species and the primary influence of pyrolysis temperature on the breakdown of cellular compounds playing a critical role [36]. Consequently, the performance of bamboo biochar in addressing specific contamination scenarios and under varying regional environmental conditions is inherently dependent on the biochar production process. This highlights the importance of conducting comprehensive preliminary studies to evaluate the suitability and effectiveness of biochar derived from different bamboo species for practical remediation applications. Once the biochar's properties are fully characterized, its application can be scaled to practical systems, such as reusable biofilters, capable of treating defined volumes of water or soil. These systems hold promise for both household and industrial applications. For water remediation, fixed-bed continuous flow columns are a viable option. The performance of such systems can be investigated large scaled up and is typically described by breakthrough curves, which estimate the volume of effluent that can be treated before the biofilter requires regeneration [6]. Regeneration processes, which involve desorbing As from the biochar, are crucial for its reuse and long-term cost-effectiveness. The efficiency of regeneration depends on factors such as the biochar's origin, the quantity used, and the specific method employed. For bamboo biochar, regeneration has been successfully demonstrated using aqueous K, $PO_4^{3-}$ or sodium bicarbonate ($HCO_3^{2-}$) solutions, particularly for Fe-modified biochars [6,36].

A comprehensive example of bamboo biochar research advancing its practical application is the investigation of the adsorption and regeneration performance of biochar derived from the bamboo specie *G. chacoensis* [6,53]. The study explored various aspects of biochar structure, alongside key parameters influencing adsorption capacity – such as pH, temperature, and initial As(V) concentration – for both pristine and Fe-loaded *G. chacoensis* biochars, before assessing regeneration performance. Regeneration studies demonstrated that Fe-modified biochar can be regenerated more efficiently than its pristine counterpart, likely due to the enhanced affinity of regeneration solution compounds ($PO_4^{3-}$ and $HCO_3^{2-}$) for iron oxide surface hydroxides, which adsorb a significant portion of As(V) [6]. These findings underscore the importance of integrating fundamental characterization with applied system design to develop efficient, scalable, and sustainable remediation strategies for As-contaminated environments.

To the best of the authors' knowledge, there are currently no examples of practical applications of bamboo biochar for cleaning As-polluted regions or its use in biofilters suitable for household or industrial purposes. Addressing the mechanisms governing As adsorption onto the bamboo biochar structure, as well as the behavior of As adsorption-desorption under different operational conditions, particularly in water, remains crucial to scaling up this remediation technology.

## 4. CONCLUSIONS AND FUTURE CHALLENGES

Although the exploration of bamboo biochar for As removal is relatively recent and limited, studies to date indicate that bamboo biochar can be effective for the remediation of both As(V) and As(III). In soil, its application generally influences As mobility and availability to plants, making it advisable to use it mainly in conjunction with a phytoremediation strategy. In contrast, bamboo biochar has demonstrated high efficiency in removing As from water. Bamboo biochar modification with composites – particularly Fe-containing compounds – significantly enhances its As remediation properties, including As removal from water and reduction of As availability in soil.

Despite the demonstrated potential of bamboo biochar for remediating both soil and water matrices, more studies are needed to focus on key factors influencing its efficacy, ensuring the effective use of bamboo-derived biochar in As remediation projects. For example, research should extend beyond paddy and agricultural soils to address As availability in various soil types and consider different As concentrations. To achieve effective As removal in soils, it is crucial to investigate the combined effects of biochar application and phytoremediation methods. Although bamboo biochar demonstrates a high capacity for As removal from aqueous systems, further research is needed to examine factors influencing its As adsorption performance. This includes exploring the use of composites other than Fe (e.g., Ti), different bamboo species, the impact on naturally contaminated water, and the ratio of adsorbent to As solution. Such studies would provide a solid foundation for the future application of bamboo biochar in both soil remediation and water purification systems, at household and potentially industrial scales.

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## 6. AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

## 7. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

## 8. ETHICAL APPROVALS

This study does not include experiments on animals or human subjects.

## 9. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

## 10. PUBLISHER'S NOTE

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## 11. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declares that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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