Mini Review

Arsenic Removal from Aqueous Solutions Using Coconut Fiber (*Cocos nucifera*): A Brief Review

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Abstract: Arsenic is a highly toxic element found in liquid effluents and can pose serious health and environmental risks. Conversely, coconut fiber, an abundant byproduct of the agrifood industry, has strong potential as an adsorbent for removing arsenic from water. Its lignocellulosic structure, which includes cellulose, hemicellulose, lignin, and functional groups such as hydroxyls and carbonyls, enhances interactions with various arsenic species. Research indicates that both raw fiber and chemically treated fiber, using methods such as acid, alkali, biochar conversion, or metal/oxide impregnation, can remove contaminants like dyes, heavy metals, and arsenic. This review shows that chemical treatments significantly improve adsorption efficiency, reaching up to 99% arsenic removal, whereas raw fibers typically achieve less than 25%. Factors such as pH, temperature, and contact time directly influence process effectiveness, with neutral or slightly acidic pH and temperatures near room temperature being ideal for better removal. Kinetic and isotherm models, including the Langmuir and the Freundlich models, help elucidate adsorption mechanisms and estimate the maximum biosorbent capacity. Additionally, coconut fiber can be regenerated and reused after adsorption and desorption cycles, making the process potentially sustainable and cost-effective. Despite promising results with synthetic solutions, challenges remain for real-world applications, such as in industrial effluents and groundwater, due to the presence of competing ions and organic matter. Developing technologies based on coconut fiber promotes the valorization of agro-industrial waste, supports green chemistry and the circular economy by enabling the reuse of low-cost, abundant materials, minimizes environmental impacts, and fosters sustainable treatment of arsenic-contaminated water.

Keywords: bioremediation; lignocellulosic materials; inorganic contaminants; biomass; solid waste; liquid effluents

1. Introduction

The food industry generates significant amounts of solid waste, much of which is improperly disposed of in landfills and dumps, causing serious environmental problems [1,2]. This waste can be solid or semi-solid and arises from various human activities, including hospitals, commercial, residential, and industrial operations, as

well as the agrifood sector [3]. In the agrifood industry, large quantities of lignocellulosic waste are generated, such as bagasse and peels, which contain cellulose, hemicellulose, and lignin [3,4]. This waste poses an environmental challenge due to its difficult disposal and the high treatment costs, but it also has significant potential for valorization [1,5].

In the coconut (*Cocos nucifera*) industry, the fruit is processed commercially to produce copra (the fruit pulp) and coconut water [6]. The husk is the main waste product, making up 80–85% of the fruit's weight. This waste can cause serious environmental problems. For example, when burned, it releases greenhouse gases. Additionally, when landfilled, it occupies large amounts of space and can take approximately 8 years to decompose naturally [7]. Therefore, recycling is essential for sustainable growth. The husk can be used for many purposes, including as fertilizer and biofertilizer; in industrial applications; to restore degraded areas; in floriculture; in crafts; in construction; for energy generation; and as an adsorbent for polluted water.

Factors such as industrialization, agricultural expansion, and urbanization have contributed to widespread pollution of natural water resources. Several water bodies are contaminated with chemical pollutants, including potentially toxic inorganic species [8]. This contamination poses public health risks and causes significant environmental damage, as the harmful effects of potentially toxic elements on ecosystems and human health can vary with concentration and valence state [9].

Various techniques can be used to treat effluents, aiming to reduce their pollution load, including potentially toxic inorganic species [1]. Among these treatment techniques, coagulation precipitation and Fenton oxidation [2] are particularly noteworthy. While these techniques are effective, they often involve high application, operation, and maintenance costs, which limit their large-scale use. In this sense, there is a growing need for water treatment strategies that are not only energy-efficient but also capable of resource recovery [1,10]. Alternatively, various agricultural residues, which are abundant and low-cost, have been proposed as adsorbents for removing inorganic species from contaminated waters [1,2,11].

In this context, coconut fiber has been used to remove various contaminants from water-based solutions. For example, the adsorption of from wastewater using coconut biochar and activated carbon as adsorbents has been examined [12–14]. Metal adsorption onto biochar from synthetic aqueous solutions has been widely reported in the literature [15–17]. The adsorption of bisphenol A using pretreated coconut fiber has also been demonstrated [18]. In addition, the sorption of cadmium, chromium, copper, nickel, lead, and zinc onto coconut fiber has been investigated [19]. The immobilization of *Saccharomyces cerevisiae* cells on coconut fiber has been evaluated as a strategy to enhance lead adsorption [20]. Chromium adsorption using green coconut fiber has likewise been reported [21], as has the adsorption of chromium and nickel onto coconut-based materials [22].

Among the potentially toxic species found in effluents that require attention, arsenic stands out. In aqueous solutions, arsenic mainly exists as As(V) (arsenate) and As(III) (arsenite) [23]. Both forms are harmful, with As(III) being 25–60 times more toxic than As(V) [24]. Arsenic can cause various health problems, including damage to blood vessels and gastrointestinal tissues; changes in skin pigmentation; nervous, heart, and brain disorders; and an increased cancer risk [24,25].

Given the availability of coconut fiber, often discarded as an agro-industrial solid waste, and the importance of focused attention on arsenic contamination in water, this review surveys studies that use this biomass to remove arsenic, a potentially toxic element.

2. Coconut Fiber

Coconut fiber comes from the common coconut palm (*Cocos nucifera* L.) and consists, mainly, of lignocellulosic materials (cellulose, hemicellulose, lignin), along with pectin and minerals [7,26]. The levels of these components in coconut fiber can vary depending on factors such as origin, fiber maturity, fiber type, and season. Typically, coconut fiber contains 30–47% cellulose, 30–45% lignin, 10–25% hemicellulose, and 1–4% ash [27].

The coconut husk consists of three layers (Figure 1): the outer layer, the epicarp; the middle layer, the mesocarp, which contains fibers; and the inner layer, the endocarp [27]. Coconut fiber is obtained from the mesocarp, the thick, fibrous middle portion of the fruit, which typically ranges from 3 to 5 cm in thickness. This fiber is notable for its superior elasticity relative to other plant fibers, along with high rigidity and excellent resistance to humidity and extreme climatic conditions [26,28].

Coconut fiber is a versatile material used for various purposes, such as agricultural substrate, biodegradable packaging, mattresses and tiles, non-structural concrete, composites, asphalt mixtures, doormats and brushes, agglomerates, car seats, paper production, enzyme production [27], as well as an adsorbent material for different chemical species [19].
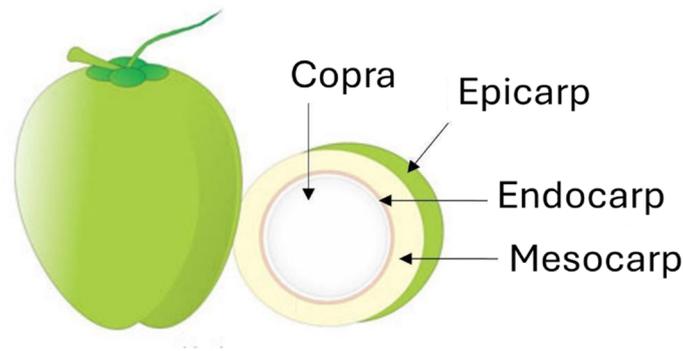
Figure 1. Schematic representation of the parts of a coconut.

Cellulose, one of the main components of coconut fiber, is a linear polysaccharide composed of linked glucose monomers. It has a high molecular weight, a crystalline structure, and is resistant to hydrolysis. Cellulose contributes to the fiber's high strength, rigidity, and structural stability [29]. Along with this structure, hemicellulose is a polysaccharide composed of sugars such as glucose, xylose, galactose, arabinose, and mannose. Hemicellulose is amorphous, has low mechanical strength, and acts as a binder between cellulose and lignin [29]. Lignin is an amorphous, phenolic polymer composed of phenylpropanoid units. Lignin provides structure to the cell wall and helps maintain its rigidity [4]. In addition to these components, pectin acts as a binding agent, helping preserve cell wall structure.

Cellulose is the most abundant polymer on Earth and serves as a key structural element in natural fibers. This polysaccharide is widely found in plants and cells as microfibers that form bundles, significantly affecting the material's mechanical properties. It has a linear structure and forms hydrogen bonds between hydroxyl groups. The structure of cellulose is shown in Figure 2. The hydroxyl (OH) group acts as an active site and is essential for adsorbing potentially toxic metals because hydroxyls strongly interact with metal ions, promoting their removal [30]. Therefore, a material's adsorption capacity is directly related to the number of available hydroxyl groups, as they form bonds with toxic metal ions [31]. Additionally, the presence of hydroxyl groups in cellulose enhances the fibers' water-absorption capacity [10,28,32].
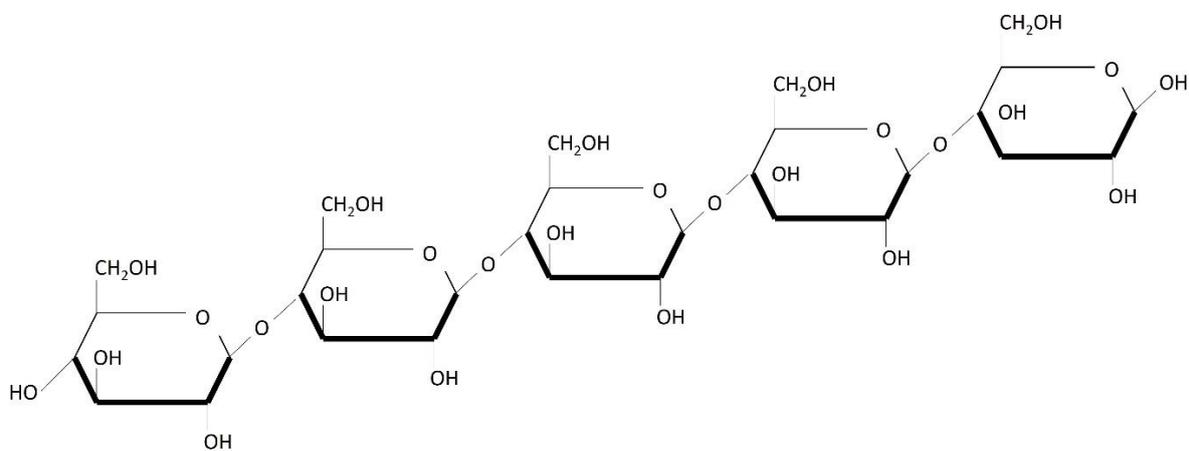
Figure 2. Cellulose structure.

3. Use of Coconut Fiber as an Adsorbent Material

Table 1 presents a selection of studies that used coconut fiber as an adsorbent for organic and inorganic species, both in its natural and modified forms. The most commonly used chemical pretreatments were alkaline (sodium hydroxide) and acid (sulfuric or phosphoric acid). Also noteworthy is the use of coconut fiber, after conversion to biochar [12], in which the biomass was subjected to high temperatures in the absence of oxygen.

Table 1. Examples of the use of coconut fiber as an adsorbent material for the removal of chemical species from aqueous matrices.

Species	Pretreatment	Removal, %	Reference
Rhodamine-B	Biochar with ferrous sulfate heptahydrate and urea	96	[12]
	Biochar with ferrous sulfate heptahydrate	89	
	Biochar with urea	81	
	Biochar	74	
Cr	Biochar	99.9	[9]
Cd	*In natura*	>95	[19]
Cr		>95	
Cu		>95	
Ni		>95	
Pb		>95	
Zn		>95	
Pb	*In natura*	99.32	[20]
	Saccharomyces cerevisiae yeast cells	99.87	
Cellulases from *Trichoderma reesei* ATCC 26921	*In natura*	91	[33]
Cellulases from *Trichoderma reesei* ATCC 26922	Sodium hydroxide	69	
Cellulases from *Trichoderma reesei* ATCC 26923	Sulfuric acid	86	
Cellulases from *Trichoderma reesei* ATCC 26924	Sulfuric acid and sodium hydroxide	53	
Cellic Cellulases Ctec2	*In natura*	81	
Cellic Cellulases Ctec3	Sodium hydroxide	48	
Cellic Cellulases Ctec4	Sulfuric acid	84	
Cellic Cellulases Ctec5	Sulfuric acid and sodium hydroxide	55	
Cu	Biochar with calcite	87.7	[15]
Malachite green dye	Biochar with phosphoric acid	99.9	[13]
Congo red dye	*In natura*	99.9	[34]
Safranin-O dye	*In natura*	98.80	[35]
	Phosphoric acid	99.31	
	Sulfuric acid	99.01	
Pb	Magnesium-coated biochar	59.35	[16]
Cr	Calcium chloride	99.75	[21]
Phenol red dye	*In natura*	89.76	[36]
Remazol-R Brilliant Blue Dye		75.78	
Nanocrystalline zinc oxide	*In natura*	90	[37]
Remazol red dye	Activated carbon with zinc chloride and hydrochloric acid	75	[38]
Bisphenol-A	Sulfuric acid	77.71	[18]
Cr	Sulfuric acid	60 *	[22]
Ni		90 *	
Cr	*In natura*	86	
Ni		99	
Dyes	Activated carbon with phosphoric acid	96.39	[14]
Li	Pyrolysis with manganese dioxide	57 **	[17]

* Estimated value from the graph presented in the paper. ** Estimated value based on the data available in the article.

The treatment applied to biomass generally plays a crucial role in the efficiency of chemical species removal, especially in environmental systems where matrices can be complex. The form and conditions of this treatment are designed to modify the biomass surface, specifically the specific surface area, pore distribution, and the presence of functional groups, to improve the removal of targeted species. In chemical treatments, functional groups are introduced into the adsorbent material to enhance electrostatic interactions and complexation with chemical species, particularly metal ions and organic dyes. Therefore, selecting the most suitable treatment must account for the nature of the biomass, the chemical species targeted for removal, and the matrix under study. Overall, the effectiveness of biomass as an adsorbent or remediation agent depends on the synergy between its intrinsic properties and surface modifications induced by treatment, which directly influences the efficiency of removing chemical species from aqueous solutions or industrial effluents.

In the safranin-O dye adsorption process, for example, the removal results obtained with raw fibers and those pretreated with phosphoric acid and sulfuric acid were compared. The acid-treated fibers exhibited slightly higher dye adsorption than the raw fibers [35]. In adsorption of *Trichoderma reesei* cellulases, both raw fiber and fibers pretreated with sodium hydroxide and/or sulfuric acid were used, and the raw fiber proved more effective for removal [33].

Table 1 shows that studies on coconut fiber focus on potentially toxic elements, including lead, nickel, chromium, and lithium. Specifically, various biomasses, including coconut fiber, have been examined for arsenic species removal because of their presence in effluents and their high toxicity potential.

4. Use of Coconut Fiber as an Adsorbent Material for Arsenic

Various biosorbents have been proposed for removing arsenic from water. For example, when orange peel was used, about 85% of arsenic was removed from real water systems [5]. The use of iron-impregnated biochar produced by thermal pyrolysis of corn straw achieved As(V) removal rates above 85% [39]. It is also possible to achieve arsenic species removal rates exceeding 90% using sorbents made from agricultural residues, such as maize powder [40], mango leaf powder, rice husk [41], pine leaves [42], and the peel and pulp of *Citrus limetta* [43]. For coconut fiber, as shown in Table 2, arsenic removal from water ranged from 20% with raw green coconut fiber as the adsorbent to 99.85% with co-doped iron oxide and graphitic carbon nanosheets on coconut biochar. These removal rates are consistent with results from other biosorbents derived from agricultural residues and highlight the potential of coconut fiber.

Studies that use coconut fiber to remove arsenic from water are shown in Table 2. Most studies suggest modifying coconut fiber to improve arsenic removal, including turning it into charcoal [24,44,45]. Some studies have proposed impregnating biochar with various compounds to enhance its arsenic adsorption capacity. For instance, coconut fiber biochar modified with cerium oxide has been reported as an effective adsorbent [46]. Similarly, coconut-derived biochar coated with graphitic carbon and iron has been reported to enhance arsenic removal [23].

Although studies using modified coconut fiber generally show better arsenic removal efficiency, raw fiber is more sustainable. Using the material in its natural form avoids the need for chemical reagents during treatment and modification, thereby preventing the creation of secondary effluents and reducing the environmental impact associated with producing these adsorbents. Furthermore, the process becomes leaner and faster by reducing the number of adsorbent preparation steps and energy consumption, indicating that raw fiber is a less environmentally burdensome alternative with a lower carbon footprint for effluent treatment, as it valorizes an agro-industrial residue. However, in studies using raw fiber, arsenic removal was below 25% [30,47], indicating practical difficulties with raw fiber.

Another observation is that, in general, studies are conducted in synthetic aqueous solutions. One exception was the study on arsenic removal from landfill leachate using green coconut fiber [47]. In an experiment using coconut fiber, the recommended sorption condition was achieved after 250 min of contact between the fiber and the effluent at 22 °C and pH 8.3, resulting in a 20.1% reduction in arsenic from the initial level. It is important to highlight that wastewater, such as leachate, is a much more complex matrix than synthetic aqueous solutions. These matrices contain various organic and inorganic species that can compete for the adsorbent's active sites [19]. Interactions among species can also be observed, further complicating the removal process [44].

Table 2. Examples of the use of coconut fiber as an adsorbent material for removing arsenic from aqueous matrices.

Biosorbent	Contact Time, Min	Temperature, ºC	pH	Removal, %	Reference
Composite based on biochar derived from coconut shell loaded with cerium oxide	20	25	7	95	[46]
Activated coconut shell	90		7	89	[48]
Co-doped iron oxide and graphitic carbon nanosheets on coconut biochar	60	25	3–9	99.85	[23]
Coconut husk	30	25	-	22	[30]
Raw coconut husk and iron-impregnated coconut husk	-	28	6–7	>93	[24]
Coconut fiber	480	50	4	96.2	[45]
Coconut charcoal	360	-	5	51.8	[44]
Anion exchanger prepared from coconut coir pith carrying dimethylaminohydroxypropyl functional group	30	30	7	99.2	[49]
Green coconut fiber	250	22	8.3	20.1	[47]

It is important to recognize that the interaction between the species to be adsorbed and the functional groups on the biomass surface depends on the specific characteristics of the sorbent and sorbate. These interactions include complexation, electrostatic attraction, and ion exchange [3]. In coconut fiber, the presence of oxygen-containing functional groups, such as hydroxyl and carboxyl groups, can enhance arsenic removal.

Given the potential interactions between arsenic and coconut fiber, adsorption studies are conducted to elucidate these processes. Understanding how arsenic is removed from water systems requires a thorough analysis

of kinetic models and adsorption isotherms to clarify the mechanism. Kinetic models in adsorption studies help determine the rate of adsorption, evaluate how quickly it occurs, and identify the steps that control the process, revealing how arsenic moves from the liquid phase to the coconut fiber surface over time. Adsorption isotherms, such as the Langmuir and the Freundlich models, describe the equilibrium between arsenic in the liquid and solid phases, enabling estimation of maximum adsorption capacity and the nature of the interaction between arsenic and the fiber. These studies are essential for assessing whether the process is favorable and reversible, and whether it occurs as a monolayer or multilayer.

Furthermore, the effectiveness of lignocellulosic materials in removing arsenic depends on experimental factors, including pH, temperature, and initial concentration. pH is especially important because it affects arsenic speciation and the adsorbent's surface charge, which, in turn, influences electrostatic attraction and repulsion. Temperature can alter activation energy and whether the process is endothermic or exothermic, whereas the initial arsenic concentration affects how quickly active sites become saturated and the overall adsorption efficiency. Therefore, studying these factors is crucial for optimizing operational conditions and developing efficient, sustainable, and cost-effective removal methods.

4.1. Effect of pH

pH is a crucial parameter that affects adsorption by altering the adsorbent's active sites and the adsorbate's charge. Generally, adsorption capacity increases with pH, reaching a peak within a narrow pH range before declining at higher pH levels [24]. Additionally, depending on pH, arsenic can exist in various forms in water, and its adsorption behavior on coconut fiber can change with different treatments. For example, in a study on As(III) removal, it was observed that the solution's pH influences the distribution of arsenic's ionic forms: As(III) exists as the neutral H_3AsO_3 between pH 1 and 9, and as AsO_2^- above pH 9. Consequently, in a study using coconut charcoal, it was found that within the pH range 1–4, stronger van der Waals forces likely existed between the solute and the adsorbent surface. As the pH approaches 5, the concentration of anionic species increases, leading to enhanced arsenic adsorption by coconut charcoal due to more specific binding. At pH levels above 5, a decrease in As(III) adsorption was observed, attributed to repulsive electrostatic forces [44].

In the case of biochar loaded with CeO_2, the recommended pH for removal was 7, indicating that the adsorbent material has a positive charge, which favors the attraction of oxyanions of arsenic species $H_2AsO_4^-$ and $HAsO_4^{-2}$ [46]. In studies on As(III) removal using co-doped iron oxide and graphitic carbon nanosheets on coconut biochar, a pH range of 3–9 was recommended, with a sharp decrease in adsorption above pH 11. This result is due to the negative zeta potential (pH_pzc) of coconut biochar, which decreases as the medium pH increases due to the adsorption of OH^- and other anions on its surface [23].

When using an anion exchanger made from coconut coir pith bearing a dimethylaminohydroxypropyl weak base functional group, As(V) adsorption was found to be quite constant over a pH range of 6–8 [49]. However, a notable decrease in As(V) adsorption was observed when this pH range was not used. The influence of pH on As(V) adsorption can be explained by the adsorbent's structure and surface charge, as well as As speciation. Given the adsorbent's pHpzc of 8.4, the surface is positively charged below this pH, promoting the adsorption of negatively charged anionic species. In the pH range of 3 to 6, As(V) mainly exists as $H_2AsO_4^-$, whereas at higher pH, the divalent anion $HAsO_4^{-2}$ becomes predominant. In the intermediate pH range (6–8), both species coexist and are adsorbed through Coulombic attraction. A decrease in pH below 6 results in reduced adsorption, even if the adsorbent surface is positively charged and the sorbate species are negatively charged. In this case, the more protonated As(V) species are less removed than the less protonated ones because there is a lack of electrostatic attraction between the surface and the protonated As(V) species.

Another comparison can be drawn with previous studies that investigated chemically modified coconut fibers for arsenic removal. In one case, As(III) removal was evaluated using fibers treated with HNO_3 and NaOH [45]. In another study, the adsorption of As(V) was investigated using fibers modified with epichlorohydrin in epoxy ether [49]. The recommended working pH differed between the two studies: one suggested an optimal pH of 4 [45], whereas the other investigated a broader pH range (2–10) and indicated pH 7 as favorable for adsorption [49]. As shown, different treatments yield distinct removal conditions that depend on both the adsorbent structure and the chemical species removed.

4.2. Temperature Study

Generally, higher temperatures promote adsorption. Several reasons explain why a material's adsorption capacity increases with rising temperature [50]. Increasing temperature increases the adsorbent's pore size, altering its surface properties. In this context, there may be more active adsorption sites and a thinner boundary layer

around the adsorbent, thereby reducing the adsorbate's mass-transfer resistance. Diffusion should also be considered, as it is an endothermic process that enables adsorbate diffusion through the adsorbent's pores at higher temperatures [45].

When comparing three studies on arsenic adsorption in coconut fiber, each study reported results at the recommended temperature. The adsorption of As(III) onto coconut fiber treated with nitric acid and sodium hydroxide was evaluated over a temperature range of 10 to 50 °C, with 50 °C identified as optimal [45]. In another study, the adsorption of As(V) was assessed using an anion exchanger derived from coconut coir pith functionalized with a dimethylaminohydroxypropyl group, at temperatures between 20 and 50 °C, with 30 °C recommended as the most favorable condition [49]. Additionally, arsenic removal using raw coconut fiber was investigated over the temperature range 25–45 °C, with 25 °C reported as optimal [30]. Table 2 shows that most studies report temperatures between 22 and 28 °C, with good arsenic removal, such as the 95% removal achieved with a composite based on biochar derived from coconut shell loaded with cerium oxide. These results indicate that, regardless of the treatment applied to the coconut fiber, the recommended removal temperatures are close to room temperature. This procedure is important for real-world applications, where adjusting temperature is difficult and costly.

4.3. Adsorption Kinetics and Adsorption Isotherm

Contact time is a key factor affecting the efficiency of the adsorption process. In tests with coconut fiber, adsorption first increases with time and then slowly levels off as it reaches equilibrium. Over time, the number of available adsorption sites decreases until saturation [45]. The suggested contact time for arsenic removal using coconut-based materials ranges from a few minutes to several hours (Table 2). For example, in an experiment using a coconut coir-derived anion exchanger, the amount of adsorbed As(V) increased rapidly during the first 30 min and then gradually approached saturation over approximately 4 h [49]. The adsorption of As(V) remained constant after 4 h, indicating that equilibrium was reached. As shown in Table 2, some studies note rapid arsenic adsorption (20–30 min) onto coconut fiber, even at low temperatures (25–30 °C) [30,46,49]. Other studies indicate longer contact times, as in the adsorption of As(III) by coconut biochar, which showed a tendency toward stability after 60 min [23].

In general, adsorption kinetics are typically studied by varying the adsorbate concentration and the adsorbent dosage to develop pseudo-first- and pseudo-second-order kinetic models. These studies help evaluate how adsorption occurs and determine its rate. Using equations such as the Langmuir and the Freundlich models enables fitting adsorption isotherms to estimate the biosorbent's maximum adsorption capacity and to select the model that best fits the data.

Comparisons of adsorption behavior between unmodified and modified coconut fiber are also performed, similar to the study with raw coconut husk and modified iron-impregnated coconut husk [24]. In addition to comparing experimental conditions to enhance As(III) removal, the kinetic data were better described by the pseudo-second-order model than by the pseudo-first-order model, with intraparticle diffusion-controlled adsorption observed for both adsorbents. Regarding equilibrium isotherms, the Freundlich and Redlich-Peterson models provided the best fit.

Other studies also have indicated that the pseudo-second-order model best fits the adsorption kinetic data, suggesting that chemical sorption is the rate-limiting step in the adsorption mechanism, as this model accounts for surface adsorption, liquid-film diffusion, and particle diffusion [23]. This was the case in the sorption study of As(III) using coconut charcoal [44], co-doped iron oxide and graphitic carbon nanosheets on coconut biochar [23], and As(V) using biochar decorated with cerium oxide composite [46]and an anion exchanger prepared from coconut coir [49]. When As(III) removal was tested using coconut fiber treated with nitric acid and sodium hydroxide, the pseudo-first-order kinetic model fit the data better than the pseudo-second-order model [45].

4.4. Recovery and Reuse of Coconut Fiber

Typically, studies on recovering adsorbent materials to evaluate their reuse potential are conducted through sequential experiments with the recycled adsorbent, which may involve solvents, acidic or basic solutions, and heating steps. For example, in the case of biochar derived from coconut shells loaded with cerium oxide, the material was placed in contact with a NaOH solution under stirring for 1 h, and it was found that, after washing and drying, there was a reduction in adsorption capacity to 82% after five continuous cyclic experiments [46]. For coconut charcoal, the highest As(III) desorption values were obtained with a 0.5 M NaOH solution [44]. In adsorption-desorption cycles repeated six times using the same material, more than 90% of the initial adsorption

capacity was retained. These studies are important for improving the economic viability and sustainability of the adsorption process [44].

5. Conclusions and Perspectives

This research emphasizes the potential of coconut fiber as an alternative adsorbent for arsenic removal from water, underscoring the value of lignocellulosic residues in bioremediation. Using agro-industrial residues, such as coconut fiber, supports green chemistry and the circular economy by enabling the reuse of abundant, low-cost materials, reducing environmental impacts associated with improper disposal, and advancing sustainable treatment methods. Structural and surface modifications to coconut fiber significantly affect removal efficiency by altering physicochemical properties and potentially enhancing the formation of functional groups that interact with arsenic species. A thorough understanding of these effects requires combining physical and chemical analyses with experimental data modeling, using kinetic and isothermal models to clarify adsorption mechanisms and identify limiting steps. The impact of experimental variables is also vital for system optimization, as these factors affect active site availability and the balance between solid and liquid phases. Systematic evaluation of these parameters clarifies interactions and identifies operational conditions that maximize efficiency. Despite these advances, significant gaps remain, particularly in applying coconut fiber to real-world samples such as industrial effluents, contaminated groundwater, and leachate, where competing ions and organic matter can significantly affect performance. Research addressing these conditions is crucial for confirming system behavior in environmentally relevant scenarios. Transitioning from benchtop experiments to full-scale applications is a critical step in developing the adsorbent, as many materials that perform well under controlled conditions may fail in complex real-world effluents due to matrix composition and flow dynamics. Therefore, understanding how matrix composition, including competitiveness and interferents, affects adsorption is necessary for scaling up and validating in real systems. This should include studies of ionic strength, the presence of other elements and organic matter, and comparative tests with various real effluent samples. Assessing the feasibility of shifting from batch to continuous-flow processes is also recommended for future research. Additionally, evaluating the overall sustainability of the process-including the potential to regenerate and reuse coconut fiber after multiple adsorption-desorption cycles-is essential. Such evaluations are needed to estimate the cost-benefit ratio and environmental impact of large-scale use. Continued research is necessary to scale up the process and apply laboratory findings in practical operations, helping establish coconut fiber as an effective, economical, and environmentally friendly solution for reducing arsenic contamination in water environments.

Author Contributions

C.L.B.S.L.: Methodology, Visualization, Writing—original draft, Writing—review & editing; L.A.M.P., V.A.L. and S.L.C.F.: Conceptualization, Writing—original draft, Writing—review & editing; L.S.G.T.: Conceptualization, Funding, Supervision, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

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During the preparation of this work, the authors used the Grammarly app to check spelling, grammar, punctuation, clarity, and writing engagement. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

References

1. Soudani, A.; Youcef, L.; Chebbi, M.; et al. Agricultural waste-based biochars for sustainable removal of heavy metals from stabilized landfill leachate. *Environ. Sci. Pollut. Res. Int.* **2024**, *31*, 57733–57747. https://doi.org/10.1007/s11356-024-34946-8.

2. Ni, H.; Arslan, M.; Qian, J.; et al. Application of basalt fibers in a biological contact oxidation reactor for the treatment of landfill leachate. *J. Clean. Prod.* **2021**, *297*, 126648. https://doi.org/10.1016/j.jclepro.2021.126648.

3. Maia, L.C.; Soares, L.C.; Alves Gurgel, L.V. A review on the use of lignocellulosic materials for arsenic adsorption. *J. Environ. Manag.* **2021**, *288*, 112397. https://doi.org/10.1016/j.jenvman.2021.112397.

4. Ge, Y.; Li, Z. Application of Lignin and Its Derivatives in Adsorption of Heavy Metal Ions in Water: A Review. *ACS Sustain. Chem. Eng.* **2018**, *6*, 7181–7192. https://doi.org/10.1021/acssuschemeng.8b01345.

5. Khaskheli, M.I.; Memon, S.Q.; Siyal, A.N.; et al. Use of Orange Peel Waste for Arsenic Remediation of Drinking Water. *Waste Biomass Valorization* **2011**, *2*, 423–433. https://doi.org/10.1007/s12649-011-9081-7.

6. Brainer, M.S.C.P.; Ximenes, L.F. *Coconut Production: Recovery of Traditional Growing Areas in Northeast Brazil*; Technical Report No. 127; Bank of the Northeast of Brazil (BNB): Fortaleza, Brazil, 2020. (In Portuguese). Available online: https://www.bnb.gov.br/s482-dspace/handle/123456789/387 (accessed on 3 August 2025).

7. Cardoso, M.G.S.; de Oliveira, D.N.P.S.; Bufalino, L.; et al. Physical and chemical treatments of residual fibers from *Cocos nucifera L.* aiming application in cement composites. *Res. Soc. Dev.* **2022**, *11*, e57311831259. https://doi.org/10.33448/rsd-v11i8.31259.

8. Suleman, R.; Zahoor, M.A.; Qarni, M.A.; et al. Assessment of heavy metals and microbial loads in Nile tilapia (*Oreochromis niloticus*) from different farms and rivers. *Sci. Rep.* **2025**, *15*, 5055. https://doi.org/10.1038/s41598-025-87152-y.

9. Berslin, D.; Reshmi, A.; Sivaprakash, B.; et al. Remediation of emerging metal pollutants using environment friendly biochar-Review on applications and mechanism. *Chemosphere* **2022**, *290*, 133384. https://doi.org/10.1016/j.chemosphere.2021.133384.

10. Raj, K.; Vora, T.; Padmapriya, G.; et al. A comprehensive review of sustainable hydrogels from lignin for advanced wastewater solutions. *Int. J. Biol. Macromol.* **2025**, *301*, 139963. https://doi.org/10.1016/j.ijbiomac.2025.139963.

11. Wae AbdulKadir, W.A.F.; Che Omar, R.; Roslan, R.; et al. Landfill leachate treatment in Malaysia: Continuous circulation motion using mixed agricultural wastes with an open grid-like Luffa's configuration. *J. Water Process Eng.* **2023**, *56*, 104532. https://doi.org/10.1016/j.jwpe.2023.104532.

12. Li, X.; Shi, J.; Luo, X. Enhanced adsorption of rhodamine B from water by Fe-N co-modified biochar: Preparation, performance, mechanism and reusability. *Bioresour. Technol.* **2022**, *343*, 126103. https://doi.org/10.1016/j.biortech.2021.126103.

13. Zakaria, W.A.N.; Mohd Ghazi, R.; Muhammad, M.; et al. Optimization of Malachite green removal using activated carbon derived from coconut shell. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2021; Volume 842, p. 012033. https://doi.org/10.1088/1755-1315/842/1/012033.

14. Bokil, S.A.; Topare, N.S.; Khedkar, S.V. Batch adsorption studies on treatment of textile industry effluent using bamboo and green coconut shell activated carbon. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2020; Volume 983, p. 012005. https://doi.org/10.1088/1757-899X/983/1/012005.

15. Wang, S.; Zhong, S.; Zheng, X.; et al. Calcite modification of agricultural waste biochar highly improves the adsorption of Cu(II) from aqueous solutions. *J. Environ. Chem. Eng.* **2021**, *9*, 106215. https://doi.org/10.1016/j.jece.2021.106215.

16. Wu, J.; Wang, T.; Wang, J.; et al. A novel modified method for the efficient removal of Pb and Cd from wastewater by biochar: Enhanced the ion exchange and precipitation capacity. *Sci. Total Environ.* **2021**, *754*, 142150. https://doi.org/10.1016/j.scitotenv.2020.142150.

17. Kamran, U.; Park, S.-J. Hybrid biochar supported transition metal doped MnO_2 composites: Efficient contenders for lithium adsorption and recovery from aqueous solutions. *Desalination* **2022**, *522*, 115387. https://doi.org/10.1016/j.desal.2021.115387.

18. Lazim, Z.M.; Salmiati; Hadibarata, T.; et al. Bisphenol A Removal by Adsorption Using Waste Biomass: Isotherm and Kinetic Studies. *Biointerface Res. Appl. Chem.* **2021**, *11*, 8467–8481. https://doi.org/10.33263/briac111.84678481.

19. Esfandiar, N.; Suri, R.; McKenzie, E.R. Competitive sorption of Cd, Cr, Cu, Ni, Pb and Zn from stormwater runoff by five low-cost sorbents; Effects of co-contaminants, humic acid, salinity and pH. *J. Hazard. Mater.* **2022**, *423*, 126938. https://doi.org/10.1016/j.jhazmat.2021.126938.

20. Chwastowski, J.; Staroń, P. Influence of *Saccharomyces cerevisiae* yeast cells immobilized on *Cocos nucifera* fibers for the adsorption of Pb(II) ions. *Colloids Surf. A Physicochem. Eng. Asp.* **2022**, *632*, 127735. https://doi.org/10.1016/j.colsurfa.2021.127735.

21. Bal, D.K.; Bhasarkar, J.B. Adsorptive degradation of hexavalent chromium from aqueous solution using coconut shell as a green adsorbent. *Environ. Prog. Sustain. Energy* **2021**, *40*, e13594. https://doi.org/10.1002/ep.13594.

22. Hanafiah, S.; Salleh, N.; Ghafar, N.; et al. Efficiency of coconut husk as agricultural adsorbent in removal of chromium and nickel ions from aqueous solution. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2020; Volume 596, p. 012048. https://doi.org/10.1088/1755-1315/596/1/012048.

23. Thinh, N.V.; Yusuke, S.; Tu, P.H.; et al. Novel co-doped iron oxide and graphitic carbon nanosheets on biochar for arsenite removal from contaminated water: Synthesis, applicability and mechanism. *Bioresour. Technol. Rep.* **2022**, *17*, 100929. https://doi.org/10.1016/j.biteb.2021.100929.

24. Gautam, S.B.; Alam, M.S.; Kamsonlian, S. Adsorptive Removal of As(III) from Aqueous Solution by Raw Coconut Husk and Iron Impregnated Coconut Husk: Kinetics and Equilibrium Analyses. *Int. J. Chem. React. Eng.* **2017**, *15*, 20160097. https://doi.org/10.1515/ijcre-2016-0097.

25. Raut, E.R.; Thakur, A.B.; Chaudhari, A.R. Review on toxic metal ions removal by using activated carbon prepared from natural biomaterials. In *Journal of Physics: Conference Series*; IOP Publishing: Bristol, UK, 2021; Volume 1913, p. 012091. https://doi.org/10.1088/1742-6596/1913/1/012091.

26. Fernando, J.A.K.M.; Yalegama, C.; Fernando, N.; et al. Characterization of the coir fiber from different coconut varieties to enhance the performance of coir fiber-reinforced natural rubber composites. *J. Elastomers Plast.* **2025**, *57*, 475–497. https://doi.org/10.1177/00952443251323933.

27. Chand, O.; Chopra, L.; Raju, N.N.; et al. Extraction of micro fibrous cellulose from coconut husk by using chlorine free process: Potential utilization application as a filter aid. *J. Mol. Struct.* **2025**, *1319*, 139325. https://doi.org/10.1016/j.molstruc.2024.139325.

28. Hidalgo-Salazar, M.A.; Correa-Aguirre, J.P.; Roman, A.J.; et al. Colombian natural fibers: Potential applications in sustainable natural fiber reinforced composites materials. *Polym. Compos.* **2025**, *46*, 5599–5617. https://doi.org/10.1002/pc.29313.

29. Schiavon, J.Z.; Andrade, J.J.d.O. Comparison between alternative chemical treatments on coir fibers for application in cementitious materials. *J. Mater. Res. Technol.* **2023**, *25*, 4634–4649. https://doi.org/10.1016/j.jmrt.2023.06.210.

30. Fauzi, W.W.; Fairuz, F.M.; Shukri, N.M.; et al. Removal of As and Cd Ions from Aqueous Solution Using Biosorption Technique. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2022; Volume 1102, p. 012088. https://doi.org/10.1088/1755-1315/1102/1/012088.

31. Bruckmann, F.S.; Gonçalves, J.O.; Silva, L.F.O.; et al. Chitosan-based adsorbents for wastewater treatment: A comprehensive review. *Int. J. Biol. Macromol.* **2025**, *309*, 143173. https://doi.org/10.1016/j.ijbiomac.2025.143173.

32. Ferreira, V.F.; da Rocha, D.R.; da Silva, F.d C. Potentiality and opportunity in the chemistry of sucrose and other sugars. *Quim. Nova* **2009**, *32*, 623–638. https://doi.org/10.1590/s0100-40422009000300007.

33. Bezerra, P.K.S.B.; Silva, O.L.; Júnior, S.D.O.; et al. Cellulolytic enzymes behavior in delignified green coconut residues and enzymatic hydrolysis with enzyme recovery. *Ind. Crop. Prod.* **2021**, *172*, 114037. https://doi.org/10.1016/j.indcrop.2021.114037.

34. Rahim, A.R.A.; Mohsin, H.M.; Chin, K.B.L.; et al. Promising Low-cost Adsorbent from Desiccated Coconut Waste for Removal of Congo Red Dye from Aqueous Solution. *Water Air Soil Pollut.* **2021**, *232*, 357. https://doi.org/10.1007/s11270-021-05308-8.

35. Ghosh, I.; Kar, S.; Chatterjee, T.; et al. Adsorptive removal of Safranin-O dye from aqueous medium using coconut coir and its acid-treated forms: Adsorption study, scale-up design, MPR and GA-ANN modeling. *Sustain. Chem. Pharm.* **2021**, *19*, 100374. https://doi.org/10.1016/j.scp.2021.100374.

36. Chong, S.N.; Hadibarata, T. Adsorption of Phenol Red and Remazol Brilliant Blue R by Coconut Shells (*Cocos nucifera*) and Ambarella Peels (*Spondias dulcis*). *Biointerface Res. Appl. Chem.* **2020**, *11*, 8564–8576. https://doi.org/10.33263/BRIAC111.85648576.

37. Droepenu, E.K.; Asare, E.A.; Dampare, S.B.; et al. Laboratory and Commercial Synthesized Zinc Oxide Nanoparticles Adsorption onto Coconut Husk: Characterization. *Biointerface Res. Appl. Chem.* **2021**, *11*, 7871–7889. https://doi.org/10.33263/BRIAC111.78717889.

38. Mustapha, R.; Harun, M.H.C.; Manas, A.; et al. Preparation and Characterization of Bio-Adsorbent from Coconut Husk for Remazol Red Dye Removal. *Biointerface Res. Appl. Chem.* **2021**, *11*, 10006–10015. https://doi.org/10.33263/briac113.1000610015.

39. He, R.; Peng, Z.; Lyu, H.; et al. Synthesis and characterization of an iron-impregnated biochar for aqueous arsenic removal. *Sci. Total Environ.* **2018**, *612*, 1177–1186. https://doi.org/10.1016/j.scitotenv.2017.09.016.

40. Srivastava, S.; Raj, K.R.; Kardam, A. Efficient arsenic depollution in water using modified maize powder. *Environ. Chem. Lett.* **2013**, *11*, 47–53. https://doi.org/10.1007/s10311-012-0376-0.

41. Kamsonlian, S.; Suresh, S.; Ramanaiah, V.; et al. Biosorptive behaviour of mango leaf powder and rice husk for arsenic(III) from aqueous solutions. *Int. J. Environ. Sci. Technol.* **2012**, *9*, 565–578. https://doi.org/10.1007/s13762-012-0054-6.

42. Shafique, U.; Ijaz, A.; Salman, M.; et al. Removal of arsenic from water using pine leaves. *J. Taiwan Inst. Chem. Eng.* **2012**, *43*, 256–263. https://doi.org/10.1016/j.jtice.2011.10.006.

43. Verma, L.; Siddique, M.A.; Singh, J.; et al. As(III) and As(V) removal by using iron impregnated biosorbents derived from waste biomass of *Citrus limmeta* (peel and pulp) from the aqueous solution and ground water. *J. Environ. Manag.* **2019**, *250*, 109452. https://doi.org/10.1016/j.jenvman.2019.109452.

44. Wu, Y.; Wen, Y.; Zhou, J.; et al. Comparative and competitive adsorption of Cr(VI), As(III), and Ni(II) onto coconut charcoal. *Environ. Sci. Pollut. Res.* **2013**, *20*, 2210–2219. https://doi.org/10.1007/s11356-012-1066-y.

45. Nashine, A.L.; Tembhurkar, A.R. Equilibrium, kinetic and thermodynamic studies for adsorption of As (III) on coconut (*Cocos nucifera* L.) fiber. *J. Environ. Chem. Eng.* **2016**, *4*, 3267–3273. https://doi.org/10.1016/j.jece.2016.06.005.

46. Mon, P.P.; Cho, P.P.; Vidyasagar, D.; et al. Synergistic sorption: Enhancing arsenic (V) removal using biochar decorated with cerium oxide composite. *Mater. Today Sustain.* **2024**, *25*, 100675. https://doi.org/10.1016/j.mtsust.2024.100675.

47. Lima, C.L.B.S.; Moreira, I.T.A.; Campos, L.M.A.; et al. Removal of arsenic from landfill leachate using green coconut fiber. *Sci. Rep.* **2025**, *15*, 37064. https://doi.org/10.1038/s41598-025-20861-6.

48. Priyadharshini, B.; Abraham, M.; Nirmala, R.; et al. Optimization Study of Adsorption parameter for the removal of Zinc (Zn) and Arsenic (As) on Activated Coconut Shell (ACS) Adsorbent using Response Surface Methodology. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2024; Volume 1365, p. 012008. https://doi.org/10.1088/1755-1315/1365/1/012008.

49. Anirudhan, T.S.; Unnithan, M.R. Arsenic(V) removal from aqueous solutions using an anion exchanger derived from coconut coir pith and its recovery. *Chemosphere* **2007**, *66*, 60–66. https://doi.org/10.1016/j.chemosphere.2006.05.031.

50. Jimenez, R.S.; Dal Bosco, S.M.; Carvalho, W.A. Heavy metals removal from wastewater by the natural zeolite scolecite—Temperature and pH influence in single-metal solutions. *Quim. Nova* **2004**, *27*, 734–738. https://doi.org/10.1590/s0100-40422004000500011.