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Removal of arsenic from landfill leachate using green coconut fiber

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Arsenic is one of the primary inorganic contaminants found in effluents due to its toxicity and detrimental environmental effects. Clean methods for pollutant removal from contaminated effluents have garnered significant attention, especially those utilizing residual biomass. This study focuses on removing arsenic from leachate generated by landfill effluents using natural green coconut fiber. The adsorption conditions were examined over different periods ranging from 50 to 450 min while keeping the original effluent pH and ambient temperature constant. In an experiment using 5.0 g of coconut fiber per 100 mL of sample, the recommended sorption condition for arsenic occurred after 250 min of contact between the fiber and the effluent at 22 °C and a pH of 8.3. Under these conditions, the arsenic concentration decreased from 0.73 to 0.58 mg L^{-1}, indicating a 20.1% reduction from the initial level. These results highlight the potential of green coconut fiber, a waste product from the food industry, as a natural material for removing arsenic from contaminated effluents.

Keywords Residual effluent, Polluted water, Solid waste, Remediation, Biomass

The green coconut (*Cocos nucifera L.*) processing industry produces a significant amount of solid waste, which is often improperly disposed of in landfills, leading to major environmental issues[1]. In this industry, coconuts are processed to extract pulp and water. The primary waste generated is the shell, which can reach more than 60% of the total mass of the fruit[2]. This waste poses serious environmental challenges; when disposed of in landfills, it creates sanitary problems, and when incinerated, it releases gases that contribute to the greenhouse effect. Furthermore, coconut shells occupy a significant amount of space in landfills and can take approximately eight years to decompose naturally, causing environmental pollution[3,4]. Given the environmental issues associated with the disposal of coconut shells, recycling them is essential for promoting sustainable development. There are several potential applications for coconut shells, including the production of fertilizer and biofertilizers, crafts, civil construction, and energy generation. The use of agricultural residue-based adsorbents in wastewater treatment shows significant potential[5,6], with lignocellulosic materials being suitable for this purpose[7].

In addition to environmental problems from food industry solid waste, addressing landfill-related challenges is also essential[8–10]. Many cities worldwide rely on landfills for waste disposal because they are cost-effective and use simple technology[11,12]. The decomposition of waste creates an effluent called leachate, a dark liquid with an unpleasant smell that can pollute surface water, groundwater, and soil[13,14]. Several proposals exist for wastewater treatment focused on removing contaminants[15]. However, it is important to highlight the need to consider environmental sustainability for the effective operation of these plants. Choosing the right treatment process is crucial to achieving this goal[16].

Leachate composition varies among landfills depending on their age and the materials disposed of. Due to its high levels of potentially polluting organic and inorganic substances, untreated leachate can pose significant environmental risks[17–19]. These potentially toxic substances, when released into the environment without prior treatment, can cause pollution and public health issues[14,20]. It is important to note that the potentially toxic effects of these species, such as inorganic elements, depend on their concentration and chemical form.

Arsenic is a toxic inorganic element commonly found in landfill leachate from solid waste disposal. Its presence in landfills can make it easily accessible, raising environmental concerns[21]. In water, arsenic mainly exists in two forms: arsenate ($(AsO_4)^{3-}$) and arsenite ($(AsO_3)^{3-}$)[22]. Both forms are toxic, but trivalent arsenic is

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25 to 60 times more harmful than pentavalent arsenic[23]. Exposure to arsenic can lead to various health issues, such as damage to blood vessels and intestinal tissue, skin changes, and disorders affecting the nervous system, heart, and brain. Additionally, arsenic has carcinogenic potential[24,25].

Leachate treatment is challenging due to its complex composition. Several techniques can be used to reduce leachate's pollution potential[26], including removing potentially toxic inorganic elements[27,28]. These methods include using activated carbon for adsorption, precipitation through coagulation, and Fenton oxidation[29]. Although they work well, these treatments are often costly. As a cheaper option, various lignocellulosic agricultural residues, which are usually available and low-cost, have been suggested as adsorbents to remove inorganic substances from landfill leachate[30]. Coconut fiber, for instance, a natural agricultural byproduct, has been used to remove several chemical species from water solutions[31–36], including arsenic[37]. However, no studies have been found on using coconut fiber for arsenic removal from landfill leachate, which highlights a research gap, especially given the complexity of the effluent matrix.

This study explored the potential of using raw coconut fiber to remove arsenic from landfill leachate, considering the environmental issues caused by disposing of green coconut fiber and arsenic contamination in wastewater. The goal is to promote coconut fiber as an affordable adsorbent, offering a simple, low-cost method for managing this type of solid waste.

Materials and methods

Reagents, solutions, and materials

All reagents were of analytical grade and used without prior treatment. The aqueous solutions were prepared with ultrapure water from a purification system (Milli-Q®, Millipore). The standard reference solutions for determining inorganic species were prepared by diluting stock solutions (1000 mg L^{-1}) containing arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), selenium (Se), vanadium (V), and zinc (Zn) (SpecSol, Quimlab Química e Metrologia).

The chemicals used in the coconut fiber characterization experiments, including concentrated sulfuric acid (H_2SO_4), potassium bromide (KBr, ≥ 99.0%), phosphate buffer solution ($H_2PO_4^-/HPO_4^{-2}$), magnesium sulfate ($MgSO_4$, ≥ 97%), ferric chloride ($FeCl_3$, 97%), calcium chloride ($CaCl_2$, ≥ 99.0%), and ammonium chloride (NH_4Cl, ≥ 99.5%), were purchased from Merck.

For chromatographic analyses, the following standards were purchased from Sigma-Aldrich: D-arabinose ($C_5H_{10}O_5$, ≥ 99%), D-glucose ($C_6H_{12}O_6$, ≥ 99%), D-xylose ($C_5H_{10}O_5$, ≥ 99%), D-cellobiose ($C_{12}H_{22}O_{11}$, ≥ 99%), 5-hydroxymethylfurfural – 5-HMF - ($C_6H_6O_3$, ≥ 98–99%), and furfural ($C_5H_4O_2$, ≥ 99%). D-mannose ($C_6H_{12}O_6$, ≥ 98–99%) and acetic acid (CH_3COOH, ≥ 99.7%) standards were purchased from Thermo Fisher Scientific and Merck, respectively. Acetonitrile (C_2H_3N, ≥ 99.0%), used as the mobile phase, was purchased from Merck.

Leachate was collected from the Sustentare Saneamento landfill located in Feira de Santana, Brazil. The leachate used in the experiments was not subjected to any pretreatment. The raw coconut fiber utilized in the study was a commercial product supplied by Jiu Fibras in Lauro de Freitas, Brazil. The fiber was washed with Extran detergent and rinsed thoroughly with deionized water. After washing, the fiber was dried in an oven for 6 h at a temperature of 90 °C.

Leachate characterization

The pH of the leachate was measured using a digital pH meter (model pH 009, Shenzhen Boco Technology). The biochemical oxygen demand over five days (BOD_5) was assessed with the System 6 EVO sensor (Velp Scientifica, Usmate Velate). For this measurement, a nutrient solution was prepared using a phosphate buffer solution (pH 7.2), magnesium sulfate (0.41 mol L^{-1}), ferric chloride (0.018 mol L^{-1}), calcium chloride (0.25 mol L^{-1}), and ammonium chloride (0.71 mol L^{-1}).

The determination of the metals present in the leachate was performed using an inductively coupled plasma optical emission spectrometer (ICP OES), model 720 series (Agilent Technologies). The instrument featured a single-pass cyclonic nebulization chamber alongside a SeaSpray nebulizer. Analysis was carried out at a radiofrequency power of 1.20 kW, with a plasma gas flow rate of 15 L min^{-1}, auxiliary gas at 1.5 L min^{-1}, and nebulization gas at 0.75 L min^{-1}. The metals examined, along with their corresponding wavelengths, included: As (188.980 nm), Ba (455.403 nm), Cd (228.802 nm), Cr (267.716 nm), Cu (324.754 nm), Fe (259.940 nm), Mn (279.800 nm), Ni (231.604 nm), Pb (220.353 nm), Se (196.026 nm), V (311.070 nm), and Zn (213.857 nm).

Characterization of coconut fiber

To characterize the coconut fiber, the chemical composition, ash content, and structural analysis were conducted. The chemical composition analysis aimed to identify the biopolymers present in the coconut fiber, specifically cellulose, lignin, and hemicellulose. The ash test assessed the amount of inorganic compounds in the fiber. The structural analysis focused on identifying the functional groups present in the coconut fibers. Chemical composition was analyzed after hydrolysis of the material with 72% sulfuric acid (H_2SO_4). High-performance liquid chromatography (HPLC), using a VWR Hitachi Chromaster (Hitachi High-Technologies Corporation), was employed to determine carbohydrates, organic acids, furfural, and hydroxymethylfurfural (HMF). The concentrations of acetic acid, methyl glucuronic acid, arabinose, furfural, and xylose were used to estimate hemicellulose, while glucose, HMF, formic acid, and cellobiose were converted to determine cellulose content. Soluble lignin was quantified using a UV-Vis spectrophotometer (model DT-MINI-2-GS, Ocean Optics). The ash content was measured using gravimetry[38].

A Fourier Transform Infrared (FTIR) spectrophotometer (model IRPrestige-21, Shimadzu) was used to confirm the presence of functional groups in the fiber. The coconut fibers were ground into a powder and mixed with potassium bromide crystals to obtain the spectra, which were collected over the range of 4000 to 400 cm^{-1}.

Morphological examinations were conducted using scanning electron microscopy (SEM) without metallization of the sample, with a Hitachi microscope (model S3400N).

Adsorption study

The original pH of the leachate (8.3) and room temperature (22 ± 2 °C) were maintained to study the adsorption of arsenic in the raw coconut fiber, varying the contact times at 50, 150, 250, 350, and 450 min. The experiments were performed in triplicate using 5.0 g of coconut fiber and 100.0 mL of leachate (Fig. 1). The arsenic mass was monitored using ICP OES only in the leachate before and after contact with coconut fiber during the experiments. Control tests were conducted on leachate samples under identical conditions as the adsorption experiments, but without coconut fiber.

Although pH influences arsenic speciation and adsorption, the pH was not adjusted in this study because the goal was to use the original pH of the landfill leachate. This approach avoids additional costs for reagents needed for pH adjustments in potential real-world applications. Likewise, although temperature affects arsenic adsorption, this study did not vary this parameter because the goal was to use ambient temperature. This approach avoids extra costs related to temperature adjustments in potential real-world applications.

It can also be inferred that sorption capacities (isotherms and kinetics) were not included in this work. Usually, adsorption kinetic and isotherm models are developed assuming monoelement adsorption, where a single adsorbate competes for the adsorbent's active sites. However, leachate is a highly complex matrix containing various organic and inorganic species, requiring new models to effectively represent the adsorption processes. The extrapolation of mono-parametric adsorption models to multi-parametric models was beyond the scope of this work and was not performed.

Results and discussion

Leachate characterization

The pH of the collected leachate was measured at 8.3. This basic pH level suggests that the waste is in an advanced state of decomposition[14]. The analysis of the BOD_5 yielded a value of (494 ± 42) mg O_2 L^{-1}. Typically, landfills that have been operating for a short time exhibit BOD_5 values around 10,000 mg O_2 L^{-1}, while those with longer operational periods show significantly lower BOD_5 values. The BOD_5 value obtained for the leachate in this study indicates that the landfill has been in operation for a few years. As a landfill ages, the decomposition of the deposited materials progresses, leading to the establishment of a methanogenic stabilization phase, during which strictly anaerobic microorganisms become predominant. This shift causes a decrease in aerobic microorganisms, resulting in a lower BOD_5 value.

Table 1 presents the concentrations of potentially toxic inorganic species found in the leachate. Notably, the concentration of arsenic exceeded the limit established by Resolution No. 430 of the Brazilian National Environmental Council (CONAMA)[39]. The arsenic level in the leachate was 0.73 mg L^{-1}, which is 46% above the permitted maximum of 0.5 mg L^{-1} for effluent disposal. Despite the importance of arsenic speciation, this work measured the total arsenic concentration since the specification sets a maximum limit for total arsenic.

Arsenic is frequently found in industrial wastewater, and its contamination poses significant risks to both the environment and human health. It is essential to monitor and control arsenic concentrations in these effluents due to the potential for soil, surface water, and groundwater contamination[40]. The World Health Organization (WHO) recommends that arsenic levels in drinking water should not exceed 0.01 mg L^{-1}[22]. Unfortunately, about 140 million people worldwide are exposed to arsenic concentrations above the safety threshold[23]. Among the elements tested, arsenic was the only potentially toxic substance that exceeded the maximum allowed level in the leachate samples (see Table 2). Due to these high arsenic concentrations, it is essential to concentrate research efforts on this contaminant, emphasizing the importance of developing effective removal methods.

Characterization of coconut fiber

Figure 2 illustrates the surface structure of coconut fiber across different scales using SEM. Micrographs at magnifications ranging from 100× to 190× (Fig. 2A and B) reveal elongated, cylindrical structures characteristic of lignocellulosic materials. Furthermore, fibrillar bundles connected by a continuous matrix are visible, which

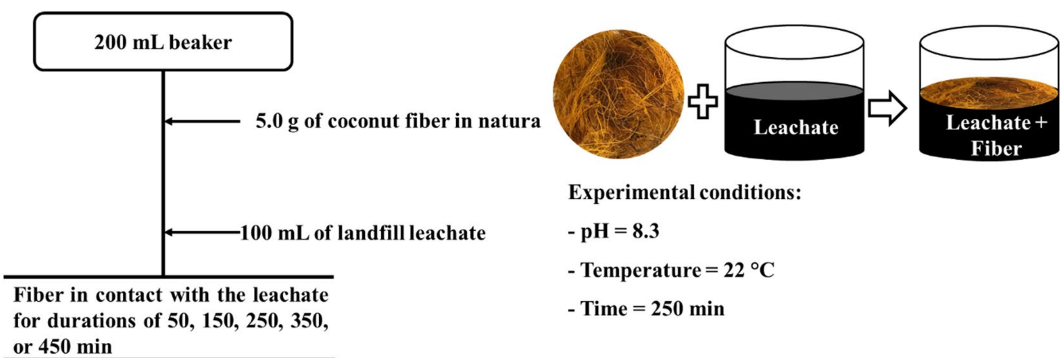

Fig. 1. Schematic diagram of the adsorption experiments for removing arsenic from a leachate sample at various contact times.

Element	Concentration found ($n = 3$), mg L^{-1}	Maximum permitted concentration,[a] mg L^{-1}
As	0.73 ± 0.01	0.5
Ba	0.607 ± 0.005	5.0
Cd	< 0.01	0.2
Cr	0.698 ± 0.009[b]	1.0[c]
Cu	0.0163 ± 0.0005	1.0
Fe	1.84 ± 0.03	15.0
Mn	0.095 ± 0.002	1.0
Ni	0.193 ± 0.009	2.0
Pb	< 0.10	0.5
Se	< 0.10	0.3
V	0.148 ± 0.001	-
Zn	0.166 ± 0.001	5.0

Table 1. Concentration of potentially toxic inorganic species in the leachate sample and the maximum allowable concentrations for disposal into receiving water bodies. [a]CONAMA Resolution No. 430 of May 13, 2011[39]. [b]Total chromium. [c]Maximum permitted concentration for Cr(III).

Component	Content, %
Cellulose	36.9 ± 3.4
Hemicellulose	13.94 ± 0.57
Total lignina[a]	49.663 ± 0.013
Ash	1.73 ± 0.14

Table 2. Chemical composition of coconut fiber used for removing arsenic from leachate samples. [a] The total lignin content is the sum of soluble lignin (6.16%) and insoluble lignin (43.50%).

may be related to lignin and hemicellulose, both of which help maintain fiber cohesion and provide mechanical strength and structural stability[41].

At an intermediate magnification of 500× (Fig. 2C and D), the surface appeared rough with irregular fissures and cavities that might connect to macropores. At a higher magnification of 1000× (Fig. 2E and F), these fissures and cavities became clearer, confirming the surface's heterogeneity. The visible structural irregularities suggest a morphology that could improve interactions with inorganic species by increasing contact area across these fissures and cavities.

The chemical composition of coconut fiber was analyzed after the material was hydrolyzed using concentrated H_2SO_4. Since coconut fiber can absorb moisture from the air, it is advisable to maintain a moisture content below 10% to prevent significant interference during the hydrolysis process. The moisture content of the raw coconut fiber was found to be 4.6%. The results regarding the fiber's chemical composition are presented in Table 2.

The chemical composition of biomass varies based on factors such as origin, fiber maturation, fiber type, and season. As shown in Table 2, coconut fiber presented large amounts of lignin and cellulose compounds (above 85%), which play an important role in removing inorganic species through several mechanisms, including complexation, cation exchange, and electrostatic attraction[7]. The analysis of cellulose, hemicellulose, lignin, and ash content aligns with the findings of Chand et al. (2025), who reported cellulose levels ranging from 30% to 47%, lignin from 30% to 45%, hemicellulose from 10% to 25%, and ash content between 1% and 4%[42]. The study by Conrad and Hansen (2007) indicated that coconut fiber consists of 36.6% cellulose, 35.1% lignin, and 20.6% hemicellulose[43]. The ash content in coconut fiber reflects the presence of inorganic compounds. It is important to note that the fiber may release inorganic species, especially nutrients like copper and zinc, into the adsorbate, as observed in a previous study[44]. Previous research has shown that the ash content in coconut fiber ranges from 1.7% to 4.2%, depending on the coconut cultivar[45], and from 1% to 4%[42].

Coconut fiber mainly consists of cellulose, a common component known for its structural properties that have enabled various uses, such as metal ion adsorption. Cellulose is a linear, hydrophobic biopolymer made of D-glucopyranose units linked by beta-1,4-glycosidic bonds. Each unit contains three hydroxyl groups, which can interact with metal species[42,46]. Hemicellulose is a hydrophilic heteropolysaccharide composed of several monosaccharides. Its branched structure has carboxyl and hydroxyl groups that can chelate metal ions[47]. Another component is lignin, a phenolic, amorphous, and hydrophobic polymer[48,49]. Lignin contains carboxylic and hydroxyl groups, which are important for the sorption of inorganic species[49].

The FTIR spectrum of coconut fiber is shown in Fig. 3. The functional groups identified by their absorptions include (Table 3): bands between 3100 and 3700 cm^{-1}, representing O-H stretching vibrations of hydroxyl groups attached to cellulose; vibrations from 2850 to 3000 cm^{-1}, corresponding to symmetric and asymmetric stretching of aliphatic C-H bonds[33,50,51]; and vibrations from 1550 to 1700 cm^{-1}, which are associated with C = C stretching, indicating the presence of hemicellulose and lignin[52,53]. The band between 900 and 1200 cm^{-1} is

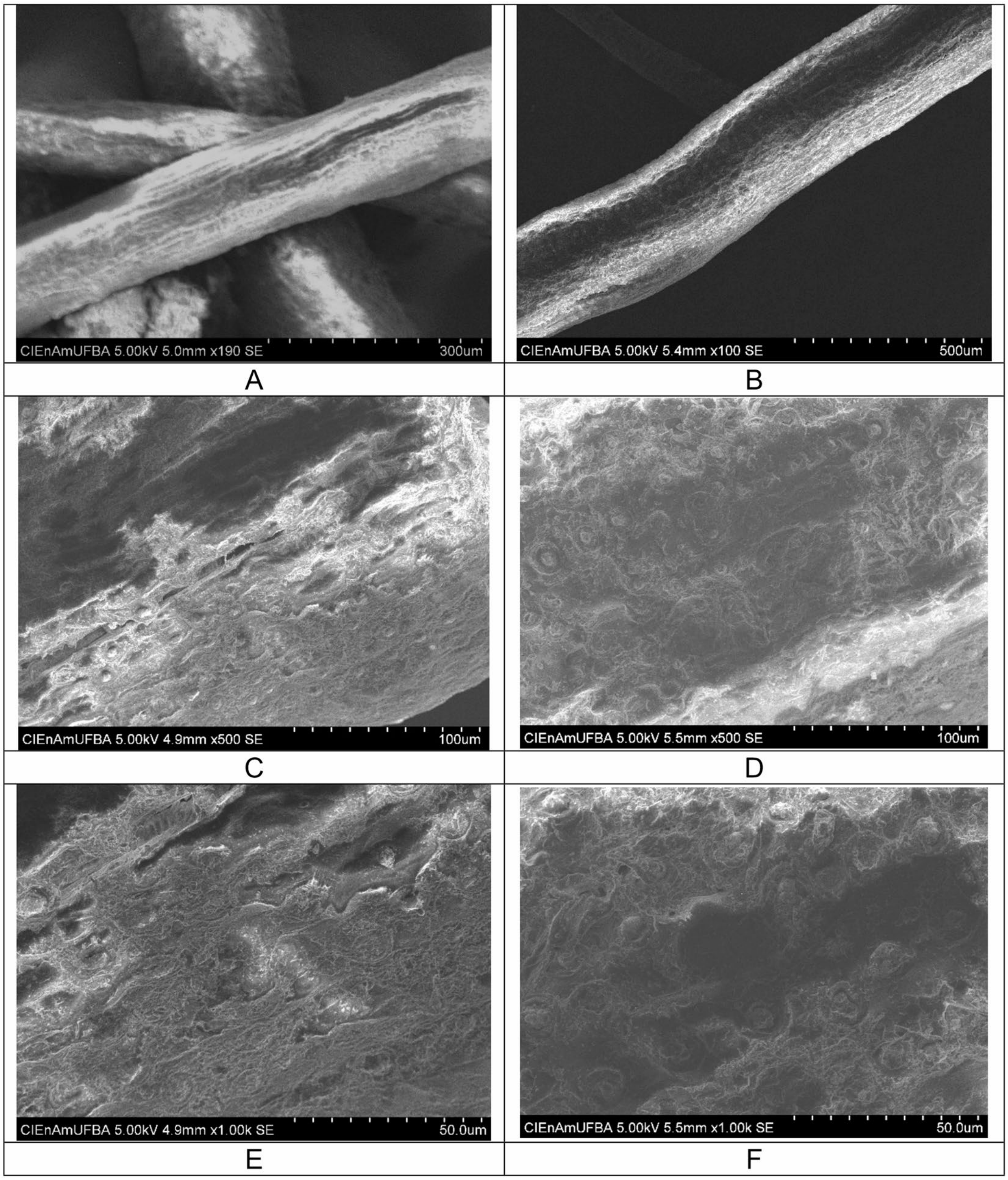

Fig. 2. SEM images of coconut fiber taken at various magnifications: 100–190× (A and B); 500× (C and D); 1000× (E and F).

linked to stretching vibrations of C-O bonds in hemicellulose and cellulose, along with bending vibrations of O-H bonds in polysaccharides[33,50,51].

Removal of arsenic from the leachate sample using raw green coconut fiber

The arsenic removal focused on utilizing coconut fiber due to several key factors: (I) the use of raw, untreated fiber allows for the direct application of this abundant agro-industrial waste without the need for pre-treatment steps or additional expenses for reagents; (II) arsenic was identified as one of the potentially toxic inorganic species in the leachate, with a concentration exceeding the established limit for effluents; (III) to ensure applicability in real-world situations, the tests were conducted at the original pH of the leachate sample and room temperature. Therefore, to investigate the adsorption of arsenic using raw coconut fiber, the pH level of the leachate was maintained at 8.3, and the temperature was kept at 22 ± 2 °C. Contact times were varied at 50, 150, 250, 350, and 450 min.

The study on arsenic removal using coconut fibers focused on a time range of 50 to 450 min, as shown by several previous studies that used similar timeframes[37,55–59]. Regarding the amount of fiber used, the typical sorbent mass recommended in previous studies ranged from 0.10 to 2.5 g per 100 mL of solution[37,51,56–58]. Due

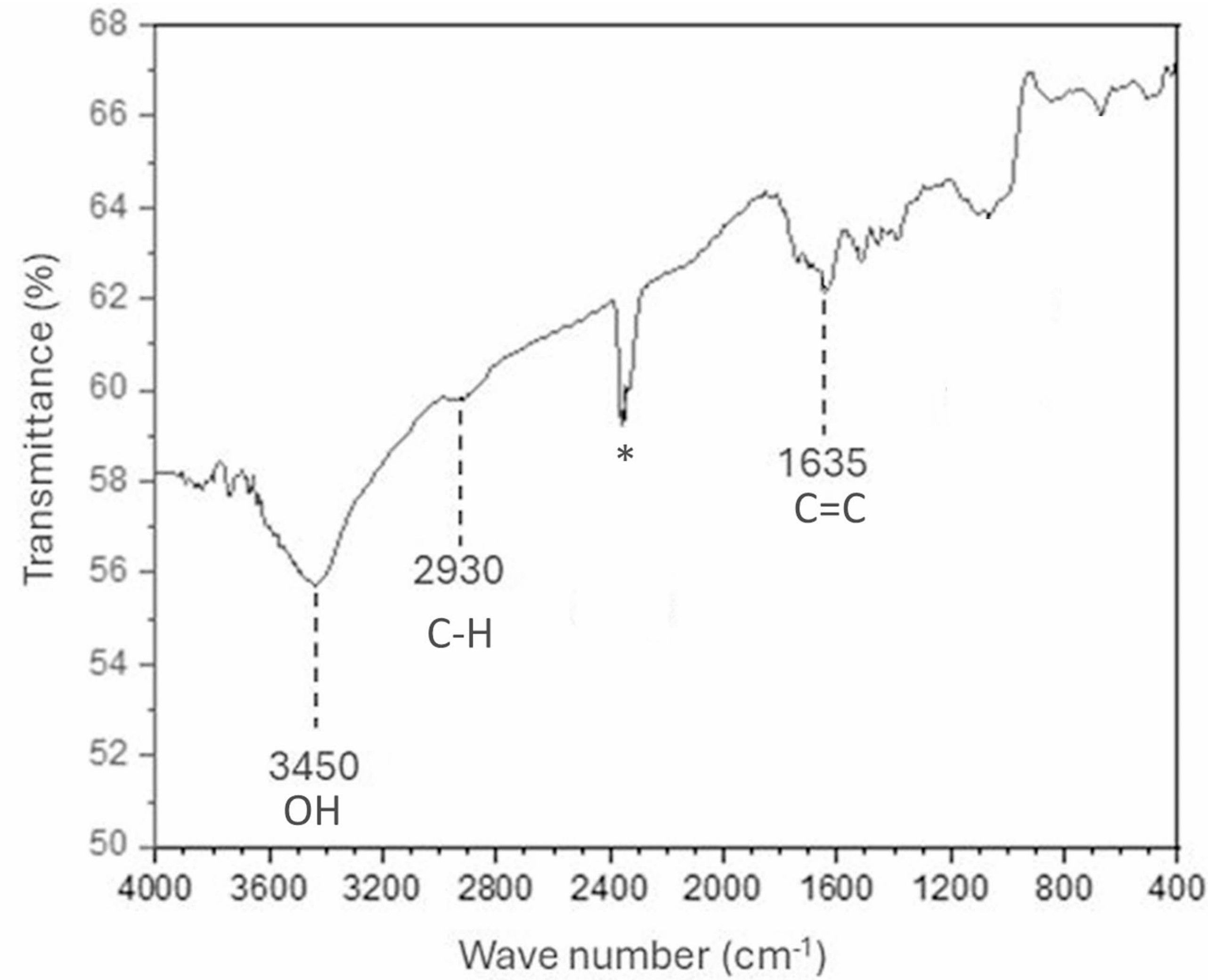

Fig. 3. FTIR Spectrum of in natura coconut fiber, displaying the main absorption bands and their associated functional groups. *The band observed at 2360 cm^{-1} corresponds to the O = C = O vibrations of CO_2 absorbed from the atmosphere[54].

Wave number, cm^{-1}	Characteristic grouping
3100 a 3700	Stretching vibration of the O-H group
2830 a 3000	Symmetric and asymmetric stretching vibrations of C-H bonds in CH and CH_2 groups
1550 a 1700	Vibration of the C = C bond
900 a 1200	Stretching vibration of the C-O bond

Table 3. Attributions related to the chemical groups observed in natural coconut fiber with their respective wave numbers.

to the complexity of the leachate matrix, which contains several species competing for the sorbent's active sites, this study used a larger fiber mass fixed at 5.0 g for experiments with 100 mL of sample. Consequently, each test involved 5.0 g of coconut fiber and 100.0 mL of leachate. Additionally, the decision to use a larger coconut fiber mass took into account residue availability.

Arsenic adsorption tests were performed at the original pH of 8.3 of the leachate. Cellulose, hemicellulose, and lignin contain hydroxyl groups, and carboxyl groups are present in hemicellulose and lignin[42,47,49]. Considering these groups, the pH of the medium significantly influences arsenic adsorption, especially in relation to the point of zero charge of the adsorbent surface (pH_{pzc}) and the specific arsenic species present. In an aqueous medium at pH 8.3, the dominant As(V) species is $((HAsO_4)^{-2})$, which is an anion, while for As(III), the main species is (H_3AsO_3). The pHpzc value is affected by the chemical and electronic properties of the functional groups on the adsorbent surface. When the solution pH is below the pHpzc, the surface

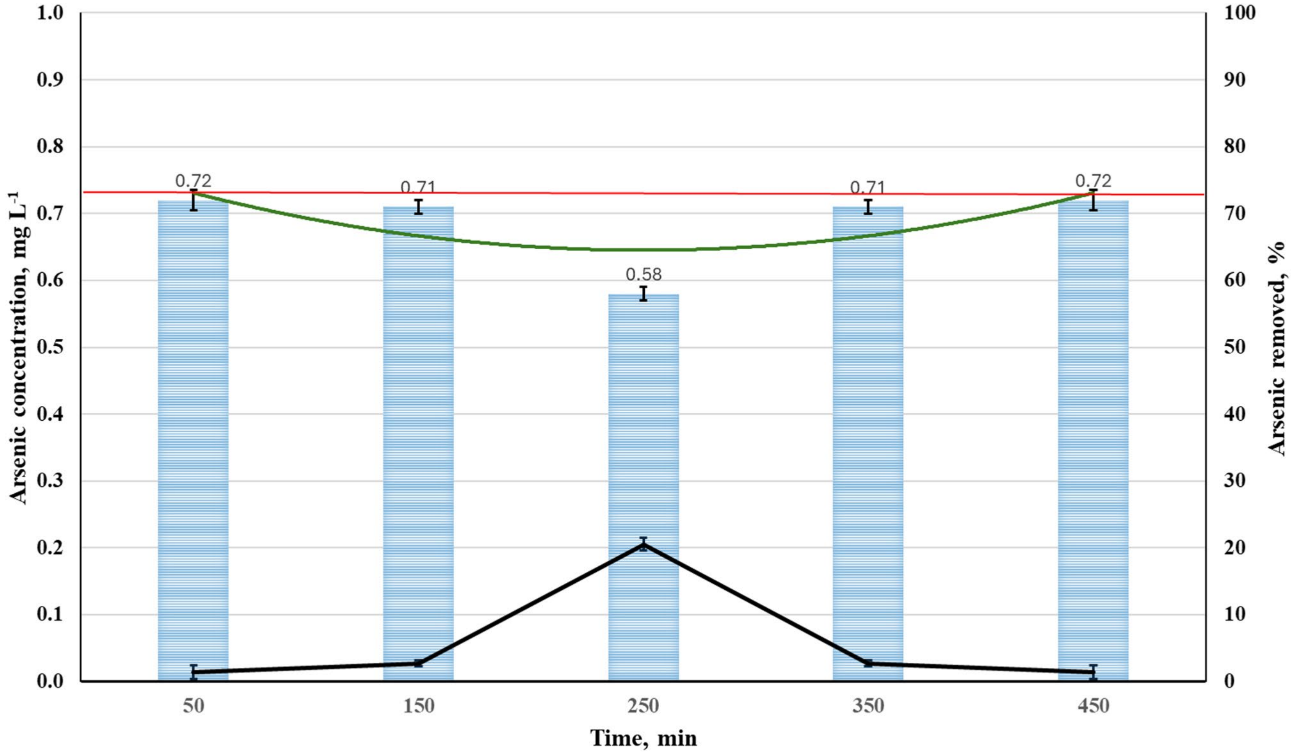

Fig. 4. Investigation of the contact time between the leachate sample and *in natura* coconut fiber: (Blue bars) arsenic concentration in the leachate after contact with the fiber, mg L^{-1}; (Green line) trend line of the arsenic concentration remaining in the leachate after contact with the fiber; (Red line) control data (leachate without coconut fiber: 0.73 ± 0.1 mg L^{-1}); (Black line) percentage of arsenic removed from the leachate after contact with the fiber. Experimental conditions: 5.0 g of coconut fiber, 100.0 mL of leachate, pH 8.3, and a temperature of 22 °C. Error bars represent the standard deviation of three replicates.

gains a positive charge, which increases anion adsorption. Conversely, if the pH is above the pHpzc, the fiber surface becomes negatively charged, promoting cation adsorption[60,61]. Coconut fiber typically has a pHpzc between 4 and 5[61,62]. It is important to note that leachate is a complex mixture of various species that can interact with the fiber, affecting its pHpzc. For instance, cation adsorption can raise the pHpzc of the sorbent[63], bringing the pHpzc of coconut fiber closer to the leachate's pH, which may enhance adsorption efficiency. Furthermore, a pH of 8.3 promotes the precipitation of several species, thereby decreasing competition for active sites on the fiber.

Figure 4 shows the arsenic removal from the leachate sample using in natura coconut fiber at different contact times. Removal was minimal at 50 and 150 min but reached a peak at 250 min, decreasing the arsenic concentration from 0.73 mg L^{-1} to 0.58 mg L^{-1}. This indicates a removal rate of 20.09% of the arsenic originally present in the sample. At contact times of 350 min and 450 min, the removal efficiency dropped again. During the adsorption process, ions migrate from the aqueous medium to the surface of the adsorbent until the solute concentration in the liquid phase stabilizes. The system is considered to have reached equilibrium when this condition is met, at which point the rates of adsorption and desorption of the ions are equal. The time it takes for a system to reach this equilibrium phase can vary from one system to another.

Leachate is a complex matrix containing various species that can compete with the fiber's active sites, leading to a multicomponent adsorptive process. In these systems, synergistic effects, antagonistic effects, or the lack of interactions between the components in the matrix may occur[32], affecting the removal of the species of interest, in this case, arsenic. Despite the complexity of the leachate, removal rates of over 20% were achieved. A similar result, with 22% arsenic removal, was observed when in natura coconut fiber was used as an adsorbent in tests with a synthetic aqueous solution[37]. In tests with banana peel, the arsenic removal achieved was 14.8%[37].

In multicomponent adsorption, the presence of other elements can interfere with the adsorption of the desired species. Initially, an increase in the adsorption of the target species may be observed. However, as time progresses, the desorption of this species can occur. This is because the desorption rate exceeds the adsorption rate[64]. As contact time increases, the overall adsorption capacity can decline, as other species may occupy the active binding sites of the adsorbent, leading to repulsion over time[65]. At the start of the adsorption process, the active sites on the adsorbent's surface are more available, significantly increasing the adsorption rate. However, extended contact time can lead to the deactivation of remaining active sites, ultimately reducing removal efficiency. The efficiency of adsorption is also influenced by the interactions between the solute and solvent, as metal ions possess distinct adsorptive properties due to their ionic and electrostatic forces[66].

Based on the results obtained, it is recommended that the contact time between the leachate and the coconut fiber be set at 250 min. This time must be carefully controlled to maintain optimal arsenic removal efficiency. Longer contact times may negatively affect the operating frequency and hinder the removal of arsenic from the effluent.

Conclusions

It was shown that raw coconut fiber, a biomass often thrown away as agro-industrial waste, can remove arsenic from landfill effluent, helping reduce the leachate's pollution load. The leachate studied was characterized, and the concentrations of the identified elements were compared to the maximum allowed levels for effluent discharge into water bodies. Arsenic was the element that exceeded the permitted limit. The results of arsenic removal with raw coconut fiber were encouraging, showing potential for use in wastewater treatment systems. Even with other ions competing for active sites, more than 20% of arsenic was removed from the leachate under simple operating conditions. Importantly, the fiber was used in its natural state without any pretreatment, and the leachate's pH was not adjusted, all at room temperature, making this method accessible. It is important to emphasize that additional studies on sorption capacities (isotherms and kinetics), adsorption mechanisms, material regeneration, and scale-up experiments are need to evaluate the feasibility of using coconut fiber in landfill leachate treatment. Future research should also focus on cost analysis and scalability for continuous or industrial-scale systems to determine the method's overall feasibility.

Data availability

The datasets used during the current study are available from the corresponding author on reasonable request.

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Declarations

Competing interests
The authors declare no competing interests.

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