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Removal of arsenic from contaminated water using Fenton's reagent–modified plantain pseudo-stem

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Abstract

Arsenic contamination of water poses a significant threat to public health and the environment, particularly in developing regions. This study investigated the effectiveness of Fenton's reagent–pretreated plantain pseudo-stem (PPS) as a low-cost and sustainable biosorbent for the removal of arsenic from aqueous solutions. The plantain pseudo-stem was chemically modified using Fenton's reagent to enhance its surface characteristics and adsorption performance. Batch adsorption experiments were conducted to evaluate the effects of adsorbent dosage, contact time, pH, and initial arsenic concentration on arsenic (III) removal. Arsenic trichloride was used to prepare synthetic contaminated water, and residual arsenic concentrations were quantified using atomic absorption spectroscopy. The results showed that arsenic removal efficiency increased with increasing adsorbent dosage and was strongly influenced by solution pH, with maximum adsorption occurring under alkaline conditions. Rapid adsorption was observed within the first few minutes of contact, indicating high affinity between arsenic species and the modified biosorbent surface. The Fenton's reagent pretreatment significantly improved arsenic uptake compared to untreated PPS, demonstrating the effectiveness of surface modification. Fenton's reagent–pretreated plantain pseudostem proved to be an efficient, eco-friendly, and economically viable adsorbent for arsenic removal from contaminated water. The study highlights the potential of agricultural waste–derived materials for sustainable water treatment applications and provides a foundation for further optimisation and scale-up studies.

Keywords: Adsorbent; Contact Time; Dosage; pH; Concentration

1. Introduction

Water scarcity and contamination are among the most pressing global challenges of the twenty-first century. Although water covers more than 70% of Earth's surface, freshwater accounts for less than 3% of the total volume, with most of it trapped in glaciers and ice caps (Mishra, 2023). Consequently, only about 1% of global water resources are readily available for human consumption and use. Rapid population growth, industrial expansion, and unsustainable water management practices have intensified pressure on this limited resource, making the protection of water quality a critical environmental and public health priority (Izah and Ogwu, 2026). Industrial activities, while essential for societal development, generate large volumes of untreated or inadequately treated effluents that contribute significantly to surface and groundwater pollution, necessitating strict compliance with environmental regulations (Rathore et al., 2025).

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Among water pollutants, arsenic (As) is of particular concern due to its toxicity, persistence, and widespread occurrence. Arsenic is a naturally occurring metalloid found in rocks, soils, and sediments, and it can be released into groundwater through geochemical processes such as mineral dissolution and reductive desorption of iron and aluminium oxides. Anthropogenic activities, including mining, fossil fuel combustion, the use of arsenical pesticides, wood preservatives, and industrial discharges, further exacerbate arsenic contamination of water resources. Elevated arsenic concentrations in groundwater have been reported in many regions worldwide, including Bangladesh, India, China, Argentina, Chile, Pakistan, Cambodia, Viet Nam, and the United States, where groundwater serves as the primary source of drinking water.

Exposure to arsenic-contaminated drinking water above permissible limits established by regulatory authorities such as the World Health Organisation and the U.S. Environmental Protection Agency poses serious health risks. Long-term ingestion of inorganic arsenic has been linked to a wide range of adverse health effects, including skin lesions, hyperpigmentation, palmoplantar hyperkeratosis, cardiovascular diseases, diabetes, neurological disorders, and cancers of the skin, bladder, lung, and liver (Friedrich et al., 2022). Arsenic is classified as a Group 1 human carcinogen, and chronic exposure is associated with increased morbidity and mortality, particularly among vulnerable populations such as children, pregnant women, and the elderly (Ganie et al., 2024). Beyond human health impacts, arsenic contamination also imposes substantial economic and social burdens. The costs associated with medical treatment, provision of alternative water supplies, remediation of contaminated aquifers, and loss of agricultural productivity place significant strain on affected communities and governments. Furthermore, arsenic-contaminated water can adversely affect crops, livestock, and aquatic ecosystems, thereby threatening food security and environmental sustainability.

Heavy metals and metalloids, including arsenic, cadmium (Cd), chromium (Cr), mercury (Hg), and lead (Pb), are characterised by their high toxicity, persistence, and tendency to bioaccumulate in living organisms (Edo et al., 2024). Increasing industrial, agricultural, and domestic use of these elements has led to their widespread release into the environment, intensifying global concern over water safety. Conventional water treatment technologies, while effective, are often expensive, energy-intensive, and difficult to deploy in resource-limited settings, highlighting the need for alternative and sustainable remediation approaches. (Sombei et al., 2025). In recent years, plant-based materials have emerged as promising low-cost and environmentally friendly options for arsenic removal from contaminated water. Agricultural wastes and plant-derived biomaterials are renewable, biodegradable, and rich in functional groups such as hydroxyl, carboxyl, and amino groups that facilitate arsenic removal through adsorption, ion exchange, complexation, and precipitation mechanisms (Paranjape et al., 2023; Ullah & Kim, 2020). Several studies have demonstrated that plant-based adsorbents can achieve arsenic removal efficiencies comparable to conventional materials such as activated carbon and iron-based adsorbents.

Among these materials, plantain (Musa spp.) pseudo-stem has gained increasing attention due to its abundance as an agricultural waste, particularly in tropical and subtropical regions, its low cost, and its favourable surface chemistry (Alvarez & Galan, 2025). Previous studies have reported effective arsenic adsorption by plantain pseudostem under varying pH, temperature, and contact time conditions, with adsorption behaviour commonly described by Langmuir and Freundlich isotherm models (Adeyemi et al., 2025). Moreover, physical, chemical, and oxidative pretreatment methods, such as acid treatment and Fenton's reagent, have been shown to enhance surface area, porosity, and the availability of active binding sites, thereby improving arsenic removal efficiency (Feng et al., 2023).

Given the widespread occurrence of arsenic contamination, its severe health implications, and the limitations of conventional treatment technologies, the exploration of plantain pseudostem as a sustainable biosorbent represents a viable and context-appropriate strategy for water purification. This study, therefore, aims to evaluate and optimise the use of plantain pseudostem for arsenic removal from contaminated water, contributing to the development of cost-effective, environmentally benign, and scalable solutions for ensuring access to safe drinking water, particularly in resource-constrained regions.

2. Materials and Methodology

2.1. Materials

All chemicals and reagents used in this study were of analytical grade and were used without further purification. The materials employed for the experimental procedures included laboratory equipment, reagents, and biosorbent precursors. A mechanical shaker was used to ensure uniform mixing during batch adsorption experiments. Conical flasks (250 mL) and beakers (500 mL) were used for solution preparation and adsorption studies. The pH of experimental solutions was monitored and adjusted using a calibrated digital pH meter. Hydrochloric acid (HCl) and sodium hydroxide (NaOH) solutions were used for pH adjustment. Plantain (*Musa* spp.) pseudostem served as the

biosorbent material for arsenic removal, while arsenic trichloride ($AsCl_3$) was used as the arsenic source for preparing synthetic arsenic-contaminated aqueous solutions. All glassware was thoroughly washed with detergent, rinsed with distilled water, and oven-dried at 105 °C before use to prevent contamination.

2.2. Preparation of Plantain Pseudostem (PPS)

The plantain pseudostem (*Musa paradisiaca*) used in this study was collected from a rural farm in Ilesha. The pseudostems were selected based on maturity and physical integrity. The collected samples were cut into small pieces and thoroughly washed with distilled water to remove adhering dirt and foreign materials. The cleaned samples were air-dried under shade for several days until a constant weight was attained. The dried pseudostems were then ground using a mechanical grinder and sieved to obtain particle sizes in the range of 50–100 μm. The resulting powder was stored in airtight containers for subsequent experimental use.

2.3. Preparation of Fenton's Reagent–Pretreated Plantain Pseudostem

Fenton's reagent–modified PPS was prepared following a reported method with slight modification (Nchoe et al., 2020). Briefly, 3.494 g of $FeSO_4 \cdot 7H_2O$ was dissolved in 250 mL of distilled water to obtain a ferrous ion solution. Forty grams of the prepared PPS powder were transferred into a 500 mL round-bottom flask, after which 200 mL of the freshly prepared Fe^{2+} solution was added. The mixture was stirred and refluxed at 60 °C for 30 min. Subsequently, 200 mL of 30% (v/v) H_2O_2 was added gradually, followed by continuous stirring and refluxing at the same temperature for an additional 30 min. The resulting suspension was filtered, washed repeatedly with distilled water to remove residual reagents, and oven-dried at 80 °C. The modified PPS was stored in airtight containers before the adsorption experiments.

2.4. Effect of Adsorbent Mass on Arsenic Adsorption

A stock solution of arsenic trichloride (0.1 g dm^{-3}) was prepared by dissolving 0.1 g of $AsCl_3$ in hydrochloric acid and diluting to 1000 cm^3 with distilled water. The solution was dispensed into five 250 cm^3 conical flasks, each containing 100 cm^3 of the arsenic solution. The pH of each solution was adjusted to 2.7 using hydrochloric acid. Different masses of Fenton's reagent–modified PPS (0.1, 0.2, 0.3, 0.4, and 0.5 g) were added separately to the flasks. The mixtures were agitated on a mechanical shaker at 120 rpm for 30 min. After agitation, the samples were filtered, and the filtrates were analysed for residual arsenic concentration using atomic absorption spectroscopy (AAS).

2.5. Effect of pH on Arsenic Adsorption

To evaluate the influence of pH on arsenic adsorption, a 0.1 g dm^{-3} $AsCl_3$ solution was prepared and distributed into five conical flasks, each containing 100 cm^3 of solution. The pH values were adjusted to 2, 4, 7, 10, and 12 using hydrochloric acid and sodium hydroxide solutions. A constant mass of 0.5 g of modified PPS was added to each flask. The suspensions were agitated at 120 rpm for 30 min, filtered, and the filtrates were analysed for arsenic concentration using AAS.

2.6. Effect of Contact Time on Arsenic Adsorption

The effect of contact time on arsenic adsorption was investigated using a 0.1 g dm^{-3} $AsCl_3$ solution adjusted to pH 2.7. Aliquots of 100 cm^3 were transferred into separate conical flasks, and 0.1 g of modified PPS was added to each. The mixtures were agitated at 120 rpm for contact times of 2, 5, 10, 30, and 60 min. At the end of each contact period, the samples were filtered, and the filtrates were analysed for arsenic content using AAS.

2.7. Effect of Initial Arsenic Concentration on Adsorption

To assess the effect of initial arsenic concentration, $AsCl_3$ solutions of varying concentrations (0.1, 0.2, 0.3, 0.4, and 0.5 g dm^{-3}) were prepared. For each concentration, 100 cm^3 of solution was transferred into individual conical flasks and adjusted to pH 2.7. A constant mass of 0.5 g of modified PPS was added to each flask, and the mixtures were agitated at 120 rpm for 30 min. After filtration, the residual arsenic concentrations in the filtrates were determined using AAS.

3. Results and Discussion

3.1. Effect of Adsorbent Dosage

The influence of adsorbent dosage on As(III) removal using Fenton's reagent-pretreated plantain pseudostem (PPS) shows a clear positive trend: increasing the amount of adsorbent improves arsenic removal. This occurs because higher dosages provide more active sites for As(III) binding, as illustrated in Figure 1. This behaviour is consistent with basic

adsorption theory, where greater adsorbent mass increases surface area and the number of functional groups, lowering the residual As(III) concentration until the adsorbent reaches saturation (Yao et al., 2014).

Similar patterns have been reported in studies of other biosorbents. For example, iron oxide-modified rice and wheat husk biochar exhibited dosage-dependent As(III) removal, achieving capacities of up to 111 μg/g without oxidation of As(III), due to increased iron oxide loading and surface availability (Zada and Azizi, 2026). Likewise, magnetic iron oxide-activated carbon composites showed As(V) removal rising from 25.8% to 89.7% as dosage increased from 1.0 to 5.0 g/L (Yao et al., 2014), reflecting the same "site-multiplication" effect observed here. In Fe(III)-modified pomelo peel biosorbents, increasing the dosage from 0.5 to 4 g/L enhanced As(V) removal to over 92% at optimal pH, highlighting how chemical modifications can amplify available binding sites, similar to the way Fenton's oxidation likely enhances phenolic and cellulosic groups in PPS (Singh et al., 2020).

The Fenton pretreatment makes this PPS particularly effective, potentially outperforming unmodified agricultural wastes by generating iron oxides and radicals that create additional anion-exchange sites for As(III). This is in line with observations in Fe/Mn-doped chitosan-alginate beads, which achieved capacities of 20.16 mg/g (Zeng et al., 2020). Unlike some adsorbents, where very high dosages can cause particle aggregation or diminishing returns (e.g., bagasse fly ash above 3 g/L), PPS showed no such limitations at pH 2.7, demonstrating its potential as a low-cost, scalable solution for arsenic remediation.

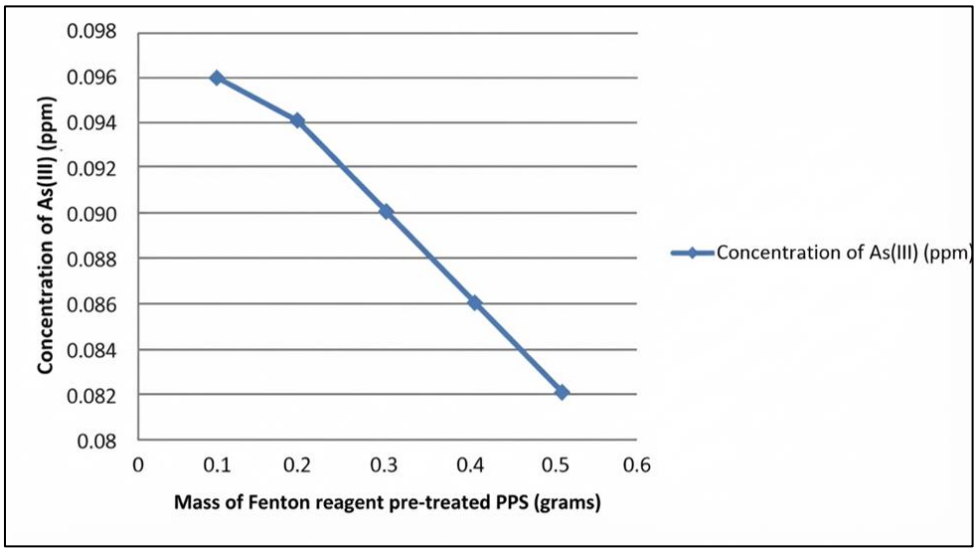

Figure 1 Graph of Concentration of As (III) against Mass of Fenton's reagent pretreated PPS

3.2. Effect of Contact Time

The effect of contact time on As(III) removal using Fenton's reagent-pretreated plantain pseudostem (PPS) shows that adsorption occurs very rapidly, reaching a peak within the first 5 minutes at pH 2.7, with an initial As(III) concentration of 0.1 g/dm^3 and 0.1 g of adsorbent. This fast uptake is due to the abundance of fresh, reactive sites on the PPS surface, allowing arsenic to bind quickly before the surface begins to saturate (Hossain et al., 2024). The early efficiency arises from the numerous vacant sites and the Fenton-induced iron oxides, which promote electrostatic attraction and complexation with As(III). This follows the classic two-stage adsorption pattern: a rapid initial capture followed by slower diffusion (Zhang et al., 2024). The slight increase in arsenic concentration after 5 minutes, up to ~0.090 ppm, likely reflects minor desorption of weakly bound species as equilibrium redistributes solutes—a common occurrence when outer surfaces fill first.

This short equilibrium time is much faster than many other biosorbents. For example, Fe-Mn chitosan beads required 60 minutes to reach 95% As(III) removal at similar dosages, and iron oxide-modified rice husk biochars needed 120 minutes to achieve their maximum capacity of around 111 μg/g (Mohammadi & Ghadi, 2024). In comparison, magnetic iron oxide-carbon composites reached 89% As(V) removal after 30–60 minutes across 1–5 g/L dosages. PPS's 5-minute peak highlights the enhancement provided by Fenton treatment, which improves cellulose and phenolic functionalities, enabling faster adsorption without the aggregation issues observed with higher doses of unmodified peels. Unlike Zr-loaded sorbents that plateau after 40 minutes, extended contact time did not improve As(III) removal for PPS (Zhao et al., 2024), confirming its efficiency for rapid, real-time water treatment. Overall, this fast adsorption profile positions

Fenton-pretreated PPS as an effective, low-cost option, significantly reducing processing time compared to slower agricultural waste-based sorbents (Akhtar et al., 2024).

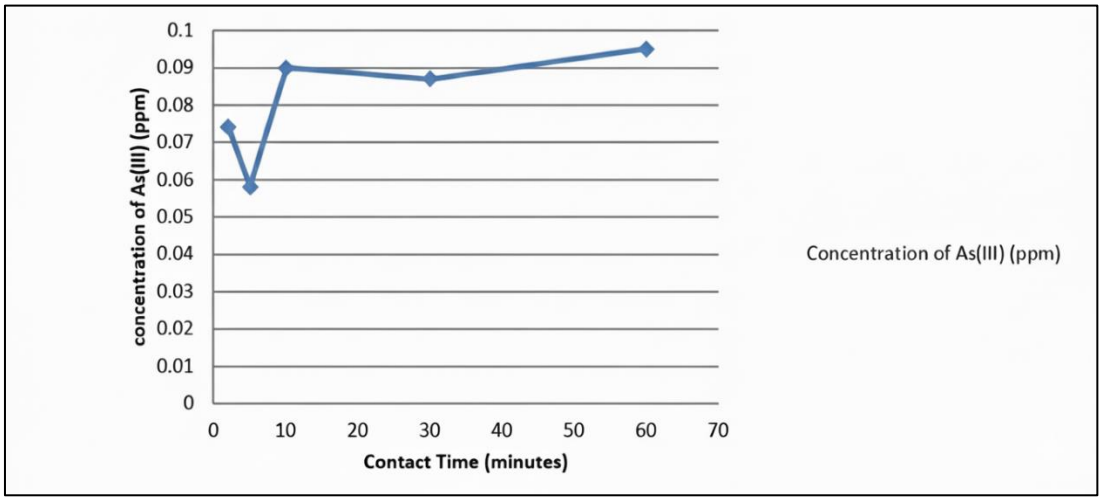

Figure 2 Graph of Concentration of As(III) against contact time using Fenton's reagent pretreated PPS

3.3. Effect of pH

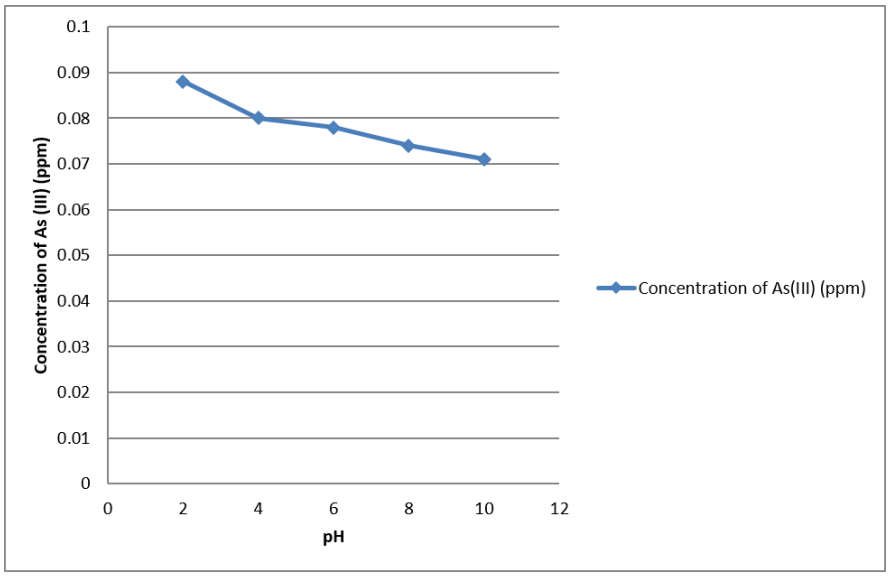

Figure 3 Graph of Concentration of As (III) against pH using Fenton's pre-treated PPS

pH plays a critical role in As(III) adsorption onto Fenton's reagent-pretreated plantain pseudostem (PPS) by controlling both arsenic speciation and the surface charge of the adsorbent. As shown in Figure 3, maximum adsorption occurred at pH 10, while uptake was minimal at pH 2, where surface protonation repels As(III) species (Hossain et al., 2024). This alkaline preference contrasts with most iron-modified biosorbents, which typically perform best in acidic conditions (pH 2–7) because neutral As(III) species and positively charged surfaces promote adsorption. $FeCl_3$-impregnated bagasse fly ash achieved peak removal around pH 6.5, declining at higher pH due to competition with oxyanions, while iron oxide rice husk biochars favoured pH below 7 by binding uncharged As(III). Similarly, magnetic iron oxide-carbon composites showed maximum As(V) uptake at mildly acidic pH, with excess H^+ at pH 2 hindering adsorption through repulsion (Suresh et al., 2022). Fenton treatment appears to reverse this trend for PPS. At pH 10, phenolic and cellulose groups are deprotonated, exposing negatively charged sites that can complex with neutral As(III) or H_3AsO_3 molecules, similar to Fe(III)-modified pomelo peels, which perform well above pH 7. Unlike Zr-loaded orange gels that work best near neutral pH or Fe-Mn chitosan beads favouring pH 5–7 ($q_{max} \approx 20$ mg/g), PPS shows a distinct alkaline shift. This is likely due to radical-generated functional groups that reduce competition from H^+ ions, while avoiding iron sludge formation that can occur in Fenton systems above pH 4. Consequently, Fenton-pretreated PPS is well-suited for treating

naturally alkaline waters, outperforming acid-dependent agricultural waste sorbents without the need for pH adjustment (Xiong et al., 2024)

3.4. Effect of Initial Arsenic Concentration

The influence of initial As(III) concentration on adsorption by Fenton's reagent-pretreated plantain pseudostem (PPS) follows a typical saturation trend. As the starting arsenic concentration increased, the residual arsenic concentration after adsorption rose steadily, as shown in Figure 4. This behavior reflects the limited number of active sites available on the fixed PPS dose: at low arsenic loadings, these sites are sufficient for effective uptake, but at higher concentrations they become progressively saturated, leaving more arsenic in solution (Hossain et al., 2024).

At relatively low initial concentrations, the abundance of vacant and highly reactive sites—enhanced by iron oxides generated during Fenton pretreatment and by oxidized phenolic groups—promotes near-complete arsenic removal through rapid surface complexation and anion-exchange mechanisms. As the As(III) concentration increases beyond the sorbent's capacity, competition for active sites intensifies, adsorption kinetics slow, and equilibrium arsenic concentrations rise. This response is consistent with Langmuir isotherm behavior, where adsorption capacity (q_e) approaches a maximum and no longer increases proportionally with equilibrium concentration (C_e) (Mohammadi and Ghadi, 2024).

Comparable trends have been reported for other biosorbents. For example, iron oxide–modified rice husk biochar effectively removed As(III) at low concentrations (≤10 mg/L) before reaching a capacity limit, while Fe–Mn chitosan beads showed a decline in removal efficiency from about 95% at 5 mg/L to roughly 60% at 50 mg/L due to site saturation. Magnetic iron oxide–carbon composites similarly achieved high removal efficiencies at moderate concentrations, but residual arsenic increased once the adsorption capacity was exceeded (Akhtar et al., 2024). Unlike some acid-treated clay sorbents that perform poorly at high arsenic levels because of aggregation effects (Aljohani et al., 2023), Fenton-treated PPS maintains consistent removal across the tested concentration range. This stability supports its suitability as a low-cost adsorbent for typical arsenic-contaminated waters (approximately 1–50 mg/L). The observed concentration-dependent behavior underscores the importance of sorbent dosage optimization or the integration of hybrid treatment processes when addressing waters with high arsenic loads (Suresh et al., 2022).

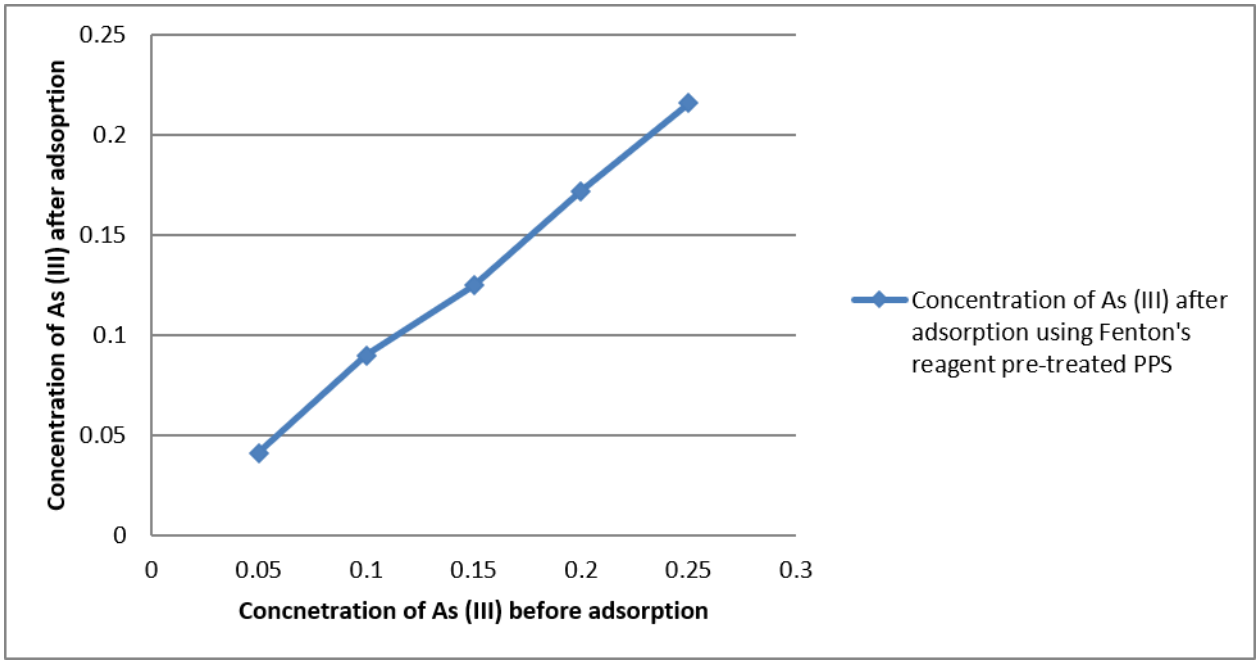

Figure 4 Graph of concentration of As (III) after adsorption against concentration of As(III) before adsorption using Fenton's reagent-pretreated PPS

4. Conclusion

Fenton's reagent–pretreated plantain pseudostem demonstrated strong potential for the removal of arsenic from contaminated water. The pretreatment significantly enhanced the surface area and increased the abundance of surface functional groups on the plantain pseudostem, leading to improved arsenic adsorption capacity.

The adsorption experiments confirmed that the pretreated plantain pseudostem removed substantially higher amounts of arsenic compared with the untreated material, highlighting the effectiveness of Fenton's reagent modification. This study demonstrates that Fenton's reagent, pretreated plantain pseudostem, is a promising, low-cost, and eco-friendly adsorbent for arsenic removal from water. The findings underscore the potential of plant-based materials in water treatment and emphasise the importance of sustainable approaches to mitigating water contamination. Further research is recommended to optimise the treatment conditions, evaluate long-term performance, and assess scalability for practical water treatment applications. Additionally, greater promotion of sustainable water treatment technologies and increased public awareness of the risks associated with water contamination are strongly encouraged.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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