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ORIGINAL RESEARCH ARTICLE

Adsorption of arsenic from gold mine wastewater onto iron oxide-coated sand and activated chars pyrolysed by the traditional-charcoal-production method

Richard Komla Nyamador[1]*, Patrick Boakye[2], Sampson Oduro-Kwarteng[1], Esi Awuah[1], and Richard Akwasi Buamah[1]

[1]Department of Civil Engineering, Regional Water and Environmental Sanitation Centre Kumasi, Kwame Nkrumah University of Science and Technology, Kumasi, Ashanti Region, Ghana

[2]Department of Chemical Engineering, College of Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ashanti Region, Ghana

Abstract

Ghana's artisanal and small-scale mining (ASM) releases harmful contaminants, including arsenic, into the environment at levels exceeding acceptable limits. For miners to reduce arsenic levels in their tailings before discharge, the cost of remediation materials and processes must be significantly lower than it is now. This study uses unactivated and activated chars produced from agricultural waste, informed by the United Nations Food and Agriculture Organization and other studies on traditional charcoal-making methods, to assess the potential of sorption techniques to reduce arsenic levels in tailings, both alone and when combined with iron oxide-coated sand (IOCS). Sorption phenomena were measured through batch and column experiments. The Freundlich and Langmuir sorption isotherms were used to characterise the adsorbents. IOCS alone achieved an average removal efficiency of 91.65%, compared with 40.20%, 37.40%, and 21.40% for the unactivated chars, and 76.83%, 73.5%, and 78.83% for the activated chars from sawdust, coconut husk, and neem wood feedstocks, respectively. The column experiment combining IOCS and activated chars in a multi-layer, four-stage system achieved 100% removal efficiency within 46 hours. Generally, the traditional charcoal preparation method can be used to produce effective, low-cost adsorbents from agricultural waste for arsenic removal from mining effluents. Employing a combination of activated chars and IOCS results in rapid arsenic removal. A consistent approach to prevent the ASM industry from contaminating Ghana's water resources with excessive arsenic is to issue directives requiring the use of activated chars made from agricultural waste, combined with IOCS for mine remediation. This strategy can also generate multiple alternative employment opportunities within the mining sector.

Keywords: Activated chars; Mining effluent treatment; Settling/Decantation ponds; Adsorbent materials; Iron oxide-coated sand; Column/Batch experiments

***Corresponding author:**
Richard Komla Nyamador
(rknyamador@knust.edu.gh)

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1. Introduction

Small-scale mining operations in Ghana (both legal and illegal) release large quantities of contaminants, including arsenic, into surface water, groundwater, and soil.[1-4] The International Agency for Research on Cancer classifies arsenic and inorganic arsenic compounds as carcinogenic to humans.[5] The United Kingdom Health Security Agency indicate that a single dose of inorganic arsenic by ingestion or inhalation could be highly toxic.[6] Similarly, the United States Department of Health and Human Services Agency for Toxic Substances and Disease Registry in 2025 ranked arsenic second on its substance priority list.[7] Some studies indicate that several people in Bangladesh and India are at risk of arsenic poisoning from contaminated groundwater.[8-12] In Ghana, some studies linked the 1990s Buruli ulcer outbreak in Amansie West, Ashanti Region, to exposure to arsenic-rich aquatic environments disturbed by mining and agricultural activities.[13-16] In most minerals-producing developing countries, including Ghana, the artisanal and small-scale mining (ASM) industry is mainly criticised for polluting surface and groundwater resources, largely due to poor management of mining effluents. Currently, in Ghana, most ASM firms lack tailings holding facilities sufficient to sustain the extended period required for the gradual remediation processes that will ensure effluents meet Ghana Standard Authority (GSA) acceptable conditions for safe release into the environment.[1]

To ensure that mining tailings do not continue to pollute the environment and water resources, Ghana's Minerals Commission published the Small-scale and Community Mining Operational Manual, which requires every ASM or gold ore processing firm to install a water storage facility comprising at least three settling/decantation ponds (Figure 1) for recycling process water.[17]

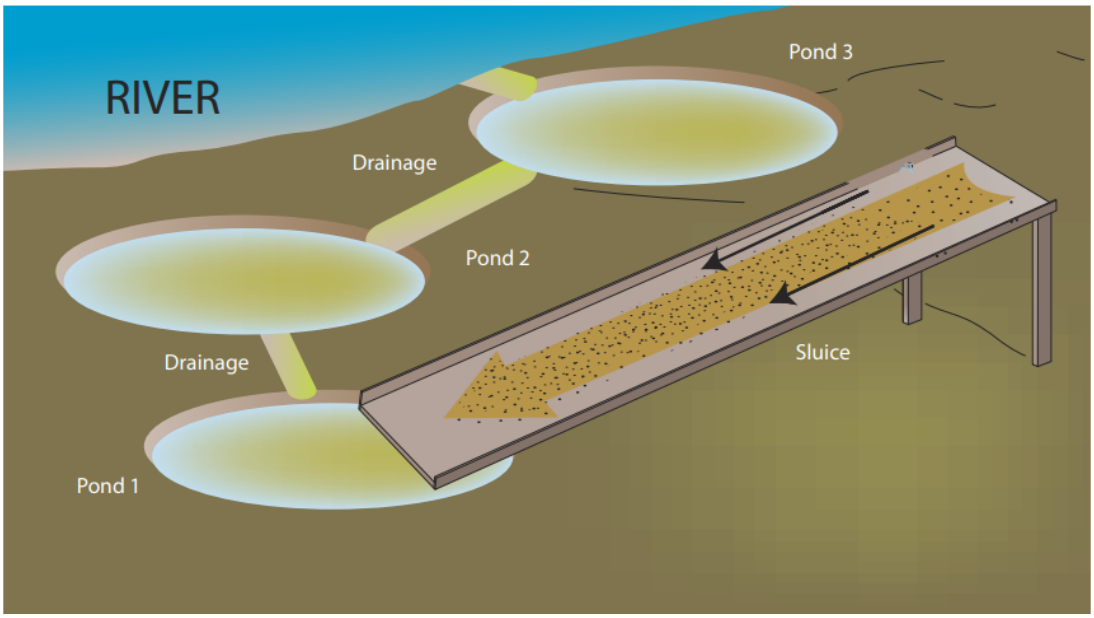

Figure 1. Suggested Ghana Minerals Commission settling/decantation pond concept. Adopted from Tychsen et al.[18]

The challenge with the decantation pond arrangement (Figure 1) is that many of the harmful chemical constituents, including arsenic, will not be removed before the effluents are discharged into the environment. To ensure that the decantation and recycling proposal really prevents environmental pollution, the system needs to reduce contaminant concentrations to acceptable levels before discharge. Thus, in this situation, it is imperative that, if ASM firms agree to comply with sustainable environmental standards, such as treating their tailings before discharge, the cost of treatment and materials must be lower than their current high market prices. Stakeholders will therefore have to adopt affordable yet effective remediation strategies, including, for example, in the case of arsenic remediation, the use of adsorbents such as activated char derived from agricultural waste and other

viable industrial waste, such as iron oxide-coated sand (IOCS).

Over the years, numerous such low-cost, effective heavy metal contaminant removal studies have been conducted,[19-22] yet have rarely been broken down for industry use to address devastating environmental challenges such as the current Ghanaian ASM challenge. Acheampong and Lens[23] and Singh *et al.*[24] buttress this assertion by noting that many of these studies have limited industrial applications due to the complex and heterogeneous nature of industrial effluents. Acheampong and Lens[23] also noted that little effort has been made to utilise agricultural and natural materials for removing heavy metal contaminants from industrial effluents. Additionally, the challenge has been that these studies were mostly conducted under laboratory conditions that yield only very small quantities of these adsorbent materials, and their large-scale replication is only possible with very expensive commercial setups. Over the years, these conditions have hindered the full implementation of these studies for long-term use by small-scale or less-resourced industries. Take, for instance, the production of activated carbon for heavy metal remediation, which is done in a laboratory muffle or tube furnace at high cost, or using expensive commercial equipment.

Given the widespread nature of surface water, groundwater, and soil pollution in Ghana and other developing countries, there is a need to integrate theoretical concepts with field-applicable research to develop cost-effective yet sustainable heavy metal adsorbents to address this situation. The primary aim of this study is to explore the arsenic removal potential of unactivated and activated chars produced from agricultural waste such as neem wood, sawdust, and coconut husk, pyrolysed by the traditional charcoal production method, and to compare the results with those of IOCS concurrently. The United Nations Food and Agriculture Organization's traditional charcoal-making process[25] and those of other studies were applied.[26-30] This study culminates in a relatively inexpensive, large-scale, improvised yet viable option for producing adsorbents, with field-ready, readily applicable sorption isotherm parameters for estimating, in real time, the quantities of adsorbent required by the average person to remove arsenic from effluents. Literature search over an extended period into affordable wastewater treatment studies uncovered very few articles on similar research projects.

To achieve the objective of this study, the following research questions were considered:

(i) How effective are the chars produced from agricultural feedstocks using traditional charcoal production methods in removing arsenic from effluents?
(ii) How effective are the activated chars produced using improvised physical activation methods at removing arsenic from effluents?
(iii) How does the arsenic removal efficiency of the unactivated chars and the activated chars compare with that of IOCS?
(iv) How suitable are the Freundlich and Langmuir isotherm models for estimating the arsenic adsorption properties of the unactivated chars, activated chars, and IOCS?
(iv) What are the percentage arsenic removal rates for the activated chars and IOCS in a pilot multi-layer four-stage quasi-field setup?

The study's specific objectives include:

(i) To produce chars from the aforementioned feedstocks using the traditional rural pit method for industrial charcoal production as outlined in previous studies.[25-30]
(ii) To produce activated chars from the chars obtained in specific objective (i), following the physical activation parameters outlined in Tchobanoglous *et al.*[30] using improvised activation arrangements.
(iii) To estimate the arsenic adsorption efficiencies of the unactivated chars (produced under specific objective (i)) and IOCS using the batch experiment method under natural field conditions.
(iv) To estimate the arsenic adsorption efficiencies of the activated chars (produced under specific objective (ii)) using the batch experiment method under natural field conditions.
(v) To establish the Freundlich (K_f and 1/n) and Langmuir (a and b) constants for each of the produced unactivated chars, activated chars, and the IOCS sample to support broader use in estimating arsenic adsorbents for remediation purposes.
(vi) To estimate the amount of adsorbent required to treat mine water to the Environmental Protection Agency (EPA) and GSA accepted arsenic level for mining and industrial efluents using either the Freundlich or Langmuir isotherm equations.
(vii) To pilot an arsenic remediation setup adopting a four-stage (multi-stage) and multi-layer (4 layers) column experiment using the estimated adsorbent amounts determined for specific objective 6 in the natural field environment at two-h intervals for 48 h.

This study is important as it (i) bridges the gap between laboratory/academic research and field-applicable studies and concepts needed for a sustainable response to the Ghanaian ASM environmental challenge; (ii) contributes to Ghana's Sustainable Development Goal 6 efforts on clean water; (iii) increase the chances of producing inexpensive,

adequate, commercial quantities of adsorbents for the removal of arsenic contaminants from mining tailings and industrial effluents; and (iv) has the potential to create a significant number of indirect employment opportunities in the categories of feedstock scavengers, absorbent processors, and remediation workers. The study is organised into six sections. After the introduction, Section 2 reviews the occurrence and treatment of arsenic and discusses the theoretical background, and Section 3 outlines the methodological framework. Section 4 reports the results of the batch experiments, presents the batch and column results, and considers a case study scenario that requires estimating adsorbent requirements for an ore processing site. Section 5 discusses the study, and Section 6 presents the conclusion.

2. Literature review

2.1. The occurrence and treatment of arsenic

Much of the gold ore found in Ghana's Birimian and Tarkwaian geological systems is associated with sulphide mineralisation, particularly arsenopyrite, which is the most abundant arsenic mineral in mineral veins.[31-35] Groundwater in these areas is mostly carbonate-deficient, resulting in poorly buffered water.[34,35] Exposure of sulphides to mining or weathering leads to oxidation, which in turn causes acid mine drainage or acid rock drainage. This acid mine drainage or acid rock drainage could infiltrate aquifers and lower groundwater pH. Low-pH groundwater readily dissolves heavy metals, such as arsenic, and other geological materials, making it unsafe for drinking over time.[32-35] Methods used in remediating heavy metals include biosorption, bioremediation, and chemical precipitation, among others. Biosorption technology for removing heavy metals from wastewater involves binding metal ions to the surfaces of sorbents such as fungi, algae, yeast, bacteria, and biopolymers. It is considered an efficient and eco-friendly technology. Its primary drawbacks are sensitivity to operating conditions and limited binding capacity.[36-38] Phytoremediation of polluted waters is based on the cultivation of plants, including aquatic and terrestrial species with a high capacity to absorb specific heavy metals. The challenge with this option is the slow cleanup rate and the risk of contaminated plants moving into the food chain.[39-41] Chemical precipitation is a common treatment method for removing toxic metals from wastewater as precipitates. Although chemical precipitation is simple to operate, it requires significant capital investment and produces excessive sludge that has long-term environmental impacts.[42]

Coagulation involves agglomerating small particles into larger aggregates, enabling them to settle quickly for easy solid/liquid separation. The process, however, generates large amounts of chemical sludge and has high operational and chemical costs.[43,44] Reverse osmosis is widely used for treating municipal and industrial water and for desalination. A major concern with reverse osmosis setups is the cost associated with energy consumption and membrane replacement.[45-47] Some studies indicate that sorption is a more appropriate method for arsenic contaminant removal, as it is low-cost, enables flexible design, and produces little by-product.[48-50] Generally, sorption adsorbent selection is based on usability, surface area, adsorption capacity and overall cost.[49,51] Sorption includes ion exchange, which is often used for demineralisation, water softening, and targeted removal of contaminants such as heavy metals and nitrates. The process involves swapping dissolved ionic contaminants with relatively harmless ions. The ion exchange option, however, generates highly concentrated wastewater that is harmful to the environment and incurs high operational costs.[52-54] Studies on IOCS and activated carbon indicate their effectiveness as primary adsorbents for removing arsenic and other metals from industrial effluents. According to Ramakrishna *et al.*[50], the United States EPA considers IOCS as one of the most sustainable options for removing arsenic from drinking water. Li *et al.*[55] argue that IOCS has one of the shortest adsorption times and the highest removal rate when treating organic matter with modified filter media. Research on the treatment of wastewater pollutants using IOCS has been well documented, with most studies indicating that iron-based adsorbents are highly effective at removing arsenic from water.[56-59]

Activated carbon can be produced on a large scale from materials with high carbon content, such as wood, coconut shells, and other agricultural waste feedstocks.[20,58,60,61] Activated carbon is mainly produced by pyrolysis of the feedstock, followed by steam activation at the required temperature.[30,62-64] Ippolito *et al.*[63] note that higher pyrolysis temperatures and feedstock type significantly affect the properties of activated carbon and biochars. Numerous studies have confirmed the high efficiency of activated carbon and biochars in remediating heavy metal contaminants in effluents.[30,62-64] Generally, the feedstock for biochar production is derived primarily from agricultural, domestic, and municipal waste.[63,64] Several other studies investigated the adsorptive performance of some biochars using the Langmuir and Freundlich sorption isotherms. Most of these studies accepted both the Langmuir and Freundlich isotherm models as suitable for explaining water treatment adsorption processes. Singh *et al.*[24] and other studies,[44,57,65-69] recommend using multiple sorption processes for continuous-flow industrial effluents as it is more economical and effective.

2.2. Theoretical background

In most studies, sorption phenomena were measured experimentally by determining the amount of a solute that a specific adsorbent interface can sorb. The experimental results are plotted as an isotherm, showing solute concentration versus the amount sorbed at the interface. Generally, the amount of solute an adsorbent can take up is a function of the solute's characteristics, concentration, and temperature; the resulting relationship is called a sorption isotherm. Sorption isotherms are important for estimating solute interactions with sorbents, enabling the optimisation and use of identified adsorbents. The sorption concepts used in this study are outlined below.

2.2.1. Linear sorption isotherm

Where there is a direct relationship between the amount of a solute sorbed onto a solid, "x/m," and the concentration of the solute, "C_e," the adsorption isotherm of C_e as a function of "x/m" plots as a straight line. The resulting linear sorption isotherm is represented as **Equation 1**:

$$x/m = K_d C_e \quad (1)$$

where "x/m (y-axis)" is the mass of material sorbed per unit dry weight of solid (mg/kg), "C_e (x-axis)" is the concentration of solute in solution in equilibrium with the mass of solute sorbed onto the solid (mg/L), and "K_d" is the distribution coefficient (L/kg), which is equal to the slope of the linear sorption isotherm. On the contrary, most studies rely on the Freundlich and Langmuir sorption models to analyse sorption data.

2.2.2. Freundlich sorption isotherm

The Freundlich sorption isotherm is a more general equilibrium isotherm, defined by a non-linear relationship similar to **Equation 1**. Thus, the Freundlich sorption isotherm is represented as follows (**Equation 2**):

$$q_e = \frac{x}{m} = K_f C_e^{\frac{1}{n}} \quad (2)$$

Sorption characteristics can be described by the Freundlich sorption isotherm when C_e is plotted against q_e. However, the data can be linearised by use of **Equation 3**:

$$Log\left(\frac{x}{m}\right) = \log K_f + \frac{1}{n}\log C_e \quad (3)$$

where q_e is the mass of material adsorbed (x) per unit mass of adsorbent (m) at equilibrium, and x/m is the adsorbate (arsenic) adsorbed per unit mass of the adsorbent, measured in "mg" adsorbate/ "g" adsorbent. K_f is the Freundlich capacity factor (sorption capacity of sorbent), C_e is the equilibrium concentration of adsorbate in solution after adsorption, which is measured in mg/L, and 1/n is the Freundlich intensity parameter (an empirical constant related to the efficiency of the sorption). The constants in the Freundlich isotherm in **Equation 2** are estimated by plotting log(x/m) versus log(C_e). Thus, a plot of log(x/m) against log(C_e) yields a slope of 1/n and an intercept of log(K_f). The Freundlich constant (K_f) is a comparative measure of the adsorption capacity for the adsorbent, and the Freundlich intensity parameter ($1/n$) is an empirical constant related to the heterogeneity of the adsorbent surface. For favourable adsorption, $0 < 1/n < 1$, while $1/n > 1$ represents unfavourable adsorption (sorption is low). Thus, $1/n < 1$ means sorption is good, and $1/n = 1$ indicates linear adsorption. If $1/n = 0$, the adsorption process is irreversible.[70,71]

2.2.3. Langmuir sorption isotherm

When all the sorption sites are filled, the surface will no longer sorb solute from the solution. The form of the Langmuir sorption isotherm is represented as **Equation 4**:

$$\frac{C_e}{x/m} = \frac{1}{ab} + \frac{C_e}{b} \quad (4)$$

The Langmuir isotherm, derived from rational considerations, is defined as **Equation 5**:

$$\frac{x}{m} = \frac{abC_e}{1 + aC_e} \quad (5)$$

where x/m is the mass of the adsorbate (amount of arsenic) sorbed per unit mass of the adsorbent, measured in mg/g; C_e is the equilibrium concentration of the adsorbate (arsenic solution) in solution after the adsorption, measured in mg/L; and a and b are empirical constants, where "a" is an adsorption constant related to the binding energy (L/mg) and "b" is the maximum amount of solute that can be absorbed by the solid (mg/kg). If the sorption of a solute onto a solid follows a Langmuir sorption isotherm, then the graph plot of the experimental data of "x/m" versus C_e will have a curved shape that reaches a maximum value. If "C_e/x/m" is plotted against "C_e," the data follow a straight line from which the empirical constants in **Equation 5** are determined. Thus, **Equation 5** is rewritten as **Equation 6**:

$$\frac{C_e}{\left(\frac{x}{m}\right)} = \frac{1}{ab} + \frac{1}{b}C_e \quad (6)$$

2.2.4. Estimation of adsorbent requirement using the Freundlich and Langmuir isotherms

Generally, the amount of arsenic adsorbed on an adsorbent is represented as: Amount of arsenic adsorbed = Initial amount of arsenic present – final amount of arsenic present. This is written as **Equation 7**:

$$q_e M = VC_o - VC_e \quad (7)$$

where q_e is the mass (mg) of arsenic constituent adsorbed per unit mass (g) of the adsorbent. M is the mass of the adsorbent (g), V is the volume of the liquid in the treatment setup (L), C_o is the initial concentration of the arsenic constituent in the solution (mg/L), and C_e is the final concentration of the arsenic constituent in the solution (mg/L) after the adsorption.

$$q_e = -\frac{V}{M}\left(C_e - C_o\right) \quad (8)$$

We deduce an expression for V/M using **Equations 2** and **8**. Thus, from **Equation 2**, q_e is:

$$q_e = \frac{x}{m} = K_f C_e^{\frac{1}{n}}$$

Therefore, the Freundlich isotherm is represented as **Equation 9**:

$$-\frac{V}{M} = \frac{K_f C_e^{\frac{1}{n}}}{\left(C_e - C_o\right)} \quad (9)$$

The Freundlich isotherm coefficients are substituted to determine the M/V. Similarly, for Langmuir isotherms:

$$q_e = \frac{x}{m} = \frac{abCe}{1 + aCe} \quad (10)$$

where a is the absorption constant related to the binding energy (L/mg), and b is the maximum amount of solute that can be absorbed by the solid (mg/kg):

$$-\frac{V}{M} = \left[\frac{\left(\frac{abCe}{1+aCe}\right)}{\left(Ce - Co\right)}\right] \quad (11)$$

Once again, Langmuir isotherm coefficients are substituted to determine the M/V.

3. Methodological framework

In this study, sorption phenomena were measured using batch and column experiments to determine the amount of arsenic solute that a specific adsorbent interface can sorb. The study was conducted in five stages, as indicated in the study framework (Figure 2). The experimental results were plotted as isotherms, showing solute concentration versus the amount sorbed at the interface. As indicated earlier, sorption isotherms are important for estimating solute interactions with sorbents, thereby enabling the optimisation and use of identified adsorbents. The Freundlich and Langmuir sorption isotherm models were used in this study to characterise the adsorbents and to determine the isotherm constants for subsequent column experiments. At the end of each batch or column experiment, the amount of arsenic remaining in the solution was measured. The batch experiments were designed to estimate the removal efficiencies of the unactivated char, IOCS and the activated char samples. The removal efficiencies (R) and the amount of arsenic adsorbed at any time were computed by using **Equations 12** and **13**:

$$R = \frac{\left(C_o - C_e\right)}{C_o} \times 100 \quad (12)$$

$$q_e = \frac{(C_o - C_e)V}{M} \quad (13)$$

where q_e is the amount of arsenic ions adsorbed on the adsorbent (mg/g), C_o is the initial arsenic ion concentration in solution (mg/L), C_e is the equilibrium arsenic ion concentration in solution (mg/L), V is the volume (L), and M is the amount of adsorbent (g). These pilot experiments were conducted directly in the field to enable the project to replicate the real ambient climatic conditions under which the miners would use the adsorbents.

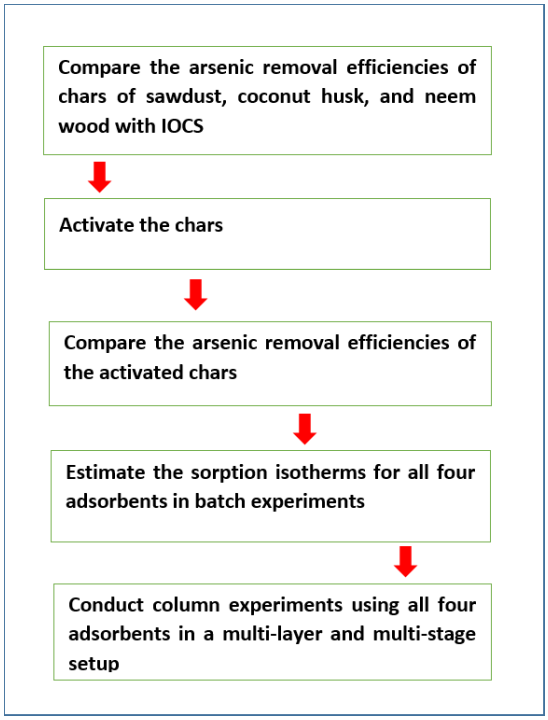

Figure 2. Study framework
Abbreviation: IOCS: Iron oxide-coated sand.

3.1. Materials

A 1,000 mg/L arsenic standard solution (Lot: HC209251) used for the batch and column experiments was obtained from Merck KGaA (Germany). IOCS was obtained from a stock retrieved from the Barekese water treatment plant in the Ashanti Region of Ghana and stored at the Regional Water and Environmental Sanitation Centre laboratory in Kumasi. Sawdust, coconut husk, and neem wood feedstocks were collected from Teshie, Accra, Ghana. A handheld BSIDE H3 infrared thermometer, which measures temperatures from −50 °C to 1,400 °C, was procured.

3.1.1. Char preparation

The industrial charcoal preparation process, as outlined by previous work[25-30] was adopted for the char preparation phase. Concerning the neem char preparation, a sizeable volume of neem wood (Figure 3) was compactly stacked in a shallow dug-out (80 cm length × 80 cm breadth × 20 cm depth). The stack was completely covered with grass and leaves and buried under a layer of moist soil (about 40 cm thick), leaving two small openings, about 15 cm × 15 cm, through which fire was lit. The slits were closed with leaves and moist soil after the stack had begun to burn. The burning was monitored day and night for 72 h (the duration depends on the size and moisture content of the wood) by opening and sealing successive vent holes in the earth mound to allow limited ventilation and to sustain burning at temperatures between 20 °C and 550 °C until the entire stack was charred (carbonised).

The burned char was separated from the soil and cooled with clean water. Regarding coconut husk char preparation, a substantial volume of coconut husk (Figure 3) was compactly stacked in a shallow dug-out (80 cm length × 80 cm breadth × 20 cm depth). The process with the wood char was repeated. The pile was allowed to burn for 48 h at temperatures between 20 °C and 300 °C until the entire stack was charred. Regarding the sawdust char, a substantial volume was placed in six airtight steel containers measuring 34 cm × 13 cm × 9 cm (Figure 4). The containers were placed in a shallow dug-out (80 cm length × 80 cm breadth × 20 cm depth) and covered with sufficient fuelwood. The process with the wood char was repeated. The firewood was allowed to burn completely between 20 °C and 300 °C for four h. The steel containers containing the charred sawdust were removed and allowed to cool.

3.1.2. Activation of the chars

The chars were physically activated without any chemical additives, following the procedure described by Tchobanoglous *et al.*[30] The chars produced from neem wood, coconut husk, and sawdust were broken into smaller bits, moistened with distilled water, placed in airtight steel containers, and then placed in an improvised oven (Figure 5). The improvised oven consisted of a hollow structure made of solid 6-inch sandcrete blocks. The inner part of the structure was plastered with about one-inch-thick clay to trap the heat from the fire. One ventilation hole was made using a 40-cm-long one-inch galvanised pipe to vent excess gas. A 30 cm × 60 cm rectangular hole was created at the base of the oven to pass the gas cylinder pipe arrangement. Subsequently, the rectangular hole was sealed with sandcrete blockwork and clay. The temperature was allowed to rise very gradually, about 10 °C/min. The setup was allowed to burn until the steam exiting the galvanised pipe reached 700–900 °C. The activated chars were then exposed to air and sunlight for 48 h to desiccate under natural conditions.

3.2. Arsenic removal batch experiments

Batch-one experiments were conducted on chars produced from neem wood, sawdust, coconut husk feedstocks, and the IOCS sample. Batch-two experiments were conducted

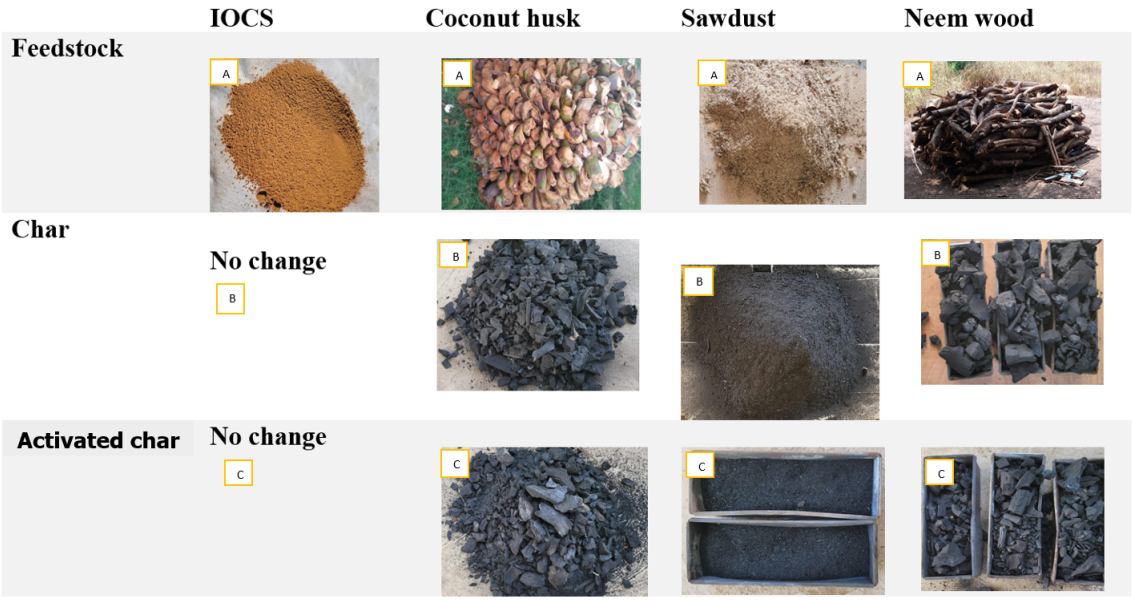

Figure 3. Adsorbent samples used for the study. Various states of the feedstocks: (A) raw, (B) charred, and (C) activated.
Abbreviation: IOCS: Iron oxide-coated sand.

Figure 4. Airtight steel containers used to produce the sawdust char

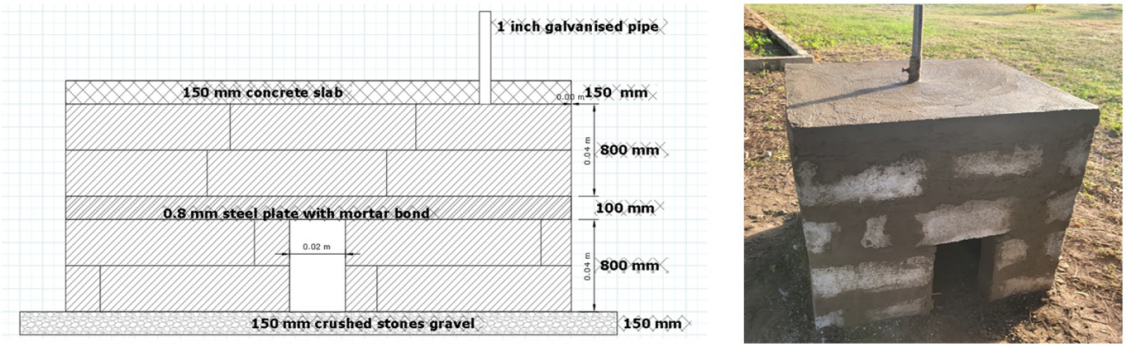

Figure 5. Sketch and picture of the improvised sandcrete/clay oven for char production

using the activated chars produced from the batch-one char samples. The experiments were not repeated for the IOCS because the sample remained unchanged. The batch experiments aim to investigate the adsorbent's removal efficiency and to determine its Langmuir and Freundlich isotherm constants as precursors for estimating the required amounts for the column experiment and for future field applications.

For the batch-one experiment, sorption isotherms were developed by placing 1,000 cm^3 (1 L) of arsenic solution at a concentration of 0.9099 mg/L in 10 containers for each adsorbent (IOCS, unactivated neem wood char, sawdust, and coconut husk), as shown in Figures 6 and 7. The adsorbents were placed in porous polyester bags to group the adsorbent granules together. The mass of the adsorbent was varied for each of the 10 containers, from 0.1 g to 1.0 g, and the setup was left in the natural field for 10 days.

For the batch-two experiment, sorption isotherms were developed by placing 1,000 cm^3 (1 L) of arsenic solution at a concentration of 0.75 mg/L in 10 containers containing activated chars (neem wood, sawdust, and coconut husk only). The adsorbents were placed in porous polyester bags to group the adsorbent granules together. The mass of the adsorbent was varied for each of the 10 containers, from 0.1 g to 1.0 g, and the setup was left in the natural field for 10 days. The test samples taken from the batch-one experiments were sent to the GSA laboratory in Accra, Ghana, for processing, and those from the batch-two

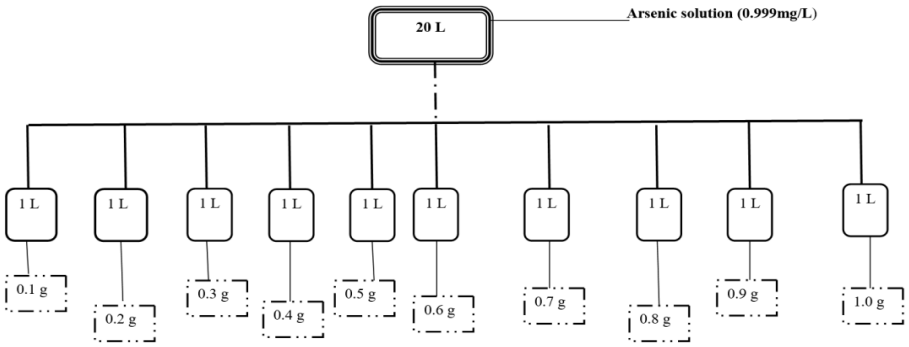

Figure 6. Outline of the batch experiment setup

Figure 7. Portion of the batch experiment setup used for the study

experiments were sent to the Jospong Central Laboratory in Accra for processing.

3.3. Arsenic removal column experiment

The column experiments were conducted to evaluate the effectiveness of absorbent materials in a quasi-pilot field setup. Quantities of 24.48 g, 12.48 g, and 19.10 g of activated chars of sawdust, coconut husk, and neem wood, respectively and 2.16 g of IOCS were used.

All the adsorbent quantities were estimated by substituting derived Langmuir isotherm coefficients in **Equation 11**. Each weighed adsorbent was divided into four equal parts and placed in four porous polyester bags (each serving as a layer). A bag of each packaged adsorbent was placed in four containers (6-L plastic bowls) arranged in series to mimic a multi-stage column flow field (Figures 8 and 9). Thus, each container had four adsorbent layers. A 60-L drum containing a 0.75 mg/L arsenic solution was connected via 1.27-cm-diameter pipes, and the flow was regulated using a partially closed 0.5-inch air valve.

The pipe flow rate was determined using the volumetric

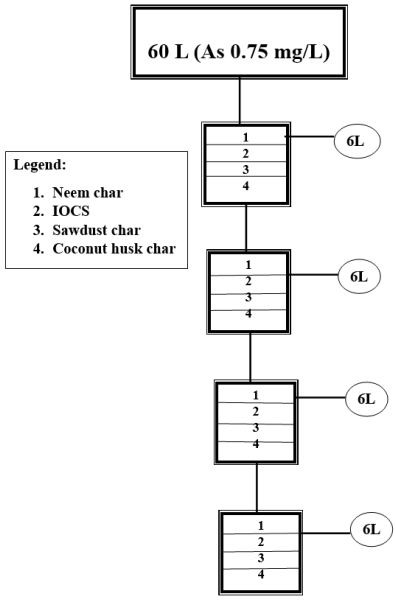

Figure 8. Outline of the multi-layer, multi-stage column experiment setup for the study

Figure 9. Portion of the multi-layer, multi-stage column experiment setup for the study

flow rate, cross-sectional area and average velocity (**Equation 14**). A similar parallel-column arrangement was established alongside, using the same parameters to enable comparison of results. The setup was such that the fluids in all four columns could mix, as would be the case in a real-field constructed treatment setup, where the fluids would move through weirs to each column. Samples were collected at two-h intervals for 48 h (0–48 h), after which they were sent to the Jospong Central Laboratory for processing.

$$Q = AV \tag{14}$$

where Q is the volumetric flow rate, A is the area of the section, and V is the average velocity of flow.

Table 1. Results for the batch-one experiment

Serial	Mass (g)	Initial conc (mg/L)	IOCS		Sawdust char		Wood char		Coconut-husk char	
			Sample	Results (mg/L)	Sample	Results (mg/L)	Sample	Results (mg/L)	Sample	Results (mg/L)
1	0.1	0.9099	AS1	0.1640	SD1	0.6714	WA1	0.8167	CA1	0.7144
2	0.2	0.9099	AS2	0.1068	SD2	0.6237	WA2	0.7524	CA2	0.6226
3	0.3	0.9099	AS3	0.0998	SD3	0.5964	WA3	0.7476	CA3	0.6152
4	0.4	0.9099	AS4	0.0806	SD4	0.5652	WA4	0.7449	CA4	0.5646
5	0.5	0.9099	AS5	0.0645	SD5	0.5536	WA5	0.7306	CA5	0.5552
6	0.6	0.9099	AS6	0.0593	SD6	0.5533	WA6	0.7259	CA6	0.5519
7	0.7	0.9099	AS7	0.0548	SD7	0.4989	WA7	0.7171	CA7	0.5315
8	0.8	0.9099	AS8	0.0457	SD8	0.4813	WA8	0.7113	CA8	0.5293
9	0.9	0.9099	AS9	0.0431	SD9	0.4500	WA9	0.7001	CA9	0.5236
10	1.0	0.9099	AS10	0.0413	SD10	0.4475	WA10	0.5812	CA10	0.4867

Abbreviation: IOCS: Iron oxide-coated sand.

Table 2. Results for the batch-two experiment

Serial	Mass (g)	Initial conc (mg/L)	Sawdust biochar		Wood AC		Coconut-husk AC	
			Sample	Results (mg/L)	Sample	Results (mg/L)	Sample	Results (mg/L)
1	0.1	0.75	SD1	0.500	WA1	0.350	CA1	0.250
2	0.2	0.75	SD2	0.250	WA2	0.250	CA2	0.250
3	0.3	0.75	SD3	0.250	WA3	0.250	CA3	0.250
4	0.4	0.75	SD4	0.250	WA4	0.250	CA4	0.250
5	0.5	0.75	SD5	0.250	WA5	0.250	CA5	0.250
6	0.6	0.75	SD6	0.087	WA6	0.125	CA6	0.250
7	0.7	0.75	SD7	0.050	WA7	0.050	CA7	0.187
8	0.8	0.75	SD8	0.050	WA8	0.050	CA8	0.125
9	0.9	0.75	SD9	0.025	WA9	0.025	CA9	0.087
10	1.0	0.75	SD10	0.025	WA10	0.025	CA10	0.087

4. Results

The results of the batch one and two experiments are presented separately, representing the unactivated and activated chars. Table 1 summarises the final effluent concentrations in the batch-one experiment. IOCS samples were represented as AS, sawdust char as SD, neem wood char as WA, and coconut husk char as CA.

Batch two experiments were conducted using activated chars produced from the batch-one char samples. Table 2 summarises the final effluent concentrations in the second-batch experiment. Sawdust char is represented as SD, neem wood char as WA and coconut husk char as CA.

The results were analysed in the order in which they were conducted. First, the batch-one experiments were analysed for arsenic removal efficiencies, after which the general suitability of the feedstocks for the Freundlich or Langmuir isotherms was investigated. Subsequently, separate Freundlich and Langmuir isotherm analyses were conducted to determine the constants in their equations.

4.1. Batch-one experiment analysis

4.1.1. Removal efficiency and sorption isotherm analysis

The removal efficiency for all adsorbents increased with increasing adsorbent mass. Table 3 and Figure 10 summarise the removal efficiencies of the adsorbents used in the batch-one experiment. Only IOCS had a removal capability above 50%.

Thus, IOCS had an average removal efficiency of 91.65%, compared to 40.20% for sawdust char, 37.40% for coconut husk, and 21.40% for neem wood. Hence, the unactivated chars from agricultural feedstocks have low arsenic-removal capacity, indicating that relatively large quantities would be required for mining remediation operations.

The plot of "x/m" versus "C_e" did not show a curvilinear shape (Figure 11); hence, the sorption characteristics do not follow the Freundlich sorption isotherm.[53] It, however, fitted the Langmuir sorption isotherm, as the experimental data for the "x/m" versus "C_e" plot showed a curved line that reaches a maximum.[53] Therefore, the char from agricultural feedstocks has some arsenic-removal capacity, although low, confirming that large quantities of adsorbents would be required for remediating arsenic contaminants.

4.1.2. Freundlich sorption isotherm analysis

Figure 12 and Table 4 summarise the Freundlich sorption isotherm parameters for the batch-one experiment. The R-squared (R^2) values for all adsorbents except the IOCS were close to 1, indicating a good fit for the regression model.

Table 3. Summary results of batch-one experiment, indicating percentage arsenic removal efficiencies

Mass (g)	IOCS R%	Coconut R%	Neem wood R%	Sawdust R%
0.1	81.98	21.49	17.31	26.21
0.2	88.26	31.57	17.84	31.45
0.3	89.03	32.39	18.13	34.45
0.4	91.14	37.95	18.63	37.88
0.5	92.91	38.98	19.71	39.16
0.6	93.48	39.34	20.22	39.19
0.7	93.98	41.59	21.19	45.17
0.8	94.98	41.83	21.83	47.10
0.9	95.26	42.46	23.06	50.54
1.0	95.46	46.51	36.12	50.82
Average	91.65	37.40	21.40	40.20

Abbreviation: IOCS: Iron oxide-coated sand.

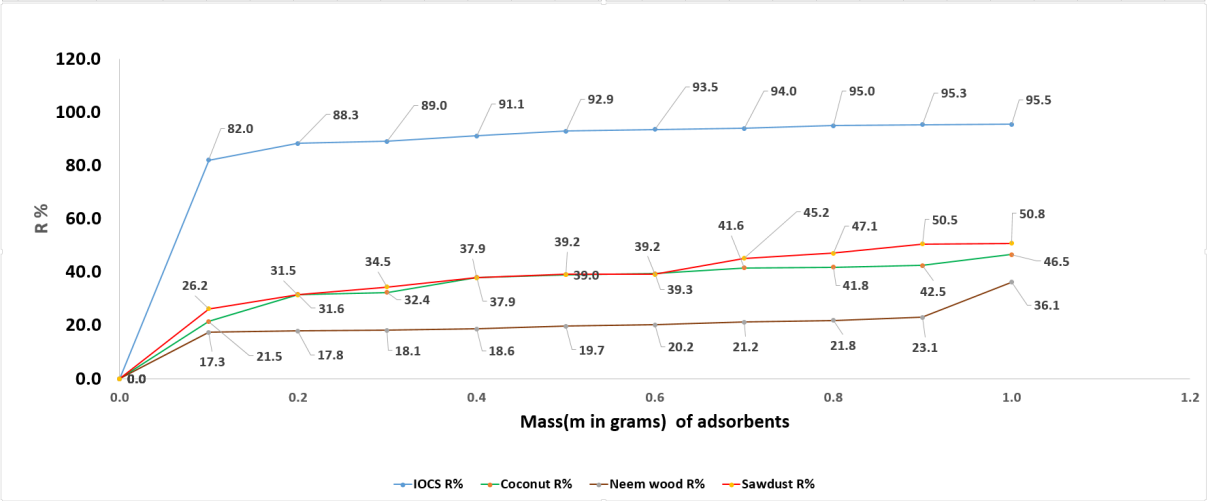

Figure 10. Graph of arsenic removal efficiencies for the batch-one experiment

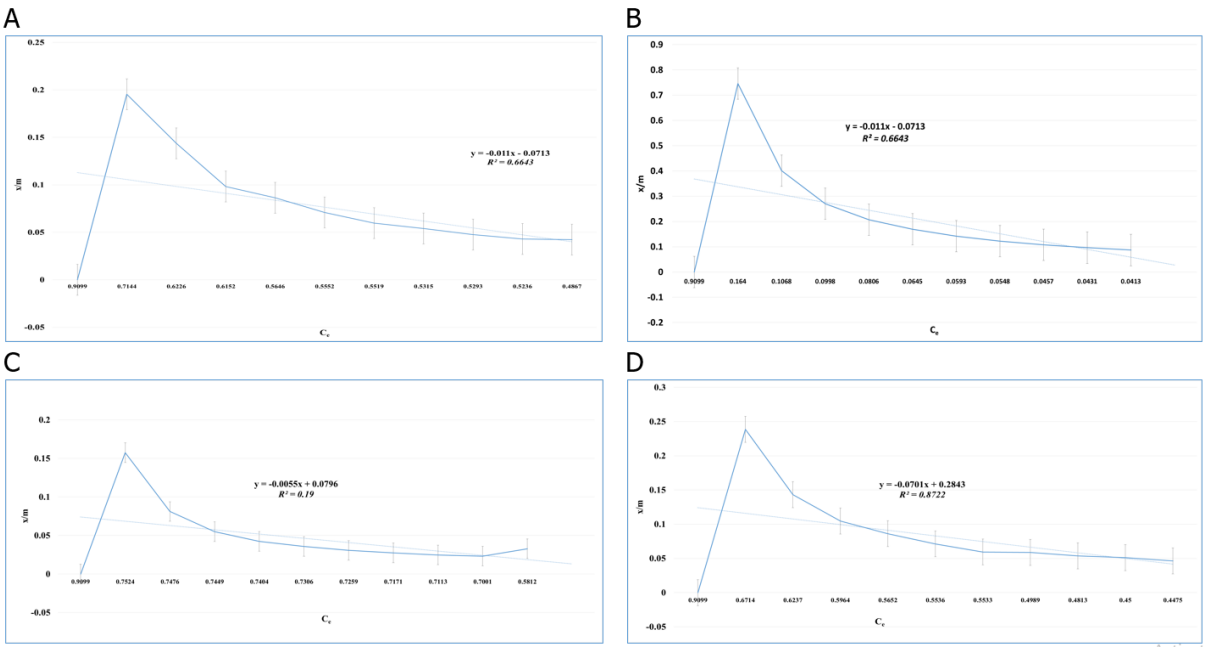

Figure 11. Graphs showing the sorption characteristics for the batch-one experiment. (A) Coconut husk, (B) iron oxide-coated sand, (C) neem wood, and (D) sawdust.

Although the Freundlich isotherm does not adequately describe the sorption characteristics of the sorbents, the Freundlich Isotherm constants ($1/n$ and K_f) for the IOCS and the other adsorbents are summarised in Table 4. Because $1/n$ is less than 1, it is expected that the chars and the IOCs are good adsorbents for arsenic contaminants in solutes.

4.1.3.Langmuir sorption isotherm analysis

Figure 13 and Table 5 summarise the Langmuir isotherm parameters for the batch-one experiments. The R^2 values for all adsorbents were close to 1, indicating a good fit for the regression model.

The sorption follows the Langmuir sorption isotherm because the experimental data of "x/m" versus "Ce"

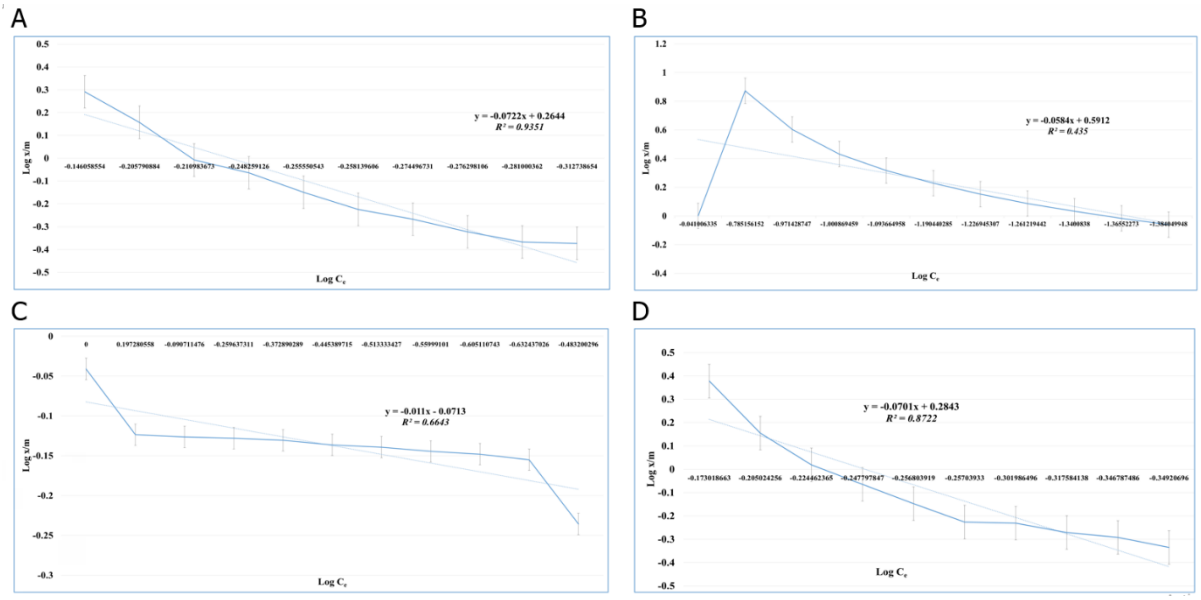

Figure 12. Graphs showing the results of the Freundlich isotherm characteristics. (A) Coconut husk, (B) iron oxide-coated sand, (C) neem wood, and (D) sawdust.

Table 4. Freundlich sorption isotherm parameters for the batch-one experiment

Adsorbent	R^2	$K_{f\,(mg/L)(L/mg)}$	$1/n$
Iron oxide-coated sand	0.44	0.058	0.228
Sawdust char	0.87	0.070	0.546
Neem wood char	0.66	1.147	0.011
Coconut husk char	0.94	0.072	0.578

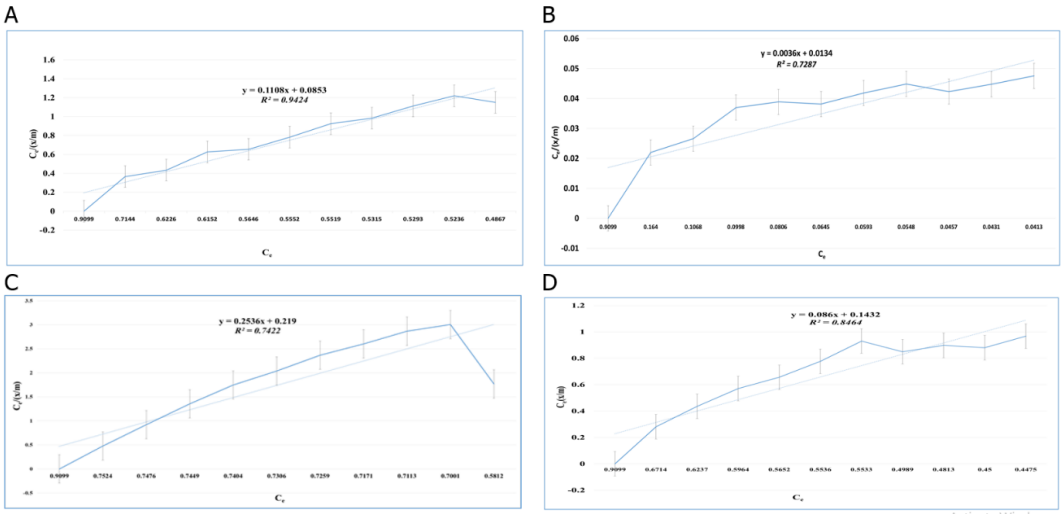

Figure 13. Graphs showing the results of the Langmuir isotherm characteristics investigation. (A) Coconut husk, (B) iron oxide-coated sand, (C) neem wood, and (D) sawdust.

plotted as a curve with a maximum (Figure 13). The maximum ion sorption and binding energy constants for each adsorbent are listed in Table 5.

4.2. Batch-two experiment analysis

4.2.1. Removal efficiency and sorption isotherm analysis

The removal efficiency for all adsorbents increased with increasing mass. Table 6 and Figure 14 summarise the removal efficiencies of the adsorbents calculated in the first batch experiment. All the adsorbents had removal capability above 50%.

Iron oxide-coated sand had an average removal efficiency of 91.65%, compared to 78.83% for neem wood, 76.83% for sawdust char, and 73.5% for coconut husk. Therefore, the activated chars from agricultural feedstocks have high arsenic-removal capacity, indicating that relatively lower quantities would be required for remediation than unactivated adsorbents.

The plot of all three activated chars did not exhibit a curvilinear shape (Figure 15); hence, their sorption characteristics cannot be described using the Freundlich sorption isotherm.[53] The sorption for all the adsorbents, however, follows the Langmuir sorption isotherm, as evidenced by the curved shapes that reach a maximum.[53]

4.2.2. Freundlich sorption isotherm analysis

The plots of x/m versus C_e (Figure 16) were not curvilinear, indicating that the Freundlich sorption isotherm does not describe the batch experimental data.[53] Table 7 summarises the Freundlich sorption isotherm parameters for the batch-two experiment.

The R^2 values for all adsorbents were close to 1, indicating a good fit for the regression model. Although the Freundlich isotherm does not adequately describe the sorption characteristics of the sorbents, the Freundlich isotherm constants ($1/n$ and K_f) for the IOCS and char adsorbents are summarised in Table 7. Because $1/n$ is less than 1, the activated chars are expected to be effective adsorbents for arsenic contaminants in solution. However, the $1/n$ values for the activated chars are much lower than those for the unactivated chars, indicating more favourable adsorption.

4.2.3. Langmuir sorption isotherm analysis

The sorption follows the Langmuir sorption isotherm because, when the experimental data of "x/m" versus "C_e" were plotted, a curve that reaches a maximum was obtained (Figure 17). The maximum ion sorption and binding energy constants for each adsorbent are listed in Table 8. The R^2 values, however, did not indicate a good fit for the regression model.

4.3. Results and analysis of the column experiment

The amount of adsorbents required for the column experiment was determined from the constants established in the batch-two experiment. The column experiment contained a total of 24 L of arsenic solution (6 L per column).

4.3.1. Estimation of the column adsorbent quantities

The Langmuir isotherm model fits the study better for both the unactivated chars and the activated carbon, as well as the IOCS. Therefore, the constants in Table 8 were used to determine the amount of adsorbents required to reduce arsenic levels in the solute using **Equation 13**. For the sawdust biochar alone:

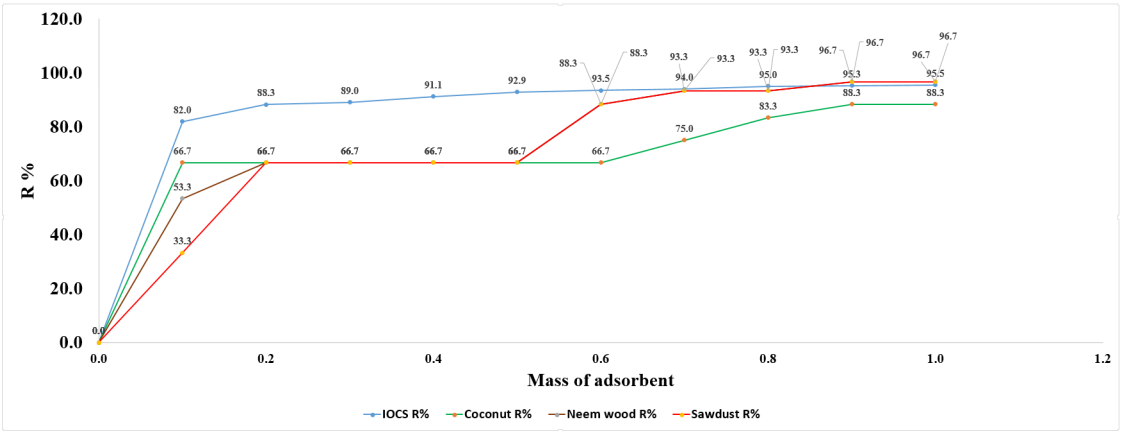

Figure 14. Graph of arsenic removal efficiencies for the batch-two experiment

Table 5. Langmuir sorption isotherm parameters for the batch-one experiment

Adsorbent	a	b	R^2	Maximum value
Iron oxide-coated sand	0.267	277.78	0.7287	7.4
Sawdust char	0.60	11.63	0.8464	2.4
Coconut husk char	1.30	8.03	0.9424	1.9
Neem wood char	1.16	3.94	0.7422	1.6

Table 6. Summary results of batch-two experiment, indicating percentage arsenic removal efficiencies

Mass (g)	IOCS R% (batch-one results)	Coconut R%	Neem wood R%	Sawdust R%
0.1	82.0	66.7	53.3	33.3
0.2	88.3	66.7	66.7	66.7
0.3	89.0	66.7	66.7	66.7
0.4	91.1	66.7	66.7	66.7
0.5	92.9	66.7	66.7	66.7
0.6	93.5	66.7	88.3	88.3
0.7	94.0	75.0	93.3	93.3
0.8	95.0	83.3	93.3	93.3
0.9	95.3	88.3	96.7	96.7
1.0	95.5	88.3	96.7	96.7
Average	91.65	73.5	78.83	76.83

Abbreviation: IOCS: Iron oxide-coated sand.

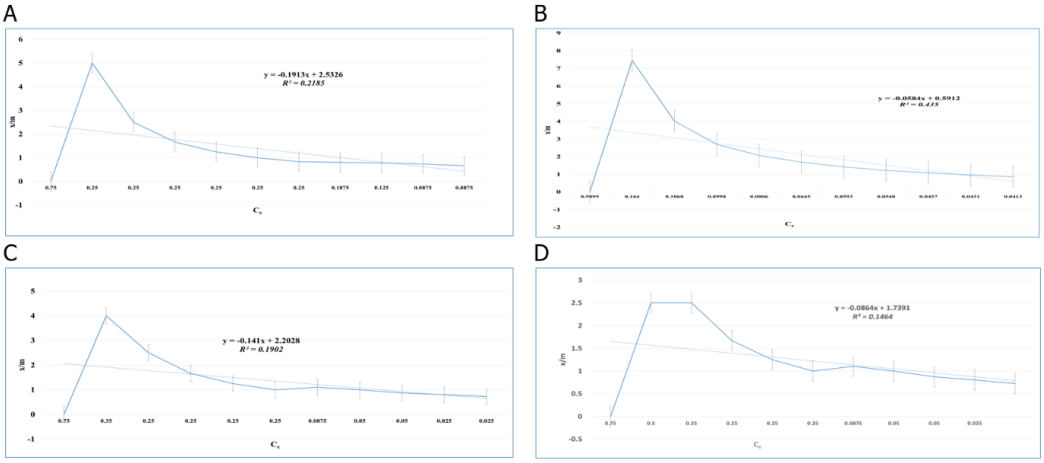

Figure 15. Graph showing the results of the initial sorption characteristics investigation for the batch-two experiment. (A) Coconut husk, (B) iron oxide-coated sand, (C) sawdust, and (D) neemwood.

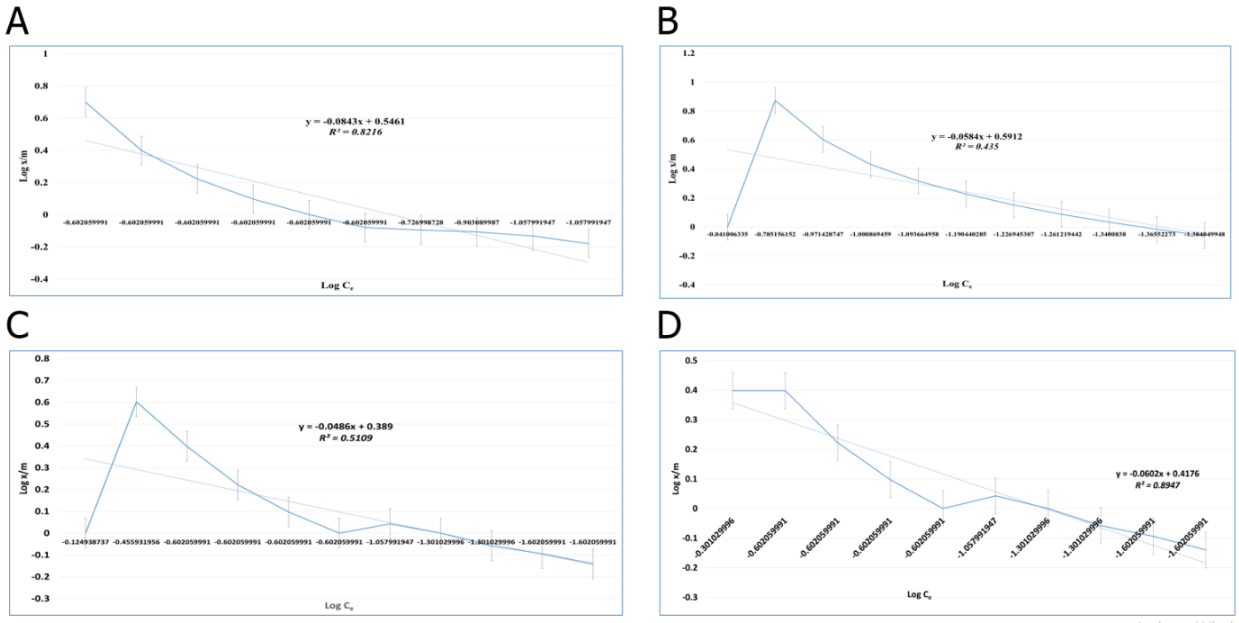

Figure 16. Graphs showing the results of the Freundlich isotherm characteristics investigation for the batch-two experiment. (A) Coconut husk, (B) iron oxide-coated sand, (C) sawdust, and (D) neem wood.

Table 7. Freundlich sorption isotherm parameters for the batch-two experiment

Adsorbent	R^2	$K_{f\,(mg/L)(L/mg)}$	$1/n$
Sawdust-activated char	0.8947	0.3792	0.0602
Neem wood activated char	0.5109	0.4101	0.0486
Coconut husk activated char	0.8216	0.2627	0.0843

Table 8. Langmuir sorption isotherm parameters for the batch-two experiment

Adsorbent	a	b	R^2
Sawdust-activated char	0.056	114.943	0.1203
Coconut husk activated char	0.16	79.366	0.2223
Neem wood activated char	0.0377	217.391	0.0392

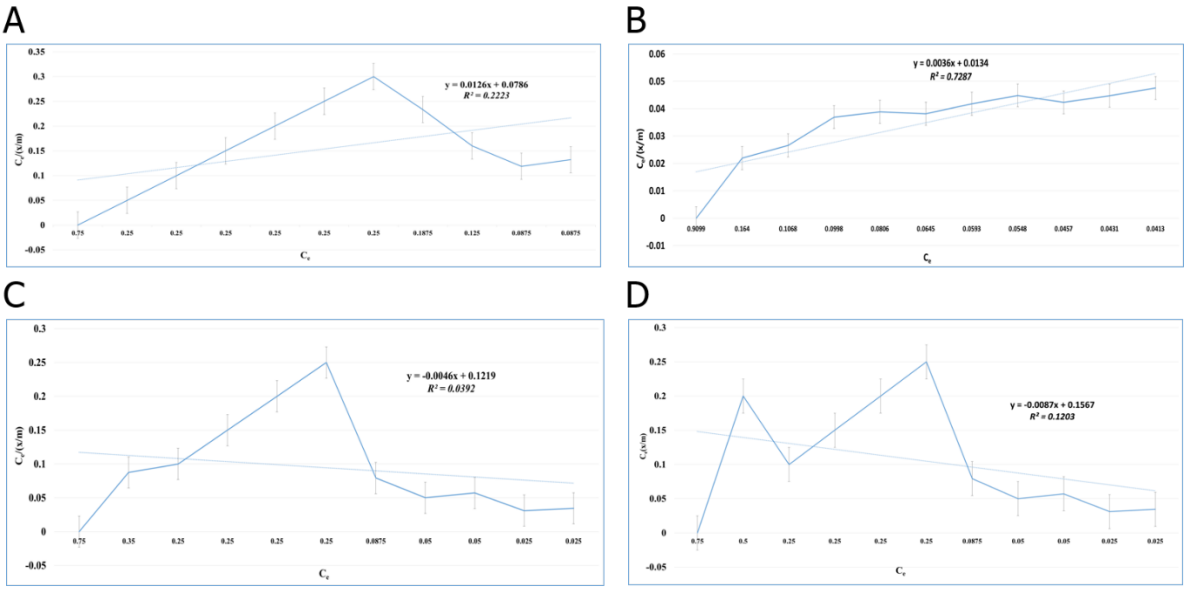

Figure 17. Graphs showing the results of the Langmuir isotherm characteristics. (A) Coconut husk, (B) iron oxide-coated sand, (C) sawdust, and (D) neem wood.

$$-\frac{V}{M}=\left[\frac{\left(\frac{abCe}{1+aCe}\right)}{(Ce-Co)}\right]=\left[\frac{\left(\frac{0.056x114.943x0.1}{1+0.056x0.1}\right)}{(0.1-0.75)}\right]=\left[\frac{\left(\frac{0.644}{1.0056}\right)}{(-0.65)}\right]=\left[-0.9853\frac{L}{g}\right]$$

$$\frac{M}{V}=\frac{1}{0.9853}=1.02g/L$$

Thus, for 24 L of arsenic solution, the column experiment required approximately 24.48 g of sawdust biochar. The amount of each adsorbent used in the column experiment to reduce arsenic levels from 0.75 mg/L to the acceptable value of 0.1 mg/L is shown in Table 9.

4.3.2 Results of the column experiment

The results of the column experiment after using the determined quantities of adsorbent are summarised in Table 10. In all, 25 samples were taken over 48 h for each column experiment.

4.3.3. Analysis of the column experiment results

The percentage removal of arsenic from the 24-L arsenic solution at a concentration of 0.75 mg/L is summarised in Table 11 and illustrated in Figure 18.

4.4. Case study: Adsorbent requirement for an ore processing site

The EPA and the GSA set a limit of 0.1 mg/L for arsenic in industrial wastewater effluents. A mining firm discharges 24 m^3 of effluent containing 0.75 mg/L arsenic into its makeshift tailings pond daily. What quantities of IOCS,

Table 9. Adsorbent requirements to reduce arsenic contaminants to an acceptable level

Adsorbent	a	b	C_o (mg/L)	C_e (mg/L)	Adsorbent amount for each L in grams	Adsorbent amount for 6 L in grams
Sawdust char	0.056	114.943	0.75	0.1	1.02	24.48
Coconut husk char	0.16	79.366	0.75	0.1	0.520	12.48
Neem wood char	0.0377	217.391	0.75	0.1	0.796	19.10
Iron oxide-coated sand	0.267	277.78	0.75	0.1	0.0899	2.16

sawdust biochar, wood AC and coconut husk activated chars will be required to reduce the arsenic concentration to 0.1 mg/L before discharge into the environment, using a free-flow four-stage column with four-layer adsorbents in each column?

Table 10. Results of the column experiment

Serial	Time (t) hrs	Conc (C_e) mg/L
1	0	0.75
2	2	0.75
3	4	0.500
4	6	0.500
5	8	0.500
6	10	0.500
7	12	0.375
8	14	0.375
9	16	0.375
10	18	0.375
11	20	0.250
12	22	0.250
13	24	0.250
14	26	0.250
15	28	0.250
16	30	0.250
17	32	0.250
18	34	0.250
19	36	0.250
20	38	0.250
21	40	0.188
22	42	0.188
23	44	0.125
24	46	0.025
25	48	0

Using the Langmuir isotherm, we substitute the "a" and "b" into **Equation 13**. For the adsorbent quantity for sawdust biochar:

$$-\frac{V}{M}=\left[\frac{\left(\frac{abCe}{1+aCe}\right)}{(Ce-Co)}\right]=\left[\frac{\left(\frac{0.056x114.943x0.1}{1+0.056x0.1}\right)}{(0.1-0.75)}\right]=\left[\frac{\left(\frac{0.644}{1.0056}\right)}{(-0.65)}\right]=\left[-0.9853\frac{L}{g}\right]$$

$$\frac{M}{V}=\frac{1}{0.9853}=1.02g/L$$

The amount of sawdust biochar required to treat 24 m^3/d is : 24 m^3 = 24,000 L = 24,000 × 1.02 = 24,480 g = 24.48 kg.

Thus, approximately 25 kg of sawdust biochar is required daily as an activated-char layer in the treatment pond. The amount of other adsorbents required to reduce arsenic contamination from 0.75 mg/L to 0.1 mg/L for the 24,000-L (24 m^3) mining effluent is summarised in Table 12.

5. Discussion

The estimated Freundlich and Langmuir isotherm coefficients for all seven adsorbents are listed in Table 13. For the Freundlich isotherm, the K_f values for the activated chars were higher than those for the unactivated chars, indicating that the activated adsorbents are more effective than the unactivated ones. The Freundlich intensity parameters were less than one for all the adsorbents, including IOCS. This indicates that both activated and unactivated chars can adsorb a significant amount of arsenic solute at a given concentration. For the Langmuir isotherm coefficients, the maximum amount of arsenic (b) that each of the activated chars can absorb was significantly higher than that of the unactivated chars. IOCS had the highest "b," meaning it could absorb more of the arsenic solute than all the other adsorbents in this study.

Regarding arsenic removal efficiency for each of the four adsorbents, it increased with the amount introduced into the remediation setup. In the study, during batch-one (samples of the unactivated chars and IOCS), IOCS achieved an average removal efficiency of 91.65% compared to 40.20%, 37.40%, and 21.40% for the sawdust, coconut husk, and neem wood chars over 10 days. For the batch-two analysis, the activated chars of neem wood, sawdust, and coconut husk yielded average removal efficiencies of 78.83%, 76.83%, and 73.5%, respectively, over 10 days. Though the efficiencies of the unactivated chars were relatively noticeable, they were significantly lower than those of the activated chars. For the column experiment, the arsenic removal efficiency ranged from 0% to 33% over the first 10 h, then increased to 50% at 18 h from the start of the experiment. The removal efficiency remained at 66.7% for an additional 18 h, then increased to about 75% at 40 h into the experiment. The efficiency gradually attained 100% by 48 h of running the setup. The general observation was that neither IOCS nor the agricultural feedstock adsorbents could achieve 100% efficiency as single-layer adsorbents, even after 240 h. However, the four-layer multi-stage option yielded 100% efficiency only at 48 h.

Table 11. Removal efficiencies in the column experiment

Serial	Time (t) h	Initial conc (C_o) mg/L	Equilibrium concentration (C_e)	x = C_o-C_e (mg/L)	R (%)
1	0	0.750	0.75	0	0
2	2	0.750	0.75	0	0
3	4	0.750	0.50	0.25	33.33
4	6	0.750	0.50	0.25	33.33
5	8	0.750	0.50	0.25	33.33
6	10	0.750	0.50	0.25	33.33
7	12	0.750	0.375	0.375	50.00
8	14	0.750	0.375	0.375	50.00
9	16	0.750	0.375	0.375	50.00
10	18	0.750	0.375	0.375	50.00
11	20	0.750	0.250	0.500	66.67
12	22	0.750	0.250	0.500	66.67
13	24	0.750	0.250	0.500	66.67
14	26	0.750	0.250	0.500	66.67
15	28	0.750	0.250	0.500	66.67
16	30	0.750	0.250	0.500	66.67
17	32	0.750	0.250	0.500	66.67
18	34	0.750	0.250	0.500	66.67
19	36	0.750	0.250	0.500	66.67
20	38	0.750	0.250	0.500	66.67
21	40	0.750	0.188	0.562	74.93
22	42	0.750	0.188	0.562	74.93
23	44	0.750	0.125	0.625	83.33
24	46	0.750	0.025	0.725	96.67
25	48	0.750	0	0	100.00

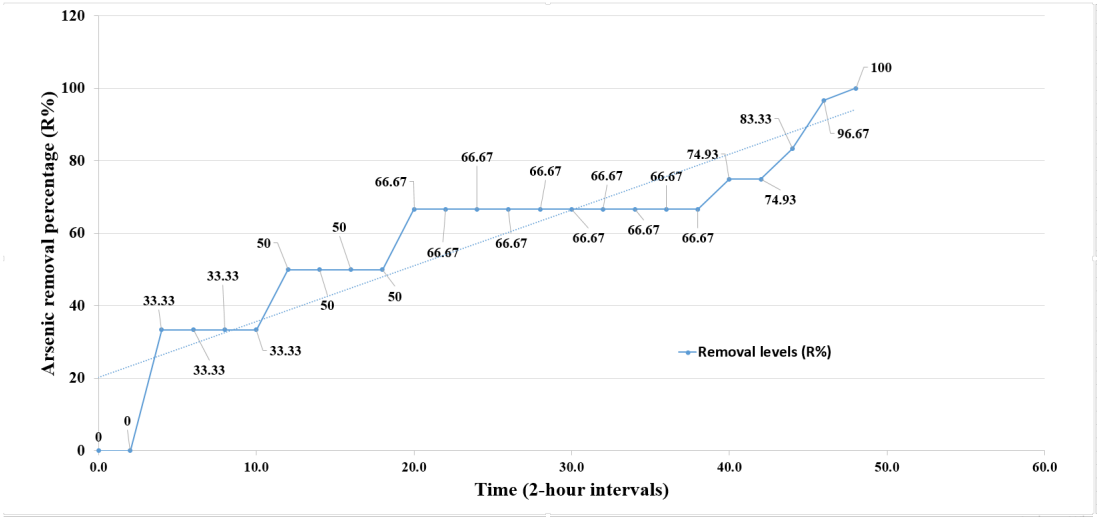

Figure 18. Graphs showing the removal efficiency of the column experiments over 48 h

Table 12. Adsorbent requirement for a case study 24,000-L treatment pond system

Adsorbent	a	b	C_o (mg/L)	C_e (mg/L)	Adsorbent amount per litre in grams	Adsorbent amount for 24 m^3 in kg
Sawdust char	0.056	114.943	0.75	0.1	1.02	24.48
Coconut husk char	0.16	79.366	0.75	0.1	0.520	12.48
Neem wood char	0.0377	217.391	0.75	0.1	0.796	19.10
Iron oxide-coated sand	0.267	277.78	0.75	0.1	0.0899	2.16

Table 13. Estimated Freundlich and Langmuir isotherm constants for the adsorbents

Adsorbent	Freundlich isotherm constants		Langmuir isotherm constants	
	K_f	1/*n*	a	b
Iron oxide-coated sand	0.058	0.228	0.267	277.78
Coconut husk char	0.072	0.578	1.16	8.03
Coconut husk activated char	0.2627	0.0843	0.16	79.366
Neem wood char	1.147	0.011	1.16	3.94
Neem wood activated char	0.4101	0.0486	0.0377	217.391
Sawdust char	0.070	0.546	0.60	11.63
Sawdust activated char	0.3792	0.0602	0.056	114.943

Several adsorbent isotherm studies,[67,68,70] especially those involving the Freundlich and Langmuir models, often end by determining the constants, the intensity parameter (1/*n*), and the binding energy (b), from which only the properties of an absorbent are deduced. The study further used these properties to estimate the required amounts of adsorbent for arsenic removal in the field. Thus, this quasi-field study extends current knowledge by practically applying the adsorbent requirements aspect of the sorption concept to address a growing challenge affecting Ghana's surface water, groundwater, and agricultural soils. Therefore, the study serves as a guide for the Ghana Minerals Commission to improve its three settling/decantation-pond concept. The idea of traditionally generating activated chars and reusing IOCS encourages waste reduction, as materials that would otherwise be waste are put to good use and pollution is mitigated. The concept uses free raw materials to lower the cost of remediating wastewater treatment to meet acceptable effluent standards. It creates jobs by building value chains for the collection and processing of agricultural and industrial waste, and for the distribution and use of the resulting adsorbents. The key limitation of this study is the anticipated increase in spent adsorbents, which could be harmful to the environment in the long term. Further research is needed on existing knowledge of adsorbent regeneration to determine how to effectively recover spent adsorbents. In the interim, stakeholders would have to insist on the use of properly engineered landfills to avoid worsening the already grave environmental menace. Even with engineered landfill use, it is necessary to determine and subsequently monitor initial baseline contaminant levels in soil and groundwater to implement appropriate natural attenuation measures.

6. Conclusion

The traditional charcoal preparation method can be used to produce unactivated and activated char for arsenic removal from mining effluents. Although unactivated char can remove arsenic, its removal efficiency is lower than that of activated char and IOCS. Activated chars and IOCS could be used individually to significantly reduce arsenic contamination levels in mine tailings before release into the environment, particularly for tailings

ponds with large holding capacity, as they would not require a short attenuation period. By contrast, the multi-layer adsorbent arrangement, owing to its high and rapid removal efficiency, could be used in small-scale mining tailings setups that require more frequent discharge due to limited storage capacity. Further column experiments should be conducted using the Freundlich isotherm coefficients to compare removal efficiencies with those predicted by the Langmuir model reported in this study. Generally, exploiting agricultural waste feedstocks to produce activated chars and IOCS for remediating arsenic contamination in mining tailings could provide alternative employment opportunities for several people in the small-scale mining sector. Further studies should focus on the cleaning, treatment, and regeneration (restoration) of spent chars and IOCS to restore their adsorptive capacities for reuse, thereby minimising disposal costs and reducing secondary environmental pollution.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the assessment outlined in this paper.

Author contributions

Conceptualization: Richard Komla Nyamador, Sampson Oduro-Kwarteng, Esi Awuah

Formal analysis: Sampson Oduro-Kwarteng, Esi Awuah, Richard Akwasi Buamah, Patrick Boakye

Investigation: Richard Komla Nyamador, Patrick Boakye, Richard Akwasi Buamah

Methodology: Richard Komla Nyamador, Sampson Oduro-Kwarteng, Esi Awuah

Writing–original draft: Richard Komla Nyamador, Patrick Boakye

Writing–review & editing: Sampson Oduro-Kwarteng, Richard Nyamador, Patrick Boakye

Availability of data

Data are available from the corresponding author upon reasonable request.

Further disclosure

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