Enhanced arsenic removal using lateritic bauxite modified by heating and blending

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ABSTRACT

The use of bauxite to remove arsenic from wastewater has been confirmed to be effective, but its removal efficiency in literature is not up to 90%, hence, the need to devise a more effective method to remove arsenic from wastewater. In this study, a novel material was prepared by thermally modifying and blending yellow and red lateritic bauxite to form thermally modified and blended yellow and red lateritic bauxite (TYB + TRB). The adsorption isotherm, morphology and chemical composition of the novel material were determined by the Langmuir and Freundlich models, Scanning Electron Microscopy (SEM) and X-ray Fluorescence (XRF), respectively. Application of the novel material in arsenic removal resulted in >97% removal efficiency within 60 min. The arsenic adsorption by TYB + TRB conformed to the Freundlich model. The SEM image depicted a compacted earth material after use of the TYB + TRB to remove arsenic from the wastewater. The XRF results also showed a drastic reduction in the chemical composition of the novel bauxite except Ti, thus suggesting the occurrence of multiple mechanisms during the arsenic removal. This study demonstrated the potential of TYB + TRB to be developed and used as the most suitable material for wastewater treatment.

Key words: arsenic, bauxite, removal efficiency, thermally modified and blended yellow and red lateritic bauxite, Wastewater

HIGHLIGHTS

- TYB + TRB was prepared to superimpose the arsenic removal performance of bauxite.
- The removal efficiency of arsenic by TYB + TRB was >97%.
- The mode of adsorption was explained by the Freundlich model.
- The chemical composition of the TYB + TRB reduced drastically after arsenic removal except Ti.
- The novel material is a promising material for highly effective arsenic removal.
INTRODUCTION

Arsenic is among the most toxic substances that pose serious threats to humans when present in drinking water (Izah & Srivastav 2015; Ahmed et al. 2017; Cao et al. 2019; Alarcón et al. 2020). It is considered as a first-class human carcinogen when assimilated, inhaled or ingested into the body (Mandal 2017). The presence of arsenic in the environment has been attributed to both natural and anthropogenic activities, with the latter being the main contributor due to gold mining and metal smelting activities (De Capitani et al. 2014; Liu et al. 2018; Moreira et al. 2021). In most developing countries, gold mining companies are famous for releasing their mine wastewater that contain arsenic into waste dams without pretreatment (Koomson & Asiam 2013). The arsenic eventually gets into the aquatic environment when the mine wastewater in the waste dam seep through ground rocks into groundwater aquifers, and also gets into surface water in conditions where the aquifers and surface water are connected (Abiye & Bhattacharya 2019; Kumar & Singh 2020; Li et al. 2020). This contaminates the aquatic environment and puts all life at risk. It is therefore important to devise an efficient technique to treat mine wastewater containing arsenic prior to its discharge into the environment.

Over the years, various techniques have been adopted to remove arsenic from wastewater. Such techniques include neutralization (Litynska et al. 2017; Leiva et al. 2018; Igarashi et al. 2020), chemical precipitation, adsorption (Mukhopadihyay et al. 2017; He et al. 2019), bioremediation (Yang et al. 2017; Alam & McPhedran 2019; Shabbir et al. 2020), ion exchange (Moreira et al. 2021), electrodialysis (Ortega et al. 2017; Aliaskari & Schafer 2021), reverse osmosis (Corroto et al. 2019) and nanotechnology (Deng et al. 2020; Lv et al. 2020; Ullah et al. 2020). Currently, iron and aluminium based adsorbents such as bauxite are also being employed to remove arsenic from wastewater (Bhakat et al. 2006; Ayoob et al. 2007; Giles et al. 2011; Lockwood et al. 2014; Nicomel et al. 2015; Venkatesan & Narayanan 2017).

Bauxite is a naturally occurring mineral with high aluminium oxide (Al₂O₃), iron oxide (Fe₂O₃) and rutile (TiO₂) contents (Authier-Martin et al. 2001; Cablik 2007). It has been reported to contain radionuclides and heavy metals such as Uranium (²³⁵U), Thorium (²³²Th), Potassium (⁴⁰K), Zirconium (⁷⁸Zr), Antimony (¹²¹Sb/¹²³Sb), Niobium (⁹³Nb), Chromium (Cr), Manganese (Mn), Nickel (Ni), Cobalt (Co), Cadmium (Cd), Zinc (Zn) and Calcium (Ca) (Ozden et al. 2019). The chemical composition of bauxite makes it a relatively good adsorbent for arsenic (Jeong 2005). Large deposits of bauxite can be found in developing countries, and is therefore a cheap alternative for wastewater treatment in such countries.

Previous studies have focused on the use of bauxite to remove arsenic (Debasish et al. 2008; Castaldi et al. 2010; Sahu et al. 2010; Venkatesan & Narayanan 2017; Ndur et al. 2019). For instance, Ndur et al. (2019) examined the use of bauxite as an
arsenic filter. Venkatesan & Narayanan (2017) used synthesized Fe₂O₃ coated and HCl treated bauxite ore waste to remove As(III) from aqueous solution, while Debasish et al. (2008) employed calcined bauxite ore to remove As(V) from aqueous medium on a laboratory scale. The reviewed studies established the relatively high efficiency of bauxite to remove arsenic from a contaminated medium. However, the removal efficiencies recorded in the above studies were <90%, hence, the need to modify the bauxite further in order to achieve >95% removal efficiency. This would significantly help to reduce the rate at which humans and the environment get affected by arsenic contamination.

In this study, heating and blending of two different kinds of lateritic bauxite (red and yellow lateritic bauxite) were employed to modify bauxite. Thermal modification has been reported to increase the surface area of an earth material, change its chemical composition, and improve its adsorption property (Dong et al. 2018; Sikora et al. 2018). Similarly, blending the yellow (YB) and red (RB) lateritic bauxite would result in a change in the chemical composition of the modified bauxite since both different kinds of bauxite have markedly significant levels of chemical composition. Considering its unique structure and potential excellent adsorption properties, the modified bauxite can be used to remove various pollutants from wastewater.

The novel bauxite known as thermally modified and blended yellow and red lateritic bauxite (TYB + TRB) was prepared to superimpose the enhanced effect of thermal modification and blending on arsenic removal. The objectives of this study include to investigate 1) the removal efficiency of TYB + TRB; 2) the adsorption isotherm and mode of reaction underlying the removal of arsenic by TYB + TRB; and 3) the morphological and chemical composition changes that occurred after arsenic removal.

**METHODS**

**Materials and chemicals**

The yellow and red lateritic bauxites were obtained from Awaso, Ghana. The mine wastewater which purposely contained arsenic (>5,000 ppb of arsenic) was also obtained from a reputable mining company in Ghana. Sodium borohydride (NaBH₄), sodium hydroxide (NaOH) and hydrochloric acid (HCl) were purchased from Wego Chemical Group, USA. The chemicals used in this study were of analytical grade and used as received.

**Material preparation**

**Preparation of yellow (YB) and red (RB) lateritic bauxite**

2 kg of each of the yellow and red lateritic bauxites was measured with an analytical balance and homogenized with the Jones Riffle Splitter. Both fine and coarse particles of the YB and RB were obtained after sieving the homogenized sample with an 850 μm sieve. The as-obtained fine and coarse particles were placed in an aluminium foil and kept in a desiccator.

**Thermally modified yellow (TYB) and red (TRB) lateritic bauxite**

The TYB and TRB were prepared the same way as YB and RB, but were subjected to 400 °C heat afterwards for 3 h in a high temperature furnace. The samples were allowed to cool at room temperature before sieving with an 850 μm sieve to obtain both fine and coarse particles which were later placed in an aluminium foil and kept in a desiccator.

**Thermally modified and blended yellow and red lateritic bauxite (TYB + TRB)**

The TYB + TRB was prepared by blending/mixing the TYB and TRB together in a 9:1 ratio because of its relatively high removal performance (within 20 min) after a series of preliminary tests with ratios of 1:9, 1:1 and 9:1 (Figure S1). The resulting mixture was also placed in an aluminium foil and kept in a desiccator.

**Batch experiments**

To investigate the removal efficiency of arsenic by the prepared materials, YB, RB, TYB, TRB and TYB + TRB (dosage = 30 g/L) were added to 1 L mine wastewater with initial concentration and initial pH of 4 ppm and 6.0 ± 0.1 (adjusted by 0.1 M HCl and NaOH before performance of the batch experiments), respectively. The bottle rolling machine (53 rev/min) was used to perform the batch experiments. Reasonable volume of samples was taken at predetermined time intervals (5, 10, 20, 30, 40 and 60 min), and filtered through a 0.45 μm nitrocellulose membrane filter for arsenic level determination. The batch experiments were performed in duplicate and the mean values were used for the analyses (Cheng et al. 2021).

The influence of temperature on the adsorption effect of arsenic was investigated by subjecting the TYB + TRB to temperatures of 25 and 800 °C. Comparison was done with the previous experiment under 400 °C. The influence of pH on the arsenic removal was performed by adding 30 g/L of the TYB + TRB to 1 L arsenic solution (4 ppm) for 1 h, under varying pH from 3
to 10 (Wu et al. 2018). The influence of concentration on the adsorption effect was also determined under similar operational conditions with concentrations ranging from 4 to 8 ppm.

The mode of reaction and adsorption were investigated by the adsorption isotherm models (Langmuir and Freundlich models). This was obtained by adding 30 g/L of the TYB + TRB to the mine wastewater with different concentrations (4 ppm, 5 ppm, 6, 7 and 8 ppm). Samples for analyses were taken at predetermined time intervals over a period of 12 h in order to avoid bias in results (Bhowmick et al. 2014). The morphological and chemical composition changes of the TYB + TRB were investigated after arsenic removal, and compared with bauxite before reaction.

Recovery of the TYB + TRB after arsenic adsorption can be done. First, the spent TYB + TRB in solution can be separated through gravitational settling and washed with distilled water. The collected and washed TYB + TRB could be subjected to leaching (addition of H2SO4, HCl or HNO3)/ion exchange in order to extract the adsorbed arsenic before washing again and reusing (Lockwood et al. 2014; Gomes et al. 2016; Ujaczki et al. 2018; Khairul et al. 2019). The stepwise procedure for arsenic extraction from the bauxite residue can be found in Lockwood et al. (2014).

### Analytical methods

The concentrations (Co and Ct, mg/L) of arsenic in solution were analyzed with Flame Atomic Absorption Spectrophotometer (SHIMADZU AA7000 Series, Japan) coupled with a hydride generator (Wang et al. 2014). NaBH4 was used in conjunction with the HCl to form the hydride of arsenic before analyzing with the Flame AAS. The removal efficiencies of arsenic by the different materials were determined with Equation (1). Specifically, the concentrations of the samples collected at predetermined time intervals were put into Equation (1), and the adsorption capacity at time t (Qt, mg/g) was calculated using Equation (2).

\[
\text{Removal efficiency (\%) } = \frac{C_o - C_t}{C_o} \times 100
\]

\[
Q_t = \frac{(C_o - C_t) \times V}{W}
\]

where \(V\) = volume (L) of the solution, \(W\) = mass of the adsorbent (g), \(C_o\) = initial concentration of arsenic, and \(C_t\) = concentration of arsenic at predetermined time intervals.

### Material characterizations

Scanning electron microscopy (SEM) (CARL ZEISS EVO MA15, Germany) was used to analyze the morphological characteristics of the TYB + TRB after use in arsenic removal. The SEM analyses were supported with Energy-dispersive X-ray spectroscopy (EDX). The chemical composition of the TYB + TRB was also analyzed with X-ray fluorescence (XRF) (XMET7000, England). This was done to determine the composition of the elements left in the TYB + TRB material after arsenic removal. The particle size distribution of the YB, RB and TYB + TRB was determined with Malvern Mastersizer 3000.

### RESULTS AND DISCUSSION

**Arsenic removal by TYB + TRB**

The removal efficiencies of arsenic by YB, RB, TYB, TRB and TYB + TRB are presented in Figure 1. The RB demonstrated the least removal efficiency of arsenic within 60 min (71.1%). It was also observed that, the removal efficiency of arsenic by YB (78.3%) and TRB (77.3%) were almost similar during the first 20 min of reaction, but the former increased to 93.9% at the end of the reaction time whereas the latter attained a removal efficiency of 87.4% at 60 min. The TYB also demonstrated a relatively high removal efficiency at 5 min (77.8%) and increased steadily to 96.9% within 60 min. The TYB + TRB proved to be better suited for arsenic removal since the material achieved 93.9% removal efficiency within 5 min of reaction and increased till the 60 min reaction time (97.2%). The high removal efficiency of the TYB + TRB can be attributed to the influence of heat and blending of the bauxites in a ratio of 9:1.

The thermal modification of the bauxite could have resulted in better crystallinity and distribution of the particles (Kim et al. 2021). For instance, the Al-oxides could have been transformed into boehmite and gibbsite due to the thermal modification (Kloprogge et al. 2002). The formed boehmite and gibbsite could have increased the removal efficiency of arsenic due to their increased content which could have been realized through heating (Kloprogge et al. 2002). This phenomenon has been proven by current researchers such as Lavecchia et al. (2012) and Dubey et al. (2017) who removed arsenic and fluoride with boehmite and gibbsite particles, respectively. The Fe-oxide content of the bauxite could have also been transformed into
high crystalline particles to facilitate increment in the arsenic removal efficiency. Moreover, blending the heated bauxites presented more adsorption sites for arsenic, thus, contributing to the high removal efficiency.

**Influence of operating parameters on arsenic adsorption**

**Solution pH**

*Figure 2* shows the influence of the solution pH on the adsorption of arsenic by the TYB + TRB over a 1 h reaction time. Even though the removal efficiency of the arsenic by the TYB + TRB was more than 90% (within 1 h) in the pH range investigated, it is plausible that, the highest removal efficiency of arsenic occurred at pH 4 (99.2%). A gradual decline in the removal efficiency was observed from pH 5 to 10. Additionally, the arsenic removal efficiency by TYB + TRB declined in strong acidic condition (pH = 3) thereby suggesting that, strong acidic (pH = 3) and alkaline (pH = 5–10) conditions negatively influence the removal efficiency of arsenic by the TYB + TRB (Ndur *et al.* 2019).

**Concentration**

The influence of initial concentration of arsenic on the removal efficiency by TYB + TRB is shown in *Figure 3*. It is obvious that the removal efficiency of arsenic decreased when the initial concentration increased. The decrease in removal efficiency could be due to the fact that, the adsorption capacity of arsenic on the bauxite surface was reached (that is, the adsorption sites on the bauxite surface became saturated) when the initial concentration increased. Therefore, limited adsorption sites for...
the arsenic were available on the TYB + TRB, thus resulting in inefficient removal of the arsenic under high concentrations (Can et al. 2014; Lyu et al. 2019; Zhang et al. 2020).

Temperature
Temperature is an important variable in adsorption reactions (Horsfall & Spiff 2005). Its increase or decrease could have a significant impact on the adsorption process. Figure 4 shows the extent to which temperature can influence the adsorption effect of arsenic by the bauxite. TYB + TRB subjected to very low temperature (25 °C) did not achieve high arsenic removal efficiency (75.8%) within 60 min. It is also evident that, an increase in temperature to 800 °C resulted in reduced arsenic adsorption (90.7%) within 60 min. The decreased arsenic adsorption at 800 °C suggests a weak interaction between the arsenic and bauxite surface (Horsfall & Spiff 2005). Considering the result exhibited in Figure 4, it can be inferred that arsenic is best removed by TYB + TRB subjected to 400 °C.

Thermodynamics of adsorption
Thermodynamic parameters like enthalpy (ΔH), entropy (ΔS) and Gibbs free energy (ΔG) were calculated with the aid of Equations (3)–(5).

\[
\ln \left( \frac{1}{b} \right) = \frac{\Delta G}{RT}
\]

Figure 4 | Influence of temperature on adsorption effect (Operational conditions: arsenic concentration = 4 ppm, dosage = 30 g/L, initial pH = 6.0 ± 0.1, time = 1 h).
\[ \ln(b) = b_0 - \left(\frac{\Delta H}{RT}\right) \]  
(4)

\[ \Delta G = \Delta H - T\Delta S \]  
(5)

The \( R \) represents gas constant; \( b \) represents the Langmuir’s constant which is related to adsorption of energy; \( b_0 \) is a constant; and \( T \) represents absolute temperature (Parga et al. 2009).

The thermodynamic parameters are presented in Table 1. The \( \Delta G \) value was negative at 298 K, thus, showing the spontaneous process of arsenic adsorption by the modified bauxite at such absolute temperature. The process of arsenic adsorption was endothermic due to the positive \( \Delta H \) value obtained. The \( \Delta S \) value was positive, thus denoting significance in the change in internal structure of the modified bauxite during arsenic adsorption under standard temperature (Goldberg & Johnston 2001; Deng & Bai 2004; Parga et al. 2009).

**Adsorption isotherms of arsenic removal by TYB + TRB**

The Langmuir and Freundlich isotherm models as expressed in Equations (6) and (7), were used to determine the kind of adsorption that occurred during arsenic removal by the TYB + TRB. The amount of arsenic adsorbed at equilibrium (\( Q_e \)) and its concentration at equilibrium (\( C_e \)) were subjected to non-linear curve fitting through the power user-defined function in Origin 2015 until the total number of iterations was reached and perfectly fitted.

\[ Q_e = \frac{K_LQ_{max}C_e}{1 + K_LC_e} \]  
(6)

\[ Q_e = K_FC_e^{1/n} \]  
(7)

where \( C_e \) = equilibrium concentration (mg/L), \( Q_e \) and \( Q_{max} \) = amounts adsorbed at equilibrium and theoretical maximum capacity (mg/g) respectively, and \( K_L \) (L/mg) and \( K_F \) (mg\(^{1-n}/\)L\(^n/g\)) = constants related to affinity and adsorption capacities of Langmuir and Freundlich models, accordingly.

\[ \chi^2 = \sum \frac{(O_i - E_i)^2}{E_i} \]  
(8)

where \( E_i \) = expected value/model calculated data and \( O_i \) = actual value/experimental data.

\[ t = \frac{\bar{x} - \mu}{s/\sqrt{n}} \]  
(9)

where \( \bar{x} \) = sample mean, \( \mu \) = population mean, \( s \) = standard deviation and \( n \) = degrees of freedom.

The chi square (\( \chi^2 \)) in Equation (8) is a statistical technique used to determine the goodness of fit of a model, hence, its adoption in this study to establish the goodness of fit of the Langmuir and Freundlich models. The \( t \) test in Equation (9) is best used in determining the magnitude and significance of a model. It was therefore employed to clearly establish the magnitude of the appropriate model (Kaushal & Singh 2017).

The associated parameters of the two isotherm models are shown in Table 2. The parameters \( \chi^2 \) (Equation (8)) and \( t \) (Equation (9)) represent the chi-square value and \( t \)-value (degree of magnitude) respectively. In Figure 5, it is evident that the adsorption of arsenic by the TYB + TRB fits the Freundlich model more than the Langmuir model. This suggests that the arsenic adsorption sites were not uniformly distributed on the bauxite surface thereby indicating a heterogenous coverage.

**Table 1** | Thermodynamic parameters for arsenic adsorption by TYB + TRB

| \( \Delta H \) (kJ/mol) | \( \Delta G \) (kJ/mol) | \( \Delta S \) (kJ/mol·K) | \( T \) (K) |
|-------------------------|------------------------|-------------------------|-----------|
| 4,724.10                | -8,193.957            | 43.45                   | 298       |
with possible interaction between the adsorbing molecules (Yadav et al. 2016; Dubey et al. 2017). This could be due to the blending of the different kinds of lateritic bauxite.

As evident in Table 2, the $R^2$ value of the Freundlich model ($R^2 = 0.9712$) was higher than that of the Langmuir model ($R^2 = 0.6337$). The Chi squared value of the Freundlich model ($\chi^2 = 7.33$) was lower than that of the Langmuir model ($\chi^2 = 93.38$). Also, the $t$ value ($t = 30.10$) of the Freundlich model was higher than that of the Langmuir model ($t = 25.17$), thus suggesting a greater magnitude and evidence of the Freundlich model as the best fit for arsenic adsorption by the TYB + TRB. Comparing the adsorption capacity of the TYB + TRB to other adsorbents such as bare nanoscale zero valent iron (Giasuddin et al. 2007), nanoscale zero valent iron-reduced graphite oxide modified composites (nZVI-RGO) (Wang et al. 2014) and activated carbon supported nZVI (nZVI/AC) (Zhu et al. 2009) in terms of the Langmuir model, it is evident that the TYB + TRB employed in this study, adsorbed arsenic better (Table 3).

### Characterization of TYB + TRB

#### SEM analyses

The SEM images in Figure 6 depict the surface morphology of bauxite before reaction and TYB + TRB after reaction with arsenic. The morphology of the pristine bauxite is characterized by a cluster of earth particles that are loosely attached (Figure 6(a)) (Reid et al. 2017). The earth particles in the TYB + TRB appear compacted and hardened after arsenic removal.

### Table 2 | Parameters of the adsorption models for arsenic adsorption on TYB + TRB at pH 6.0 (±0.1) and 25 ± 1 °C

| Model     | $Q_{max}$ (mg/g) | $K_L$ (L·mg⁻¹) | $R^2$  | $\chi^2$ | $t$-value | $p$ value |
|-----------|------------------|----------------|--------|----------|-----------|-----------|
| Langmuir  | 57.77            | 27.31          | 0.6337 | 95.38    | 25.17     | 0.00518   |
| Freundlich| 43.66            | 0.9712         | 7.33   | 30.10    | 0.00007   |

### Table 3 | Arsenic adsorption capacities of other iron-based materials

| Material                                      | pH  | Isotherm model | $Q_{max}$ (mg/g) | References          |
|-----------------------------------------------|-----|----------------|------------------|---------------------|
| Bare nZVI                                     | 7.0 | Langmuir       | 55.0             | Giasuddin et al. (2007) |
| nZVI-reduced graphite oxide modified composites (nZVI-RGO) | 7.0 | Langmuir       | 35.8             | Wang et al. (2014)   |
| activated carbon supported nZVI (nZVI/AC)     | 6.5 | Langmuir       | 18.2             | Zhu et al. (2009)    |
The compaction can either be attributed to the formation of an amalgam by the elements present or the changes in chemical/elemental composition that occurred during blending and arsenic removal (Figure S2) (Gore et al. 2016). The average particle size distribution of the TYB + TRB was 689 μm (Figure S5) while that of the YB and RB were 564 μm (Figure S3) and 189 μm (Figure S4) respectively. Significant increase in the particle size distribution of the TYB + TRB was due to the application of heat and blending of YB and RB.

The EDX spectrum of TYB + TRB shows peaks for Al, Fe, Ti, Fe, C and O. It is observed that the Al content was dominant in the TYB + TRB after its application in arsenic removal. The Fe, O, Ti and C contents were relatively low (Figure S2).

**XRF analyses**

XRF characterization aided in the investigation of the chemical/elemental composition of the bauxite before and after arsenic removal. The investigation was carried out between YB and RB before use in arsenic removal, and TYB + TRB after use in arsenic removal (Figure 7). A clear-cut distinction between the radionuclides and heavy metals present in the pristine and reacted bauxites are also presented in Figures S6 and S7. Majority of the radionuclides’ composition in the pristine YB and RB, and reacted TYB + TRB were either negligible or entirely absent. However, those that showed some desirable

**Figure 6** | SEM images of pristine raw bauxite (a) (Reid et al. 2017) and TYB + TRB (b).

**Figure 7** | XRF characterization results for YB and RB before arsenic removal, and TYB + TRB after arsenic removal.
composition were reported in Figure S6. It is evident that the Ti and Zr contents in the modified bauxite after arsenic removal were higher than those in the pristine RB and YB. The high content of Ti and Zr in the TYB + TRB suggests an increase in their concentration following arsenic removal (Moipone et al. 2021).

It is evident in Figure 7 that the Fe (37%), Ca (10.9%) and Cr (4.9%) contents in the pristine YB were higher than those in the pristine RB and reacted TYB + TRB. It is also observed that the Al contents of the pristine YB (63%) and RB (80%) were higher than the Al content in the reacted TYB + TRB (11.5%). Similar decrease in the contents of the other elements was observed with the reacted TYB + TRB, with the exception of Ti. The increase in Ti may also be due to its non-dissolution in the solution since the operational pH of the study was near alkalinity (Deng et al. 2017). From the results obtained, it can be suggested that the Fe, Al, Ca, Cr, Ni, Mn, Cu and Zn in the TYB + TRB helped to remove the arsenic through adsorption, complexation, precipitation or cation exchange, due to their reduced contents (Figure S5). Similarly, the present elements could have been transformed into their hydr(oxide) forms during the reaction with arsenic, water and dissolved oxygen in the water (Lin & Puls 2000; Youngran et al. 2007; Adegoke et al. 2013), thus resulting in the reduction of their contents (Figure S5). Nonetheless, the Al content in the reacted TYB + TRB was higher than the contents of the other elements. Therefore, the XRF findings are consistent with the findings in the EDX.

The Fe content of the bauxite may facilitate arsenic removal through complexation and precipitation after undergoing corrosion upon reaction (Hashim et al. 2011; Saha & Sarkar 2012; Bjorn & Roychoudhury 2015; Cheng et al. 2021). Interaction of Fe with water can result in the formation of Fe hydr(oxides) (Aeppli et al. 2019; Anang et al. 2021). The formed Fe hydr(oxides) can be complexed with H2O as proposed in the Stumm model (Stumm 1992) in order to undergo hydroxylation to form = FeOH (Cheng et al. 2021). Arsenic has been reported to form surface complexes with = FeOH (Manning et al. 2002; Kanel et al. 2005; Bhowmick et al. 2014). This therefore confirms the usage of the surface complexation technique as part of the means by which arsenic was removed by the Fe content in the modified bauxite. Considering that the arsenic solution pH was 6.0 ± 0.1, the arsenic could be precipitated with Fe(III) to form FeAsO4·2H2O (Robins et al. 2001; Han et al. 2011). Ion exchange between arsenic and the heavy metals supposedly occurred because of the high reduction/absence of the heavy metal contents in TYB + TRB after arsenic removal (Figure. 7 and Figure S7) (Chaviola et al. 2015).

CONCLUSION

This study investigated the removal of arsenic by novel modified bauxite (TYB + TRB). The results obtained showed that, the prepared novel material removed >97% of arsenic from mine wastewater as compared to the YB, RB, TYB and TRB. Highest removal efficiency of the arsenic was achieved at pH 4 and 400 °C, whereas a decline in the removal efficiency occurred in strong acidic and alkaline conditions as well as in very high and low temperatures. The thermodynamics of the adsorption proved that, the adsorption process was endothermic and spontaneous. Moreover, the adsorption isotherm of arsenic removal by the TYB + TRB was identified to be Freundlich model exclusively, hence, the arsenic adsorption occurred on a heterogenous surface. This was attributed to the blending of the different kinds of bauxite. Furthermore, the results proved that, thermal modification and blending significantly altered the surface morphology of the novel bauxite and increased its particle size distribution. Also, the chemical composition of the novel bauxite reduced drastically after reaction with arsenic (except Ti), thereby showing that the chemicals/elements in the bauxite were significantly affected by the arsenic removal process. The high Ti composition was attributed to an increase in its concentration after arsenic removal. The preparation of the novel material is critical in iron and aluminium based technology. Additionally, its removal efficiency, adsorption, morphological and chemical/elemental composition changes investigated in this study are important in the pretreatment of arsenic-containing wastewater before discharge into the environment.

DECLARATION OF COMPETING INTEREST

The authors declare no competing financial interests.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.
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