Adsorption of fluoride from aqueous solution using low cost adsorbent
R. Buamah, R. Asare Mensah and A. Salifu

ABSTRACT

High fluoride levels beyond the recommended value of 1.5 mg/L have been detected in several groundwater wells in Northern Ghana. This occurrence has led to the capping of many high yielding wells that hitherto have been major sources of drinking water for the populace in these arid areas. Most of the fluoride removal technologies applied in the area has not been versatile in effectively removing fluoride because of the varying water qualities. This study focused on screening adsorbents including high aluminium or iron containing bauxite ores, fabricated zeolite and activated Neem seeds for removal of fluoride from drinking water. The model water used was prepared by simulating the prevailing groundwater quality in Northern Ghana. The high aluminium bauxite ore (HABO) had the highest fluoride removal capacity. Within the pH range tested (5–7), the fluoride removal decreased with increasing pH. Occurrence of sulfate, chloride and nitrate in the model water reduced the fluoride removal capacity by 57, 24 and 38% respectively. The combined effect of these anions showed a 60% reduction in the fluoride removal capacity. The Freundlich and Langmuir isotherms gave an adsorption capacity \( K \) of 0.90 mg/g for the HABO. The adsorption kinetics fitted well the pseudo second-order kinetic model. The HABO is thermally stable and has kaolinite \( [Al_2Si_2O_5(OH)_5] \) and gibbsite \( [Al(OH)_3] \) as its major components. X-ray fluorescence (XRF) and energy dispersive X-ray (EDX) results showed Al, Fe, Ti, O, C and Si as the predominant elements in the HABO.

Key words | adsorption, bauxite ore, EDX, fluoride, Northern Ghana, XRD

INTRODUCTION

Generally, groundwater has a relatively better quality due to the barrier effects provided by the overlying soil and its unsaturated zone which serve as a filter. As a result, groundwater generally has low levels of suspended particles and microbial contamination except in cases where a contaminating point source such as a landfill site is in close proximity to the groundwater source. With some groundwaters, concentrations of inorganic contaminants such as Fe\(^{2+}\), Mn\(^{2+}\), Mg\(^{2+}\), F\(^-\), As, Cl\(^-\) and Ca\(^{2+}\) may be high and as such may pose serious health risk to consumers. It is against this background that the World Health Organisation (WHO) has set health based guideline values for the occurrence of these contaminants in drinking water to safeguard consumers. Regarding the level of fluoride in drinking water, the WHO recommended guideline value is 1.5 mg/L (WHO 2008).

Fluorine, the first member of the halogens and the most electronegative element, has the highest electron affinity (Hem 1985). As a result, elemental fluorine does not exist in nature but occurs as fluoride mineral complexes. The concentrations of fluoride in the environment are highly variable and often depend on the geology of an area, the quality of the water and/or ambient air. For example, in Ghana, the occurrence of dental fluorosis in Bolgatanga, Sekoti and Bongo (all communities in Northern Ghana) have been associated with granitic rocks in the area (Smedley et al. 1995). In India and Sri Lanka, fluorosis has been linked with fluoride-rich alkaline groundwaters.
(Dissanayake 1991). In China, the inhalation of fluoride from coal smoke and the use of high fluoride contaminated groundwaters have been cited as the causes of fluoride related problems in consumers (Zheng et al. 1999).

As an essential micronutrient, fluoride is useful for the calcification of dental enamel and the formation of bones. Concentrations of fluoride between 0.5 and 1.5 mg/L are good for bone development and prevention of dental caries. Mottling of teeth (dental fluorosis) is likely to occur with fluoride concentration above 1.5 mg/L and concentrations between 3 and 6 mg/L cause skeletal fluorosis. Prolonged consumption of water with levels of fluoride above 10 mg/L may give rise to crippling fluorosis (WHO 2008). Apambire et al. (1997) undertaking research to investigate the causes of stained teeth in schoolchildren in the Bongo district of Ghana found the high levels of fluoride (≥4 mg/L) in the groundwater used as drinking water to be a major contributory factor. The research revealed that 62% of the entire population of schoolchildren in the district had dental fluorosis. In tropical conditions, with high ambient temperatures, a consumer of fluoride contaminated groundwater becomes more susceptible to fluoride poisoning as his/her daily water intake increases (Apambire et al. 1997). The regular consumption of water with fluoride concentrations exceeding WHO guidelines may not only cause dental and skeletal fluorosis, but may also lead to mutations in the consumer’s deoxyribonucleic acid (DNA) (Tsutsui et al. 1984).

Numerous defluoridation technologies have been established but only a few have shown to be promising for field application. A good defluoridation technology should be versatile, simple for field application and preferably use locally available and cheap material with a high potential for fluoride removal. Adsorption processes are the most widely applied fluoride removal methods due to their relative ease of operation. Adsorption is a mass transfer process in which a constituent in the liquid/gas phase is accumulated on a solid/liquid phase and separated from its original environment. The adsorption is a consequence of binding forces between the individual atoms, ions or molecules of the adsorbate and the adsorbent surface. The interaction between the adsorbate and adsorbent involves molecular forces embracing permanent dipole, induced dipole and quadruple electrostatic effects. These molecular forces may be classified into short range and long range forces. The short range forces normally give rise to either covalent or hydrophobic bonds or hydrogen bonding or steric effect whiles the long range forces normally involve electrostatic interactions (Yang 1999).

With respect to de-fluoridation, there is found no fluoride removal technique that is versatile enough to remove fluoride under various environmental and geological conditions (Fawell et al. 2006; Feenstra et al. 2007). Adsorbents such as bone char (Bregnhøg 1995), activated charcoal, activated alumina, bauxite (Dysart 2008; Sajidu et al. 2008), chitosan and coated silica (Krishnaiah & Vijaya 2009) have been used in various ways for the removal of fluoride from drinking water.

The goal of this study was to screen several locally available adsorbents for media with the highest defluoridation capacity. The specific objectives were: (i) to determine the fluoride removal capacity of various adsorbents (i.e. high aluminium content bauxite ore, high iron content bauxite ore, pulverised activated Neem seeds and a fabricated zeolite), (ii) to characterise the adsorbent with highest fluoride removal potential, (iii) to investigate the effect of pH and co-existing anions on the fluoride removal potential of the best performing adsorbent, and (iv) to fit the adsorption data to the Freundlich and Langmuir isotherms, pseudo first-order and second-order kinetics models.

Derived empirically, the Freundlich isotherm (Equation (1)) is mainly used to describe the adsorption characteristics for heterogeneous surfaces (Krishnaiah & Vijaya 2009). Expressed mathematically,

\[ q_e = K C_e^n \]

where \( q_e \) is the amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (mg/g), \( C_e \) is the equilibrium concentration of adsorbate in bulk solution (mg/L), \( K \) is the adsorption capacity (mg/g) and \( n \) is a measure of the adsorption intensity.

The Langmuir isotherm (Equation (2)) assumes that adsorption cannot proceed beyond the monolayer and the ability of a molecule to be adsorbed at a given site is independent of the occupation of neighbouring sites (Zawani
Expressed mathematically,

\[ q_e = \frac{q_m K_a C_e}{1 + K_a C_e} \]  

(2)

where \( q_e \) is the amount of adsorbate adsorbed per unit mass of adsorbent at equilibrium (mg/g), \( C_e \) is the equilibrium concentration of adsorbate in bulk solution (mg/L), \( K_a \) is the adsorption equilibrium constant (L/mg) and \( q_m \) is the adsorption capacity for a complete monolayer (mg/g).

### MATERIALS AND METHODS

#### Preparation of adsorbents

Adsorbents used in this study are high aluminium content bauxite ore (HABO), high iron content bauxite ore (HFBO), pulverised activated Neem seeds and a locally fabricated zeolite. The HABO and HFBO were acquired from Awaso in the Western region of Ghana. The ores were washed and crushed. The Neem seeds were washed, dried, calcined at 600°C and crushed. The crushed bauxite ores and Neem seeds were then sieved to particle size of 75 μm and used for the experiments.

The zeolite used in this study was synthesised in the Environmental Quality laboratory of the Civil Engineering Department of the Kwame Nkrumah University of Science and Technology in Ghana according to the standard method used by Kühl (1987). The source materials of sodium hydroxide, potassium hydroxide, sodium aluminate, sodium silicate and distilled water were mixed in a continuous batch mode. The resultant solution was heated for 3 h at 70°C. Afterwards the temperature was raised to 100°C and maintained for 2 h. The solution was then cooled to room temperature, filtered and the residue dried and stored in a plastic container. All chemicals used in the study were of analytical grade.

#### Screening of adsorbents and batch fluoride adsorption experiments

The groundwater quality in Northern Ghana (Table 1) was adopted as the matrix for the study because of the high prevalence of dental fluorosis in the area and the occurrence of high fluoride concentrations in the groundwater of the area. The high fluoride concentration in the groundwater has led to the capping of several hitherto functional boreholes.

A stock fluoride solution of 1,000 mg/L was prepared and used to prepare standard fluoride solutions within the range of 2–10 mg/L. These standard fluoride solutions were used to prepare standard curves for fluoride determination using WTW F 800 fluoride ion selective electrode (ISE).

From the literature, fluoride removal has been reported to be effective within a pH range of 3–6 (Tang et al. 2009). The pH of the groundwater in Northern Ghana ranges between 6.9 and 7.5. In screening of the various adsorbents (HABO, HFBO, pulverised activated Neem seeds and synthesised zeolite) to determine the one with the highest fluoride removal capacity, batch adsorption experiments were performed using the Jar test apparatus at pH 6. In each of the batch experiments, five 1,000 mL beakers were filled with 1 L fluoride solutions with concentrations ranging from 2 to 10 mg fluoride/L. Each of the solutions was dosed with 150 mg NaHCO₃/L to serve as a buffer for the adsorption process and to mimic the alkalinity of the groundwater in Northern Ghana (Table 1).

A sixth beaker, serving as a blank test was prepared and run under similar conditions in the Jar test equipment but without any adsorbent. The various experimental reactions were initiated by adding 2 g of the adsorbent to 1 L of the fluoride solutions and stirred continuously at 80 revolutions per minute (rpm). The solution in each beaker was sampled at pre-determined time intervals and immediately filtered using a 25 μm cellulose acetate filter. Each filtered sample was mixed with a Total Ionic Strength Adjustment Buffer
The concentration of fluoride in the sampled solutions was measured with a WTW F 800 fluoride ISE. The percentage removal of fluoride from the aqueous phase and the amount of fluoride adsorbed per unit mass of adsorbent were then calculated. The experiment was conducted for all the adsorbents.

Effect of pH on the fluoride adsorption

To determine the influence of pH on the fluoride removal process at room temperature (27 °C), several sets of batch experiments were conducted for pH values ranging from pH 5–7 using the adsorbent with the highest fluoride removal capacity. The tests were performed with model water dosed with sulfate (SO\textsubscript{4}\textsuperscript{2–}), chloride (Cl\textsuperscript{–}), nitrate (NO\textsubscript{3}\textsuperscript{–}) and bicarbonate (HCO\textsubscript{3}–) to simulate the water quality conditions prevailing in fluoride contaminated wells in Northern Ghana (Table 1). All solutions including the blanks were adjusted to the required pH using 0.1 mol/L NaOH and 0.1 mol/L or 10% HCl. The fluoride removal tests were conducted using the protocol described above with an initial fluoride concentration of 2.5 mg/L. The pH of the solutions in the various beakers were monitored continuously throughout the test period and prevented from drifting by spiking with a few drops of either 0.01 mol/L NaOH or 0.01 mol/L HCl. The equilibrium pHs were therefore kept at pHs 5.00 ± 0.05, 6.00 ± 0.05 and 7.00 ± 0.05.

Effect of co-existing anions

The effects of co-existing anions (i.e. chloride, sulfate and nitrate) and contact time on the fluoride removal capacity of the selected adsorbent were investigated using the protocol mentioned above with little modification. In investigating the effect of a particular anion, known amounts of the anion-containing salt were dosed into the beakers containing the fluoride solutions with the adsorbents. The individual anion effect as well as the combined anion effect on the fluoride removal process was monitored.

Characterisation of the HABO adsorbent

Samples of the HABO were sent to the laboratories of the School of Applied Sciences, University of Wolverhampton, UK, for characterisation. The thermal stability of the adsorbent was analysed using the Perkin Elmer Thermogravimetric Analyser. The mineralogy and crystallinity of the HABO were characterised by X-ray diffraction (XRD). The diffraction patterns were recorded on a Philips PW 1710 X-ray powder diffractometer over a 2θ range of 3° to 50°. The elemental composition of the adsorbent was determined using X-ray fluorescence (XRF) and energy dispersive X-ray (EDX) spectrometry analysis.

RESULTS AND DISCUSSION

Screening of adsorbents

The results of the blank tests conducted indicated that the interaction within the reaction vessel was solely between the adsorbent and the adsorbate. As shown in Figure 1, the HABO was found to have the highest fluoride removal potential and as a result, subsequent studies such as the influence of pH, co-existing anions and contact time were conducted using the HABO. The surface area of the HABO was found to be 0.0635 m\textsuperscript{2}/g.

Fluoride removal capacity of HABO

After the adsorbent screening, the fluoride removal phenomenon and capacity of HABO was determined using increasing initial fluoride concentrations. If all the adsorptive sites on the HABO were accessible, it was expected that, as the initial fluoride concentration increases, the amount of fluoride adsorbed would increase or remain constant.
constant. On the contrary, the adsorption of fluoride onto the HABO reduced with increasing initial fluoride concentration within the period of analysis (Figures 2(a) and 2(b)). This decreasing trend in de-fluoridation points to the probable occurrence of entities or molecules that interact with the fluoride ions or the adsorptive sites, thereby making them inaccessible. There is also the possibility that the bicarbonate ions in the solution compete with the fluoride ion for adsorption as the adsorption sites are not fluoride specific; eventually limiting the fluoride uptake.

**Effect of pH**

The effect of pH on the HABO’s fluoride removal capacity was investigated considering pHs 5, 6 and 7. The results obtained show that the fluoride removal reduced with increasing pH (Figure 3). This trend could be a consequence of increasing concentration of hydroxyl (OH\(^-\)) ions in solution. This increase probably reduced the net positive charge on the surface of the adsorbent and subsequently reduced the adsorbent’s affinity for the negatively charged fluoride ions. Moreover, OH\(^-\) and F\(^-\) are iso-electronic and hence could have competed for the same adsorptive sites.

This observation is in consonance with what was observed by Sajidu et al. (2008), who conducted experiments using bauxite ore with major components of gibbsite (Al\((\text{OH})_3\)) and kaolinite (Al\(_2\)Si\(_2\)O\(_5\)(OH)\(_4\)) as adsorbent for fluoride removal. At pHs 5, 6 and 7, the fluoride removal capacities recorded were 0.66, 0.36 and 0.12 mg/g respectively (Figure 3).

**Effect of co-existing anions on the fluoride removal capacity**

Drinking water usually contains anions such as sulfate, chloride, nitrate, bicarbonate, phosphate, which could compete with fluoride for adsorption sites. Figure 4 gives the influence of the individual as well as the combined co-existing anions on the fluoride removal process.

**Sulfate**

In determining the effect of sulfate on fluoride removal, various fluoride-containing model waters with sulfate concentrations of 28, 30, 32 and 35 mg/L were used in the
batch adsorption process. The results indicate that sulfate in the model water reduced the fluoride removal capacity of the HABO by 40–67% (Figure 4(a)). The sulfate ions probably inhibited or competed with the fluoride for adsorption.

Chloride

In the case of chloride, batch adsorption experiments were performed with model water containing chloride concentrations of 4.5, 5.0, 5.5 and 6.5 mg/L. From the results (Figure 4(b)), there was a 13–27% reduction in the fluoride removal capacity of the HABO. The results also indicated that within the range of Cl\(^{-}\) concentrations tested, the reduction in fluoride removal peaked at 5 mg Cl\(^{-}\)/L corresponding to 27% reduction.

Nitrate

To investigate the effect of nitrate, model water containing nitrate concentrations of 16, 19, 24 and 30 mg/L were used. From Figure 4(c) nitrate also showed a negative effect on the fluoride removal capacity of the HABO. The fluoride removal capacity was reduced by 33–40%. Like the chloride, within the range of nitrate concentrations tested, it was observed that dosing nitrate in excess of 19 mg/L gave no further reduction in the fluoride removal capacity.

The observations made so far are in consonance with the results obtained by Tang et al. (2009), who investigated the effect of co-existing anions on fluoride adsorption onto granular ferric hydroxide. In their study, the following trend for the effects was obtained: H\(_2\)PO\(_4\)/C\(_0\) > HCO\(_3\)/C\(_0\) > SO\(_4^{2-}\)/C\(_0\) > Cl\(^{-}\).

Effect of combined co-existing anions

With respect to the combined effect of all the anions, the model water employed was prepared using the averages of the concentration ranges of the anions given in Table 1 and an initial fluoride concentration of 2.5 mg/L. The results obtained indicated that the removal capacity of the HABO was reduced by 60% (Figure 4(d)).

Adsorption equilibrium isotherms

Batch adsorption experiments conducted under oxic conditions at pH 6 with various initial fluoride concentrations always proceeded to an equilibrium position after 80 h (Figure 5).
The experimental data were fitted to the Freundlich and Langmuir adsorption isotherms. From Figure 6, the coefficients of correlation, $R^2$, of 0.988 and 0.997 obtained for the Freundlich and the Langmuir plots respectively indicate that the adsorption data fitted reasonably well the Freundlich and Langmuir adsorption models. Table 2 shows the Freundlich and Langmuir isotherms constants computed from the plots.

**Adsorption kinetics**

Adsorption is a time-dependent process and it is very important to know the rate of the adsorption process for design purposes. The kinetics data of the fluoride adsorption onto the HABO were tested by fitting to adsorption kinetics models such as the pseudo first-order (Lagergren model) and the pseudo second-order kinetic models to determine the reaction order and the mechanism of the adsorption process. The pseudo first-order kinetics equation is generally expressed as:

$$\frac{dq_t}{dt} = K_1(q_e - q_t)$$  \hspace{1cm} (3)

where $q_e$ and $q_t$ are the amount of adsorbate adsorbed onto the surface of the adsorbent at equilibrium and at time, $t$ respectively (mg/g) and $K_1$ is the rate constant of the first order adsorption process (L/min). Integrating Equation (3) and applying the boundary conditions $t = 0$ to $t = t$ and $q_t = 0$ to $q_t = q_e$, gives the linear form of the equation as:

$$\log(q_e - q_t) = \log q_e - \frac{K_1t}{2.303}$$  \hspace{1cm} (4)

A plot of $\log(q_e - q_t)$ against $t$ gives a straight line with $K_1$ and $q_e$ as the slope and intercept respectively (Zawani et al. 2009).

The pseudo second-order kinetics model which assumes that measured concentrations are equal to cell surface concentrations is generally expressed as:

$$\frac{dq_t}{dt} = K_2(q_e - q_t)^2$$  \hspace{1cm} (5)

where $K_2$ is the rate constant of the pseudo second-order adsorption process (g/min/mg). After integrating Equation (5) and applying the boundary conditions $t = 0$ to $t = t$ and $q_t = 0$ to $q_t = q_e$, a linear form of the equation is obtained as:

$$\frac{t}{q_t} = \frac{1}{K_2q_e^2} + \frac{t}{q_e}$$  \hspace{1cm} (6)

A plot of $t/q_t$ against $t$ gives a straight line with $K_2$ and $q_e$ as the intercept and slope respectively (Zawani et al. 2009).

As shown in Figure 7, the coefficient of determination, $R^2$ of 0.998 obtained from the linear plot of the pseudo second-order kinetics model was greater than that (i.e. $R^2$
of 0.9463) obtained for the Lagergren model, meaning that the adsorption of fluoride onto the HABO followed more the pseudo second-order kinetics. The linear relationship obtained for a plot of \( t/q_t \) against \( t \) is an indication that the adsorption process is likely chemisorption (Ho et al. 1995). The constants for the pseudo first-order and second-order kinetics models are shown in Table 3.

### Thermogravimetric analysis (TGA)

The thermogram of the HABO (Figure 8(a)) shows an initially gradual drop in mass up to about 275°C followed by a very sharp drop in mass with increasing temperature. This could probably be due to the fact that water molecules are not only physisorbed to the surface but also trapped within the crystal structure. Probably, heating the HABO at a temperature above 275°C changes its morphology, making the water molecules easily removed. Within the temperature considered (21.63–800°C), change in mass was about 27.74%. The TGA suggests that the HABO is thermally unstable at very high temperature (>275°C). However, the HABO would be suitable for use as a fluoride removal adsorbent as the operating temperature for drinking water production is normally between 10 and 35°C.

### X-ray diffraction (XRD) analysis

The XRD pattern of the HABO suggests that the HABO is highly crystalline and has the major components kaolinite and gibbsite (Figure 8(b)). Intense peaks for kaolinite \([\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_5]\) at 12° and 25° and for gibbsite \([\text{Al(OH)}_3]\) at 18° and 20.5° are evidence of this fact.

### Energy dispersive X-ray (EDX) and X-ray fluorescence (XRF) analysis

The EDX spectrum indicates that C, O, Al, Si, Ti and Fe are the elements predominant on the surface of the HABO (Figure 9). A similar result was obtained using XRF analysis. The percentage composition of the major elements obtained using the EDX and the XRF analysis are given in Table 4. The EDX and XRF analysis (Figure 9 and Table 4) recorded an appreciable amount of titanium (Ti) on the surface of the HABO, indicating the likelihood of soluble fluorotitanate complexes being formed. The formation of these complexes could probably be preventing the fluoride ions from assessing all the adsorptive sites. This inhibition effect probably increases as the fluoride ions in solution increase.

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### Table 2 | Freundlich and Langmuir isotherm constants

<table>
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<tr>
<th>Isotherm</th>
<th>Linear form</th>
<th>Constant</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freundlich</td>
<td>( \log q_e = \log K + \frac{1}{n} \log C_e )</td>
<td>K (mg/g)</td>
<td>0.90</td>
</tr>
<tr>
<td>Langmuir</td>
<td>( \frac{C_e}{q_e} = \frac{1}{K_m q_m} + \frac{1}{K_s} )</td>
<td>K₂ (L/mg)</td>
<td>−6.19</td>
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</table>

### Table 3 | Kinetic model constants

<table>
<thead>
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<th>Kinetic model</th>
<th>Linear form</th>
<th>Constant</th>
<th>Value</th>
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<tr>
<td>Pseudo first-order</td>
<td>( \log(q_e - q_t) = \log q_e - \frac{K_1 t}{2.303} )</td>
<td>K₁ (L/h)</td>
<td>0.04</td>
</tr>
<tr>
<td>Pseudo second-order</td>
<td>( \frac{t}{q_t} = \frac{1}{K_2 q_e^2} + \frac{t}{q_e} )</td>
<td>K₂ (g/h/mg)</td>
<td>0.30</td>
</tr>
</tbody>
</table>

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CONCLUSIONS

Of all the adsorbents tested, the high aluminium content bauxite ore (HABO) had the highest fluoride removal capacity and a surface area of 0.0635 m²/g. Fluoride removal capacities of 0.91, 0.20, 0.06 and 0.06 mg/g were recorded for HABO, HFBO, Zeolite X and Neem seeds respectively.

The removal of fluoride reduced with increasing pH within the pH range tested. With SO₄²⁻, Cl⁻ and NO₃ in the
model water, the fluoride removal capacities of the HABO were 0.66, 0.36 and 0.12 mg/g at pHs 5, 6 and 7 respectively. Averagely, co-existing anions such as sulfate, chloride and nitrate reduced the fluoride removal capacity of the HABO by 57, 24 and 38% respectively but collectively they reduced the fluoride removal capacity by 60%.

The adsorption data fitted both the Freundlich ($R^2 = 0.988$) and the Langmuir ($R^2 = 0.997$) adsorption isotherms with the adsorption capacity being 0.9 mg/g at pH 6.

The adsorption process followed pseudo second-order kinetics ($R^2 = 0.998$).

Table 4 | Elemental composition of HABO

<table>
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<tr>
<th>Element</th>
<th>Symbol</th>
<th>Atomic no.</th>
<th>Abundance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>C</td>
<td>6</td>
<td>3.5</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O</td>
<td>8</td>
<td>63.59</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Al</td>
<td>13</td>
<td>24.88 &gt;32.38</td>
</tr>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>14</td>
<td>1.66 2.684</td>
</tr>
<tr>
<td>Titanium</td>
<td>Ti</td>
<td>22</td>
<td>1.12 2.234</td>
</tr>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>26</td>
<td>5.25 7.145</td>
</tr>
</tbody>
</table>
The TGA results indicated that the HABO will be thermally stable when used as an adsorbent in water treatment. The XRD pattern of the HABO indicated that it is highly crystalline and has kaolinite [Al$_2$Si$_2$O$_5$(OH)$_5$] and gibbsite [Al(OH)$_3$] as major components.

The EDX and XRF results showed that the predominant elements on the surface of the HABO include Al, Fe, Ti, O, C and Si.

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**REFERENCES**


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