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# Simultaneous Adsorption of Iron and Lead in Queenstown Borehole Water Using Activated Carbon from Nigerian Bamboo

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ABSTRACT

This study investigated the effect of multiple parameters on the simultaneous removal of iron ($Fe^{2+}$) and lead ($Pb^{2+}$) ions from an aqueous solution utilizing Nigerian bamboo activated carbon (NBAC) as an adsorbent. Factors that were considered included initial metal concentration, activated carbon dosage, pH, particle size, and contact time. The results were evaluated using Langmuir and Freundlich isotherms to ascertain the appropriate model for the adsorption process. The removal percentage of heavy metals by the NBAC was observed to rise with higher dosage, pH, and contact duration, but decreased with an increase in initial metal concentration and larger particle size. At optimum conditions, the NBAC eliminated 99.95 % of $Fe^{2+}$ ions and 99.94 % of $Pb^{2+}$ ions. Equilibrium adsorption was attained after 9 hours for both ions. The Freundlich isotherm more accurately represented the adsorption data for $Fe^{2+}$ and $Pb^{2+}$ ions compared to the Langmuir isotherm, suggesting that the adsorption process is predominantly a multilayered adsorption. The study demonstrated that activated carbon produced from waste Nigerian bamboo can substitute commercial adsorbents for water purification.

## 1. Introduction

Over the years, a wide range of techniques have been developed and applied in the treatment of water and wastewater. These include methods such as precipitation, flotation, chlorination, ion exchange, sedimentation, membrane filtration, electrocoagulation, reverse osmosis, chemical oxidation, and adsorption (Rajasulochana and Preethy, 2016). Although these technologies are generally effective at removing contaminants, they come with significant limitations. Common drawbacks include excessive sludge production, potential for secondary pollution, high operational costs, membrane fouling, and the need for frequent maintenance (Bisht *et al.*, 2020).

Amongst many approaches, adsorption has emerged as one of the most promising solutions for wastewater purification. Its popularity stems from its affordability, operational simplicity, environmental sustainability, and ease of use (Abdolali *et al.*, 2017; Sukmana *et al.*, 2021). Moreover, many adsorbent materials can be regenerated and reused, thereby reducing both operating costs and waste output (Asghar *et al.*, 2019; Alsawy *et al.*, 2022). Nevertheless, adsorbents that are chemically synthesised or altered may pose environmental risks during disposal and tend to be expensive (Bisht *et al.*, 2020).

In addressing these concerns, researchers have explored the development of adsorbents from agricultural by-products. Examples include sawdust (Semerjian, 2018), sunflower seed pulp ash (Mohadesi *et al.*, 2024), cashew nut shells (Papadaki *et al.*, 2021; Samiyammal *et al.*, 2022), and wheat bran (Bisht *et al.*, 2017), which have shown potential in removing heavy metals from wastewater. Activated carbon derived from Nigerian bamboo has also demonstrated a high removal capacity under favourable adsorption conditions (Ademiluyi and Nze, 2016; Ademiluyi and Nwanam, 2016).

Traditional water treatment systems are often resource-intensive and costly, making them inaccessible for many underserved communities. Utilising readily available local materials for activated carbon production offers a cost-effective and environmentally friendly alternative. In Nigeria's Niger Delta region, bamboo is an abundant renewable resource that can be used to create activated carbon with favorable adsorption properties, as it possesses unique physical (excellent pore structure and high surface area) and chemical properties (can be optimized to produce activated carbon with specific pore sizes suited for targeted applications).

Bamboo activated carbon when compared to commercial activated carbon, is highly effective in the removal of multiple contaminants, sometimes outperforming chemical purification methods and commercial carbon products, have superior surface area and porosity, and possess higher or comparable adsorption capacity in many water and wastewater applications (Lamaming *et al.*, 2022; Hassan *et al.*, 2023; Chaturvedi *et al.*, 2023).

The Queenstown area in the Opobo community—one of nine small islands that make up the larger Opobo cluster—faces ongoing challenges in accessing potable water, particularly as its population continues to grow. Recent analyses of water samples collected from the Queenstown area revealed significant contamination by heavy metals, specifically lead and iron, rendering the water unsafe for consumption according to WHO standards. This research investigates the efficacy of activated carbon made from locally sourced Nigerian bamboo in purifying drinking water drawn from wells in Queenstown, Opobo.

To assess the effectiveness of the treatment, groundwater samples from local boreholes were analysed. The bamboo-derived activated carbon was subjected to a series of characterisations, and various operational parameters were evaluated. Both batch and continuous adsorption experiments were conducted to understand the removal dynamics of iron and lead. Furthermore, a water treatment system incorporating filtration units was designed to address the community's needs.

The adsorption behaviour was further examined using established isotherm models, including the Freundlich and Langmuir. The study explored how process variables influenced the capacity of the bamboo-based adsorbent to simultaneously remove $Fe^{2+}$ and $Pb^{2+}$ ions from the borehole water in Queenstown, shedding light on the underlying mechanisms of the sorption process.

## 2. Materials and Methods

### *2.1 Materials*

The materials utilised in this study included activated carbon derived from waste Nigerian bamboo, groundwater samples, distilled water, nitric acid, and analytical-grade salts containing $Fe^{2+}$ and $Pb^{2+}$ ions. Additional equipment and tools comprised amber bottles, measuring cylinders, beakers, a digital and analytical balance (±0.001, Adams AFP 360 L), pH meter, filter papers, desiccators, heating mantles, crucibles, retort stands, spatulas, crushers, mortar and pestle, petri dishes, burettes, conical flasks, a pyrolysis unit with Pyrex condenser, wash bottles, cuvettes, a muffle furnace, sieves of various sizes, cutting machine, oven, and Atomic Absorption Spectrophotometer (APHA 301A).

## 2.2 Methods

### 2.2.1 Preparation of Nigerian Bamboo

Bamboo waste collected from the Niger Delta riverine region was chopped into ~2 cm pieces using a cutting machine. The pieces were washed thoroughly with distilled water to eliminate surface impurities and debris, then oven-dried to remove residual moisture.

### 2.2.2 Carbonization of Nigerian Bamboo

Approximately 1.5 kg of dried bamboo pieces were loaded into a pyrolysis reactor and subjected to thermal treatment at temperatures between 300 °C and 400 °C for four hours (Ademiluyi and Nze, 2016). The pyrolysis vapours were collected via a condenser into a distillate receiver. Upon cooling the char to ambient temperature, the product was transferred to a sealed, clean container. The char was then ground with a mortar and pestle, sieved to a uniform particle size of 1.18 mm, and preserved in an airtight container for subsequent use.

### 2.2.3 Activation of Nigerian Bamboo

A 100 g sample of the carbonized bamboo was transferred into a beaker. Diluted nitric acid ($HNO_3$) was added to the sample in a measured quantity and mixed thoroughly to form a consistent paste. Additional nitric acid was applied to enhance the activation process. This mixture was heated in an oven at 105 °C before being transferred into crucibles and placed inside a muffle furnace, where it was heated at 650 °C. After cooling to room temperature, the activated carbon was rinsed repeatedly with distilled water until a neutral pH (~7) was achieved. It was then oven-dried at 105 °C for three hours and stored in an airtight polyethylene bag for future application.

### 2.2.4 Characterisation of Activated Carbon

The physicochemical properties of the activated carbon were analysed using standardised ASTM protocols as described by Ademiluyi and Nze (2016). The major parameters assessed included iodine number, bulk density, surface moisture content, ash content, methylene blue adsorption capacity, and surface area.

## 2.3 Adsorption of Iron and Lead Ions

The prepared activated carbon from waste bamboo was utilised to adsorb $Fe^{2+}$ and $Pb^{2+}$ ions from polluted water samples. A series of batch adsorption experiments were conducted to explore the influence of several factors, including pH, initial metal concentration, adsorbent dose, particle size, and contact duration.

### 2.3.1 Effect of Initial Metal Concentration

To study the impact of metal concentration on adsorption performance, iron and lead ion solutions were prepared in varying concentrations: 20, 40, 60, 80, 100, and 120 mg/L. These solutions were obtained by dissolving specific weights of iron (III) oxide ($Fe_2O_3$) and lead (II) chloride ($PbCl_2$) in distilled water. Each solution was spiked simultaneously with both metal ions and adjusted to pH 6.5 using NaOH and $H_2SO_4$. A fixed amount (1g) of 300 μm activated bamboo carbon was added to 20 mg/L metal solutions. The beaker containing the mixture was placed on a rotary platform equipped with a magnetic stirrer set at 120 rpm for thorough agitation over 12 hours. Afterward, the solution was filtered, and the concentration of remaining $Fe^{2+}$ and $Pb^{2+}$ ions was analyzed using an Atomic Absorption Spectrophotometer (AAS). This procedure was repeated for each concentration level, maintaining all other variables constant.

### 2.3.2 Effect of Nigerian Bamboo Dosage

The effect of varying adsorbent dosage on metal ion removal was examined using activated carbon amounts of 0.1, 0.3, 0.5, 0.7, and 1.0 g, all with a particle size of 300 μm. For each trial, the sample was added to metal ion solutions and stirred on a rotary disc at 150 rpm for 12 hours. Post-stirring, the mixture was filtered to separate the solid adsorbent from the solution. The residual metal concentrations in the filtrate were quantified using AAS. The experiment was repeated across all dosage levels while keeping other conditions—metal concentration (20 mg/L), particle size (300 μm), pH (6.5), and contact time (12 hours)—unchanged.

### 2.3.3 Effect of Particle Size

The effect of particle size on the adsorption capacity of activated bamboo was examined at four different sizes: 150 µm, 212 µm, 300 µm, and 600 µm. For each test, a 1.0 g dose of activated bamboo (300 µm particle size) was added to the solution. The beaker containing the solution was placed on a rotary disc, set at a speed of 150 rpm, and stirred with a magnetic stirrer. After 120 minutes of stirring, the solution was filtered to separate the adsorbent and adsorbates (as residue) from the water (as filtrate). The filtrate was then analyzed to determine the concentration of iron and lead ions remaining in the solution using an Atomic Absorption Spectrophotometer (AAS). This procedure was repeated for particle sizes of 150 µm, 212 µm, and 600 µm, keeping all other parameters constant.

### *2.3.4 Effect of pH*

The effect of pH on adsorption was studied at solution pH levels of 3, 5, 6.5, and 9. The pH was adjusted by adding $H_2SO_4$ and NaOH to the solution. Other conditions such as the initial concentration of iron and lead (20 mg/L), adsorbent dosage (1 g), particle size (300 µm), and contact time (12 hours) were maintained. After the allotted contact time, the solution was filtered, and the filtrate was analysed for iron and lead ion concentrations using AAS.

### *2.3.5 Effect of Adsorption Time*

To evaluate the impact of contact time, experiments were conducted at 3, 6, 9, and 12 hours. A 1.0 g dosage of activated bamboo (300 µm particle size) was added to the solution and stirred at 150 rpm for various contact times. After each interval, the solution was filtered, and the concentration of iron and lead ions in the filtrate was measured using AAS.

### *2.4 Metal Uptake*

The uptake of heavy metal ions was calculated based on mass balance, expressed as the amount of solute adsorbed per unit weight of adsorbent. This corresponds to the amount of solute removed from the solution (Ademiluyi and Nze, 2016). The equation for metal uptake is given as:

$$Q_e = \frac{(C_i - C_e)}{S} \tag{1}$$

S is expressed as the mass of solute per volume of solution. Thus:

$$S = \frac{m}{V} \tag{2}$$

Equation (2) can also be expressed as:

$$Q_e = \frac{V(C_i - C_e)}{m} \tag{3}$$

The percentage of heavy metals adsorbed per time by the Nigerian-activated bamboo was determined using the formula.

$$M_{ad}(\%) = \frac{C_i - C_t}{C_i} \times 100\% \tag{4}$$

Similarly, the adsorption capacity at any given time was determined using the formula:

$$Q_t = \frac{V(C_i - C_t)}{m} \tag{5}$$

### *2.5 Adsorption Isotherms*

To understand the adsorption process at equilibrium, experimental data were fitted to the Langmuir and Freundlich isotherms.

### *2.5.1 Langmuir Isotherm*

The Langmuir isotherm model, in its linear form according to Yu-Ting and Ming-Cheng (2016) is given by:

$$\frac{C_e}{q_e} = \frac{C_e}{q_m} + \frac{1}{q_m K_L} \tag{6}$$

A plot of $\frac{C_e}{q_e}$ against $C_e$ is used to determine the maximum adsorption capacity, $q_m$ (mg/g) and is constantly related to the affinity between the adsorbent and the adsorbate, $K_L$

The Langmuir isotherm can also be used to determine the favorability of adsorption and can be evaluated using a dimensionless parameter called the separation factor, $R_L$ This was expressed according to Huang and Garcia-Bennett (2021) as:

$$R_L = \frac{1}{1 + a_L C_0} \tag{7}$$

From the above equation (7), if $0<R_L<1$, the adsorption is said to be favourable. If $R_L>1$, the adsorption is said to be unfavourable, but if $R_L = 1$, the adsorption is said to be linear, or if $R_L = 0$, the adsorption is said to be irreversible (Huang and Garcia-Bennett, 2021).

### *2.5.2 Freundlich Isotherm*

The Freundlich isotherm is expressed as:

$$q_e = K_f C_e^{1/n} \quad (8)$$

The Freundlich constant, $K_f$ and heterogeneity of adsorption energy across the adsorbent surface, $n$, can be obtained by taking the logarithm of both sides of equation (8) (Ademiluyi *et al.*, 2021), which gives:

$$\ln q_e = \ln K_f + \frac{1}{n} \log C_e \quad (9)$$

A plot of $\ln q_e$ against $\ln C_e$ is used to determine $K_f$ and $n$ from the slope and the intercept.

## 3 Results and Discussion

### *3.1 Result of Water Analysis from Queenstown, Opobo Community*

A detailed water quality analysis was conducted on samples collected from four groundwater supply sources in Queenstown, Opobo Community. The objective was to assess the suitability of the water for drinking purposes based on established standards. The analysis included testing for physico-chemical, microbial, and heavy metal parameters.

Iron and lead concentrations were found to exceed the permissible limits set by the WHO and NIS standards. Specifically, lead and iron levels in water from the Queenstown Community Borehole were notably high as shown in Table 1 below. WHO and NIS guidelines recommend limits of 0.01 mg/L for lead and 0.3 mg/L for iron in drinking water.

**Table 1:** Water Analysis of Queenstown, Opobo

| S/No | Parameters | Community Borehole | WHO (2004) | Health Impact (Source: NIS-554-2015) |
|---|---|---|---|---|
| 1 | pH | 8.53 | 6.5–8.5 | None |
| 2 | Conductivity | 692 | <1000 | None |
| 3 | Iron | 3.698 | 0.3 | None |
| 4 | Lead | 3.134 | 0.01 | Cancer, mental development in infants, toxic to central/peripheral nervous system |

This highlights the necessity to treat the Queenstown community borehole water supply using an efficient treatment method to remove these metals and other impurities and ensure the safety of groundwater quality in the area.

The presence of other metal ions such as Zn, Ni, Cu, and Cd was within the permissible limits for drinking water standards.

### *3.2 Effects of Parameters on Iron and Lead*

The effect of various parameters on the removal of iron ($Fe^{2+}$) and lead ($Pb^{2+}$) ions from aqueous solutions using Nigerian bamboo activated carbon (NBAC) has been a critical aspect of the study. Several factors, such as initial concentration of the metals, dosage of the adsorbent, particle size of the activated carbon, pH of the solution, and contact time, were explored to determine their influence on the removal efficiency.

#### *3.2.1 Effect of Initial Concentration*

As illustrated in Figure 1, the initial concentration of $Fe^{2+}$ and $Pb^{2+}$ ions plays a significant role in their removal efficiency. The results indicate that as the initial concentration of the metals increases, the percentage removal of both $Fe^{2+}$ and $Pb^{2+}$ by NBAC decreases. Specifically, at initial concentrations ranging from 20 mg/L to 120 mg/L, the removal efficiency dropped from 99.95 % to 85.77 % for $Fe^{2+}$ and from 99.94 % to 82.98 % for $Pb^{2+}$ after 12 hours of contact. This suggests that the adsorbent becomes less effective at higher contaminant concentrations.

In terms of specific concentrations, at an initial concentration of 20 mg/L, the concentration of $Fe^{2+}$ and $Pb^{2+}$ reduced to 0.0093 mg/L and 0.0112 mg/L, respectively. However, at 120 mg/L initial concentration, the concentrations of $Fe^{2+}$ and $Pb^{2+}$ were reduced to 17.076 mg/L and 20.424 mg/L, respectively.

The reduction in removal efficiency with an increase in initial concentration can be attributed to several factors. Primarily, higher metal concentration leads to a saturation of the available adsorption sites on the activated carbon surface. This saturation hinders the effective diffusion of metal ions into the unreacted functional groups on the adsorbent, thus reducing its capacity to adsorb further ions. This phenomenon has been confirmed by previous studies (Muthusamy and Murugan, 2016; Augustine *et al.*, 2019; Chen *et al.*, 2023), which noted a similar decrease in removal efficiency as the concentration of heavy metals in aqueous solutions increased.

While the results of this study align with the general understanding that adsorption efficiency tends to decrease with an increase in initial metal concentration, some studies have reported different outcomes. For example, certain bio-adsorbents have demonstrated an increase in removal efficiency with rising initial concentrations (Sharma *et al.*, 2016; De Angelis *et al.*, 2017; Radoor *et al.*, 2022). Additionally, the volume of contaminated water treated at higher initial concentrations can also impact the removal efficiency. Larger volumes might reduce the contact time between the adsorbent and the contaminants, thus leading to reduced efficiency at high concentrations (Mashangwa *et al.*, 2017). In summary, the study indicates that the initial concentration of $Fe^{2+}$ and $Pb^{2+}$ ions significantly impacts their removal efficiency by Nigerian bamboo activated carbon. The results suggest that while the adsorbent performs excellently at lower concentrations, its efficiency diminishes as the concentration of the metals increases. This highlights the importance of optimising various adsorption parameters to ensure the most efficient removal of heavy metals in real-world applications.

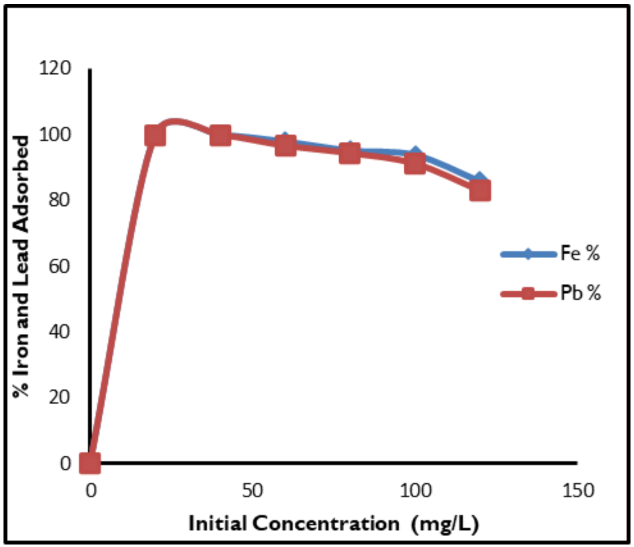

**Figure 1:** $Fe^{2+}$ and $Pb^{2+}$removal against initial metal concentrations

### *3.2.2 Effect of NBAC Dosage on the Removal of $Fe^{2+}$ and $Pb^{2+}$*

As presented in Figure 2, the effect of Nigerian bamboo activated carbon (NBAC) dosage on the removal of $Fe^{2+}$ and $Pb^{2+}$ ions from aqueous solutions shows a clear trend; as the dosage of NBAC increases, the percentage removal of $Fe^{2+}$ and $Pb^{2+}$ ions also increases. This demonstrates the importance of the adsorbent dosage in optimising the removal process.

At a low dosage of 0.1 g, the specific concentrations of $Fe^{2+}$ and $Pb^{2+}$ ions reduced from an initial concentration of 20 mg/L to 3.0188 mg/L and 3.7854 mg/L, respectively. However, when the NBAC dosage was increased to 1.0 g, the concentrations of $Fe^{2+}$ and $Pb^{2+}$ dropped significantly to 0.0093 mg/L and 0.0112 mg/L, respectively. The percentage removal for $Fe^{2+}$ increased from 84.91 % to 99.95 %, and for $Pb^{2+}$, it increased from 81.07 % to 99.94 %. This shows that the optimum removal efficiency was achieved at a dosage of 1.0 g of NBAC.

The results of this study align with findings from previous research, such as Mashangwa *et al.* (2017), who reported the optimum adsorption of $Pb^{2+}$ at a higher dosage of 7 g. The increase in removal efficiency with increasing adsorbent dosage can be explained by the availability of more active adsorption sites on the surface of the NBAC. As the dosage increases, more sites become available for the adsorption of $Fe^{2+}$ and

$Pb^{2+}$, leading to improved removal efficiency (Badrealam *et al*., 2018).

However, it is also important to note that increasing the dosage beyond the optimal value (1.0 g in this case) may not result in a significant increase in removal efficiency. This is because, as the dosage increases further, the adsorbent particles may begin to overcrowd, causing overlaps of adsorption sites. This overlap reduces the effective surface area available for adsorption, thus limiting the efficiency of the process (Mashangwa *et al*., 2017). Therefore, while higher dosages improve removal efficiency up to a certain point, any increase beyond the optimal dosage may lead to diminishing returns.

The study emphasises the crucial role of adsorbent dosage in the effective removal of $Fe^{2+}$ and $Pb^{2+}$ ions from aqueous solutions. The results confirm that the removal efficiency increases with NBAC dosage, peaking at 1.0 g. Beyond this, excessive dosages may not offer significant improvements and could lead to overcrowding of adsorption sites. Thus, selecting an optimal dosage is essential for achieving the most efficient metal removal from contaminated water.

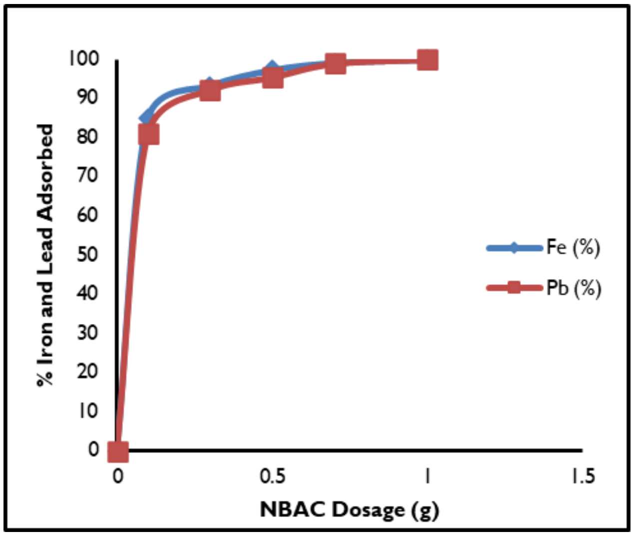

**Figure 2:** $Fe^{2+}$ and $Pb^{2+}$removal against dosage

### *3.2.3 Effect of Particle Size on the Removal of $Fe^{2+}$ and $Pb^{2+}$*

Figure 3 illustrates the impact of the particle size of Nigerian bamboo activated carbon (NBAC) on the removal of $Fe^{2+}$ and $Pb^{2+}$ ions from aqueous solutions. The results demonstrate a clear trend; as the particle size of the NBAC increases, the percentage removal of both $Fe^{2+}$ and $Pb^{2+}$ ions decreases. At a particle size of 150 µm, the percentage removal of $Fe^{2+}$ and $Pb^{2+}$ was 99.97% and 99.96%, respectively. However, at 600 µm, the percentage removal dropped slightly to 99.94% for $Fe^{2+}$ and 99.93% for $Pb^{2+}$. This suggests that within the particle size range of 150 – 600 µm, there was no significant difference in the removal efficiency of $Fe^{2+}$ and $Pb^{2+}$. However, the optimum removal was achieved at the smaller particle size of 150 µm. These findings align with earlier studies, such as Singh and Patel (2023), who reported optimum adsorption at a particle size of 201 µm for sesame adsorbent, and *Gaur et al.* (2018), who observed optimum adsorption of lead and arsenic ions at a much smaller particle size (0.1 µm) of soya beans.

The enhanced removal efficiency observed with smaller particle sizes can be attributed to several factors. First, smaller particles have a greater surface area, providing more binding sites for the uptake of contaminants. This increased surface area enables more $Fe^{2+}$ and $Pb^{2+}$ ions to adsorb onto the surface of the NBAC, leading to higher removal efficiencies (Emenike *et al*., 2016; Abd elhafez *et al*., 2017).

In conclusion, smaller particle sizes of NBAC, particularly around 150 µm, provide the most efficient removal of $Fe^{2+}$ and $Pb^{2+}$ ions from aqueous solutions. The higher surface area and reduced diffusion resistance of smaller particles contribute to more effective adsorption. While larger particle sizes (such as 600 µm) do not significantly decrease the removal efficiency in this study, they may limit the accessibility of adsorption sites and reduce the overall removal rate. Therefore, selecting the optimal particle size is crucial for maximising the adsorption of metal ions.

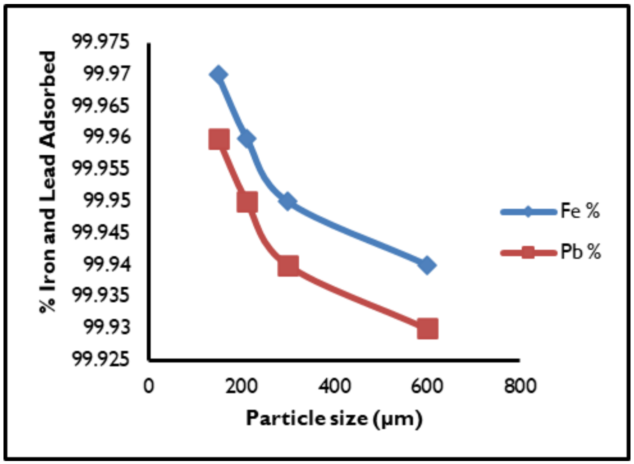

**Figure 3:** $Fe^{2+}$ and $Pb^{2+}$removal against particle size

### *3.2.4 Effect of pH on the Removal of $Fe^{2+}$ and $Pb^{2+}$ Ions*

Figure 4 illustrates the influence of pH on the removal of $Fe^{2+}$ and $Pb^{2+}$ ions from aqueous solutions. The data revealed that the percentage removal of both ions decreased as the pH level increased from 3 to 6.5 and then declined further with a continued increase in pH. The results showed that at a pH of 3, the specific concentration of $Fe^{2+}$ and $Pb^{2+}$ ions removed was 0.9254 mg/L and 1.1146 mg/L, respectively. However, at a pH of 6.5, the concentrations of $Fe^{2+}$ and $Pb^{2+}$ decreased to 0.0093 mg/L and 0.0112 mg/L, corresponding to removal percentages of 99.95 % for $Fe^{2+}$ and 99.94 % for $Pb^{2+}$. At pH 9, the removal efficiencies were still high, with 97.54 % for $Fe^{2+}$ and 97.14 % for $Pb^{2+}$.

*Optimal pH for Maximum Removal*

The maximum removal of both metals was achieved at a near-neutral pH of 6.5, which aligns with other studies that found the optimum pH for the removal of metals like $Cd^{2+}$ and $Pb^{2+}$ to be in the range of 6 to 6.5 (Sohail *et al.*, 2019; Mohapatra *et al.*, 2019). This suggests that the adsorbent (NBAC in this case) has an ideal interaction with metal ions at a slightly acidic to neutral pH.

While the optimal pH for $Fe^{2+}$ and $Pb^{2+}$ removal in this study was found to be around 6.5, some previous research has observed maximum adsorption at lower pH levels. For instance, studies on the removal of $Fe^{2+}$ from wastewater using activated banana peel (Shrestha, 2018a, 2018b) and sawdust (Shrestha, 2018a) indicated optimal adsorption at pH values between 3 and 4.5. Similarly, some research, including Choińska-Pulit *et al.* (2018) and Gonçalves *et al.* (2018), found effective adsorption within the pH range of 3 to 4.5. Additionally, Villen-Guzman *et al.* (2019) noted the highest adsorption capacity for $Ni^{2+}$ on lemon peel at a pH of 5.

The variability in pH-dependent adsorption performance can be attributed to several factors. At low pH, hydrogen ions ($H^+$) compete with metal ions for adsorption sites on the adsorbent. This competition can lead to a reduction in the adsorption capacity, as the adsorbent's surface becomes protonated, hindering the formation of stable ionic complexes between the metal ions and the adsorbent (Yao *et al.*, 2020). Additionally, the precipitation of metal ions as hydroxides in highly alkaline conditions further decreases the efficiency of adsorption.

At higher pH levels, the decrease in metal ion solubility can reduce the availability of metal ions for adsorption, thus lowering the removal efficiency. Furthermore, an increase in pH can weaken the electrostatic attraction between the metal ions and the adsorbent surface due to the reduced positive charge density of the metal ions, which weakens their interaction with the negatively charged sites on the adsorbent (Moreira *et al.*, 2019).

The study's findings demonstrate that near-neutral pH (around 6.5) is optimal for the removal of $Fe^{2+}$ and Pb ions using NBAC, with high removal efficiencies of up to 99.95% and 99.94%, respectively. Although other studies have shown varying pH preferences for metal ion adsorption, the results emphasize the importance of maintaining a suitable pH for maximizing adsorption efficiency. It is crucial to consider the competing effects of hydrogen ions and the solubility of metal ions when selecting the optimal pH for metal removal processes.

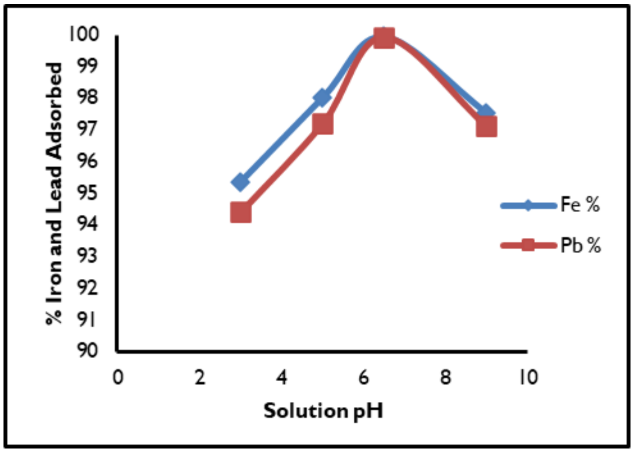

**Figure 4:** $Fe^{2+}$ and $Pb^{2+}$removal against pH

### *3.2.5 Effect of Contact Time on the Adsorption of $Fe^{2+}$ and $Pb^{2+}$ Ions*

Figure 5 presents the effect of contact time on the adsorption of $Fe^{2+}$ and $Pb^{2+}$ ions from an aqueous solution onto NBAC. The data shows that the percentage of $Fe^{2+}$ and $Pb^{2+}$ adsorbed onto NBAC increased as the contact time increased. Specifically, the concentration of $Fe^{2+}$ and $Pb^{2+}$ removed from the solution rose from 1.3514 mg/L and 1.8778 mg/L after 3 hours, to 0.0093 mg/L and 0.0112 mg/L after 12 hours of adsorption, respectively. In terms of percentage removal, the amount of $Fe^{2+}$ and $Pb^{2+}$removed increased from 93.24 % and 90.61 % after 3 hours to 99.95 % and 99.94 % after 12 hours.

*Rapid Initial Adsorption*

During the first 3 hours, the removal of $Fe^{2+}$ and $Pb^{2+}$ ions was significantly higher, with the concentration of $Fe^{2+}$ and $Pb^{2+}$ reduced by 18.6486 mg/L and 18.1222 mg/L, respectively. This rapid adsorption during the initial period is attributed to the abundance of available active sites on the adsorbent surface and the increased diffusion of metal ions from the solution to the adsorbent. As the adsorption progressed, the amount of $Fe^{2+}$ and $Pb^{2+}$ removed between 3 and 12 hours increased by only 1.3421 mg/L and 1.8666 mg/L, indicating a slowing down of the adsorption process after the initial stages.

*Equilibrium and Comparison with Other Studies*

The equilibrium for the adsorption of both $Fe^{2+}$ and $Pb^{2+}$ was reached around 9 hours, which is a relatively short contact time compared to other studies. For example, studies by Ahmad *et al.* (2019), Mohapatra *et al.* (2019), and Moreira *et al.* (2019) have reported longer equilibrium times. Interestingly, Mashangwa *et al.* (2017) recorded equilibrium at 120 minutes for the adsorption of $Pb^{2+}$ onto eggshell adsorbents. This shorter equilibrium time observed in the current study suggests a faster adsorption process, possibly due to the high efficiency of NBAC as an adsorbent.

The rapid removal of metal ions in the initial stages of adsorption is primarily due to the abundance of available active sites on the adsorbent surface and the high diffusion rate of the metal ions to these sites. However, as the adsorption progresses, the available active sites decrease, resulting in a slower rate of adsorption. This is a well-known phenomenon in adsorption processes, where the initial rapid adsorption phase slows down as fewer active sites are available, and the adsorbate concentration in the solution decreases (Tatah *et al*., 2017; Okoya *et al*., 2020).

The results suggest that the adsorption of $Fe^{2+}$ and $Pb^{2+}$ onto NBAC occurs rapidly in the initial stages, with equilibrium being reached in around 9 hours. This behaviour is consistent with previous studies on the adsorption of heavy metals, where most of the metal removal occurs in the early stages due to the availability of active adsorption sites. However, as the number of available sites decreases, the rate of adsorption slows down. The relatively short contact time required for equilibrium in this study highlights the efficiency of NBAC as an adsorbent for heavy metal removal.

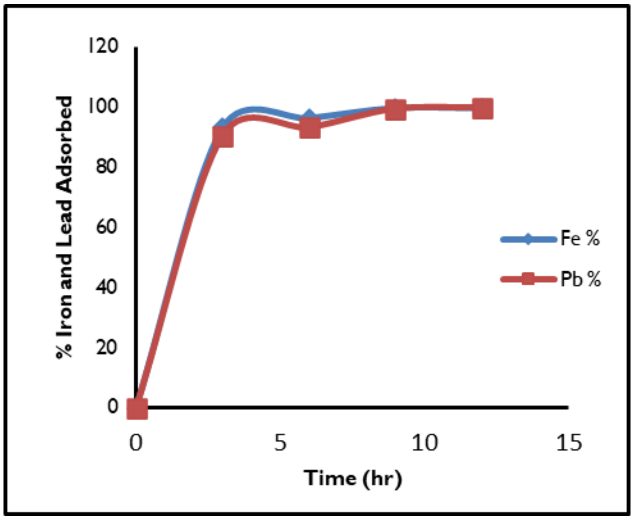

**Figure 5:** $Fe^{2+}$ and $Pb^{2+}$removal against time

### *3.3. Adsorption Isotherm for Iron and Lead*

The adsorption of $Fe^{2+}$ and $Pb^{2+}$ ions onto NBAC was analysed by fitting the experimental data into Langmuir and Freundlich isotherm models. This approach was used to determine which model best describes the adsorption behaviour of these metals on NBAC.

### 3.3.1 Langmuir isotherm

Figure 6 illustrates the Langmuir isotherm for the adsorption of $Fe^{2+}$ and $Pb^{2+}$ ions onto NBAC. The linearised Langmuir plot shows that the ratio of the equilibrium concentration of $Fe^{2+}$ and $Pb^{2+}$ in the liquid phase $(C_e)$ to the amount of metal ions adsorbed by NBAC at equilibrium $(q_e)$ increased with increasing $C_e$. This trend is consistent with the typical behaviour described by the Langmuir model, where adsorption occurs on a surface with a finite number of identical sites, leading to saturation at higher concentrations.

From the Langmuir isotherm plots, the maximum adsorption capacities $(q_m)$ were determined. For $Fe^{2+}$, the maximum adsorption capacity was found to be 26.8817 mg/g, while for $Pb^{2+}$, it was significantly higher at 125 mg/g. These values represent the highest amount of metal ions that can be adsorbed by a unit mass of NBAC, indicating that NBAC has a higher capacity for $Pb^{2+}$ adsorption compared to $Fe^{2+}$.

The Langmuir constant $(K_L)$, which is related to the affinity between the adsorbent and the adsorbate, was calculated for both ions. The values of KL were 41.3333 L/g for $Fe^{2+}$ and 26.6667 L/g for $Pb^{2+}$. A higher $K_L$ value suggests a stronger interaction between NBAC and the adsorbed ion, indicating that NBAC has a greater affinity for $Fe^{2+}$ than $Pb^{2+}$.

The correlation coefficients ($R^2$) for the Langmuir isotherm model were 0.9641 for $Fe^{2+}$ and 0.9581 for $Pb^{2+}$, which suggests that the Langmuir model provides a good fit for the experimental data, particularly for $Fe^{2+}$.

The results indicate that the Langmuir isotherm model better fits the experimental data for the adsorption of $Fe^{2+}$ by NBAC, as evidenced by the higher $R^2$ value and the maximum adsorption capacity of 26.8817 mg/g. The adsorption of $Pb^{2+}$ also followed the Langmuir model, but with a lower $R^2$ value (0.9581) and a significantly higher maximum adsorption capacity (125 mg/g). These findings suggest that NBAC is more efficient in adsorbing $Pb^{2+}$ compared to $Fe^{2+}$ and that the adsorption process for both metals is well described by the Langmuir isotherm, which assumes monolayer adsorption on a surface with a finite number of identical adsorption sites.

Similar studies using activated bamboo as an adsorbent have reported varying results for the maximum adsorption capacity $(q_m)$ and Langmuir constant $(K_L)$ For instance, in a study by Ademiluyi and Ujile (2013), $q_m$ and $K_L$ were reported as 166.70 mg/g and 29.47 L/mg, respectively, for the single adsorption of $Fe^{2+}$. In another study by Ademiluyi and Nze (2016), $q_m$ and $K_L$ values for multiple adsorptions of $Pb^{2+}$ were recorded as 166.67 mg/g and 550.06 L/g, but with a lower $R^2$ value of 0.769, indicating a less reliable fit of the Langmuir model to the data. These variations in $q_m$ and $K_L$ values, despite using the same type of adsorbent, could be attributed to different operational conditions, such as pH, contact time, and temperature, as well as the nature and concentration of the pollutants in the solution.

Further comparisons with other research show a range of maximum adsorption capacities for various adsorbents. Studies involving garlic, ginger, corn cob, and plantain pseudo-stem as adsorbents reported $q_m$ values between 2.90 mg/g and 6.65 mg/g (Dagde and Ndaka, 2019; Singh and Waziri, 2019; Chie-Amadi *et al*., 2020). These values are considerably lower than those obtained with NBAC and activated bamboo. On the other hand, Liang *et al*. (2013) reported a very high $q_m$ of 209 mg/g for the adsorption of $Pb^{2+}$ onto an unspecified adsorbent, showcasing the considerable variability in the adsorption capacities for different materials.

The differences in these adsorption capacities suggest that various factors, including the adsorbent's physical and chemical properties (such as surface area, pore size, and functional groups), as well as experimental conditions, significantly influence the adsorption performance. These findings highlight the importance of optimising adsorption conditions to achieve the best performance for a particular adsorbent in removing specific contaminants.

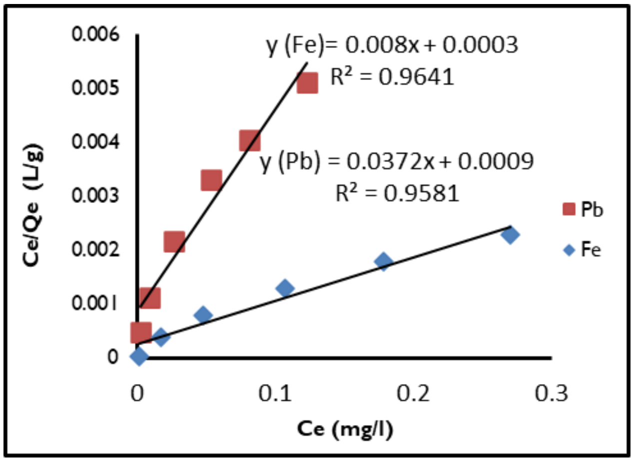

**Figure 6:** Langmuir Isotherm plot for adsorption of Fe$^{2+}$ and Pb$^{2+}$

*3.3.2 Freundlich Isotherm*

In this study, the experimental data for the simultaneous adsorption of Fe$^{2+}$ and Pb$^{2+}$ ions by NBAC were fitted to the Freundlich isotherm model to assess the adsorption behaviour. The Freundlich isotherm equation was used to describe the adsorption by plotting In $q_e$ against In $C_e$, as shown in Figure 7.

From the plot, the Freundlich constants were determined. For Fe$^{2+}$, the Freundlich constants were found to be $K_f$ = 33.3214mg/g and $n$ = 3.1378 while for Pb$^{2+}$, the constants were $K_f$ = 58.1718mg/g and $n$ = 2.3316. Additionally, the $R^2$ values for the model fit were 0.9837 for Fe$^{2+}$ and 0.9987 for Pb$^{2+}$, indicating a better fit for the Pb$^{2+}$ adsorption data compared to Fe$^{2+}$.

The higher R² value for Pb$^{2+}$ suggests that the Freundlich isotherm describes the adsorption process for Pb$^{2+}$ ions more accurately than for Fe$^{2+}$ ions. The $n$ value, which indicates the intensity of adsorption, is greater for Fe$^{2+}$ than Pb$^{2+}$, suggesting a stronger favorability for Fe$^{2+}$ adsorption. The $K_f$ values, representing the adsorption capacity, are also higher for Pb$^{2+}$, indicating that NBAC has a higher capacity for Pb$^{2+}$ compared to Fe$^{2+}$ ions.

Overall, the results imply that the adsorption of Pb$^{2+}$ onto NBAC follows the Freundlich isotherm more closely, showing more complex adsorption behaviour, possibly due to the heterogeneous nature of the adsorbent surface. This provides further insight into the adsorption characteristics and the efficiency of NBAC for removing both iron and lead ions from aqueous solutions.

In comparison to other studies that have investigated the adsorption of Fe$^{2+}$ and Pb$^{2+}$ ions using various agricultural wastes, the Freundlich constants obtained in this study are relatively higher for Fe$^{2+}$ adsorption. In other research, Freundlich constants, $K_f$ ranging from 0.427 to 3.906 mg/g have been reported for Fe$^{2+}$ adsorption using agricultural wastes (Indah *et al*., 2016; Augustine *et al*., 2019), which are lower than the $K_f$ value found in this study for Fe$^{2+}$ adsorption (33.3214 mg/g). However, Shrestha (2018b) reported a $K_f$ value of 48.34 mg/g using sawdust as an adsorbent, which is higher than the value found in this study for Fe$^{2+}$.

Similarly, for Pb$^{2+}$ adsorption, other studies reported lower ranges of the Freundlich constant $K_f$ for Pb$^{2+}$ between 1.998 and 3.440 mg/g, which are lower than the $K_f$ value of 58.1718 mg/g obtained in this study. The values reported by other studies using agricultural wastes as adsorbents indicate the variability of adsorption capacities, with values as high as 355.3 mg/g for Pb$^{2+}$ adsorption onto coconut shell (Singh and Waziri, 2019) and 204.7 mg/g for corn cob (Singh and Waziri, 2019).

These variations in $K_f$ and $n$ values across different studies can be attributed to several factors such as the type of adsorbent used, operational conditions, and the nature of the pollutants in the solution. These differences suggest that each adsorbent material has its unique adsorption characteristics that depend on surface properties and interactions with the metal ions.

In the context of this study, the Freundlich isotherm provided a better fit than the Langmuir isotherm for both $Fe^{2+}$ and $Pb^{2+}$ adsorption, indicating that the adsorption process is primarily multilayered. This is consistent with findings from other studies (Muthusamy and Murugan, 2016; Augustine *et al.*, 2019), which also reported better experimental fits with the Freundlich isotherm, suggesting the presence of heterogeneous surface adsorption sites.

Thus, the multilayer adsorption characteristic observed in this study emphasizes the complex nature of the adsorption process for both $Fe^{2+}$ and $Pb^{2+}$ ions onto NBAC, supporting the idea that the adsorption sites are not uniform and the interaction between the adsorbent and the metal ions varies across the adsorbent surface.

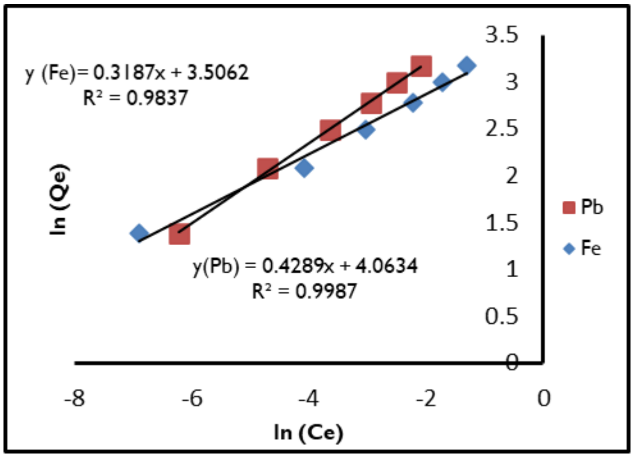

**Figure 7:** Freundlich Isotherm plot for adsorption of $Fe^{2+}$ and $Pb^{2+}$

**Table 2: Langmuir and Freundlich Isotherm Constants**

| Metal | Langmuir Isotherm | | | Freundlich Isotherm | | |
|---|---|---|---|---|---|---|
| | $Q_m$ (mg/g) | $K_L$ (L/g) | $R^2$ | n | $K_f$ (mg/g) | $R^2$ |
| $Fe^{2+}$ | 26.8817 | 41.3333 | 0.9641 | 3.13775 | 33.3214 | 0.9837 |
| $Pb^{2+}$ | 125 | 26.6667 | 0.9581 | 2.33155 | 58.1718 | 0.9987 |

## 4. Conclusion

This study investigated the removal of $Fe^{2+}$ and $Pb^{2+}$ ions from aqueous solutions using activated carbon derived from waste Nigerian bamboo. The findings indicated that various factors, such as the initial concentration of metals, pH, adsorbent dosage, particle size, and contact time, significantly impacted the adsorption process. As the adsorbent dosage, pH, particle size, and contact time increased, so did the percentage of heavy metals were removed from the solution. Conversely, higher initial metal concentrations resulted in decreased removal efficiency. Under optimal conditions, 99.95 % of $Fe^{2+}$ and 99.94 % of $Pb^{2+}$ were removed, with equilibrium reached after 9 hours during the simultaneous adsorption of both ions.

The adsorption behavior followed the Freundlich isotherm model more closely than the Langmuir model, indicating a multilayer adsorption process.

Overall, the activated carbon produced from Nigerian bamboo proved to be an effective adsorbent, suggesting that this waste material can serve as an alternative for both single and multiple metal ion removal.

## Nomenclature

| Symbol | Meaning | Unit |
|---|---|---|
| $C_e$ | Equilibrium concentration of adsorbate | mg/l |
| $C_i$ | Initial concentration of adsorbate | mg/l |
| $C_t$ | Concentration of adsorbate at time, t | mg/l |
| $K_f$ | Freundlich constant | mg/g |
| $K_L$ | Langmuir constant | L/mg |
| $m$ | Mass of Nigerian activated bamboo (dosage) | g |
| $n$ | Freundlich constant related to adsorption intensity | |
| | | mg/g |

| | | |
|---|---|---|
| $q_e$ | amount adsorbed at equilibrium | |
| $q_m$ | maximum adsorption capacity | mg/g |
| $q_t$ | amount adsorbed at time, $t$ | mg/g |
| $V$ | Volume of the solution | L |
| $R_L$ | Separation factor | - |

## Declarations

### *Author contribution*

Maclayton N.L: Writing – original draft, methodology, investigation, review, and editing.

Ademiluyi F.T: Writing – conceptualisation, methodology, review, and formal analysis.

Ukpaka C.P: Formal analysis.

Dagde K.K: Formal analysis.

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### *Competing interest.*

The authors declare that they have no conflicts of interest.

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