

# Detoxification of E-waste polluted site using cashew nut shell-based activated carbon

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## Research

**Keywords:** E-waste Detoxification, Activated Carbon, Agro-based Waste Materials, Heavy Metals Adsorption, Agbogloshie-Ghana

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2 **carbon**

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10  
11 **Abstract**

12 This study considered the potential use of activated carbon (AC) produced from  
13 cashew nuts for remediation of electronic waste (E-waste) polluted soil sites at  
14 Agbogbloshie, Accra, Ghana. The AC supplied by Climate-Environmental Research  
15 and Technology (CLERET) Laboratory, one of the research and development (R&D)  
16 umbrellas of Explore Scientific Innovations Ltd., Ghana. It was prepared by a two-  
17 stage process involving wood-fired reactor for thermal pyrolysis at temperature  
18 ranging from 800-1000 °C, followed with activation with oxidizing gas generated by  
19 wood-fired steam boiler at 160 °C and 7.5 atm pressure for 30 minutes. The product  
20 was characterized based on bulk density, particle size, iodine number, electrical  
21 conductivity (EC), porosity, and pH. Three replicates of soil samples were scooped  
22 from at a depth of 0-15 cm using a soil auger from two randomly selected sites. The  
23 samples were digested with 10 ml of ternary solution (20 ml of HClO<sub>4</sub>; 500 ml of  
24 HNO<sub>3</sub>; 50 ml of H<sub>2</sub>SO<sub>4</sub>) on a hot plate at 90°C for 30 minutes to an hour and analyzed  
25 for selected heavy metals (Pb, Fe, Cu, Cr and Cd) using Atomic Absorption

26 Spectrophotometer (AAS). The cashew nut shell-based AC significantly removed the  
27 heavy metal contents of the E-waste polluted soil with removal efficiency in the  
28 order: Cd (100%) > Pb (93%) > Fe (87%) > Cu (87%) > Cr (76%) for granular and  
29 Cd (100%) > Pb (98%) > Fe (96%) > Cu (94%) > Cr (87%) for powdered activated  
30 carbons. The slopes of the linear graph of the adsorption isotherms of the tested  
31 metals which is indicative of the quality of adsorption of the metals were in the order:  
32 Pb (0.9754) > Fe (0.9093) > Cr (0.8799) > Cu (0.8176) > Cd (0.7511). These agro-  
33 based waste materials therefore have great potential for effective detoxification of E-  
34 waste polluted sites.

35 **Keywords:** E-waste Detoxification; Activated Carbon; Agro-based Waste Materials;  
36 Heavy Metals Adsorption; Agbogloshie-Ghana

37

## 38 **1. Introduction**

39 There is an exponential growth in the demand for electrical and electronic equipment  
40 (EEE) globally due to rapid population growth, changing lifestyle, taste and  
41 preferences [1]. This growth coupled with the speedy obsolescence of EEE as a result  
42 of consistent technological advancement, diminishing product lifetimes, lack of  
43 separate collection and disposal has led to enormous amounts of electronic wastes (E-  
44 wastes) getting into the environment. In 2014, the United Nations estimated that 20 –  
45 50 million tons of E-wastes were generated yearly around the globe and the situation  
46 is aggravated by low global recycling rates amidst illegal trans-boundary movement  
47 from developed to developing countries who have lower capacities to manage E-  
48 wastes [2].

49 Like other developing nations, the influx of E-waste into Ghana has been on  
50 the rise over the years, increasing from 1,400 tons in 2004 to 10,300 tons in 2011 [3].

51 According to Amoyaw-Osei et al. [4], of the 215,000 tons of EEE imported into  
52 Ghana in 2009, only 30% were new products. The E-waste sector is also dominated  
53 by informal recyclers and retrievers, who are exposed to the associated high risk.  
54 Regulation of E-waste management has been challenged by the lack of legislation,  
55 even though efforts are made to curb illegal inflows [3]. E-waste produces substances  
56 that can be very injurious to the environment and humans [1, 5, 6]. They form a  
57 significant component of toxic wastes spread across contaminated sites throughout the  
58 world. Heavy metal contamination of soils is subsequently the most important  
59 environmental problem that poses significant impacts to human and ecosystem health  
60 as contaminants infiltrate and pollute groundwater as well as surface water [1, 7, 8].

61 The burning of cables which is a common practice in E-waste material  
62 recovery in developing countries is recognized as a practice that has the most severe  
63 impact on human health and environment. Exposure to these hazardous substances  
64 results in health challenges that affect the development of the nervous system, thyroid  
65 gland, liver, kidney and causes heart damage, eye and throat irritation [9]. Animals  
66 may suffer from reduced fertility, slower growth and development and in some cases  
67 death while plants experience phytotoxic effects. Recycling which is an emergent  
68 solution is also associated with varying degrees of hazards to workers and the  
69 environment. In incineration, orderly and total burning of E-waste is carried out in  
70 specially designed incinerators at high temperatures ranging from 900 – 1000 °C.  
71 Though incineration has the advantages of waste reduction and the utilization of the  
72 energy content of the combustible materials, the emission of hazardous substances  
73 into air poses a threat [6, 9].

74 The most common biological technique for treating soil and groundwater  
75 contamination is bioremediation [6, 10]. An important factor limiting the efficiency of

76 soil bioremediation is the high toxin levels of chemical contaminants to soil micro and  
77 macro organisms including plants used in phytoremediation. This often limits  
78 utilization of this approach for treating contaminated soils [11].

79 An effective heavy metal removal technique is required in detoxification of  
80 the environment from E-waste pollution. The potential of activated carbon (AC) in  
81 reducing the toxicity of heavily contaminated soils has been demonstrated by previous  
82 studies [10-12]. AC is useful in the ousting of volatile organic compounds and  
83 polychlorinated biphenyls such as chlorine-based solvents for the adsorption of  
84 contaminants from groundwater as part of the bioremediation process. The  
85 detoxification potential of AC on contaminated soils has also been studied  
86 significantly. AC can be developed from many sources, such as palm husks, coconut  
87 shells and almond husk. The use of agricultural by-products to replace wood as the  
88 carbon source helps in utilizing biomass residues in a proper and efficient way  
89 thereby reducing ecological impacts. The increasing generation and demands for  
90 proper disposal of agricultural waste make their use as AC a promising bioresource.  
91 This study therefore investigates the potential of AC produced from cashew nuts for  
92 remediation of soil from E-waste polluted sites.

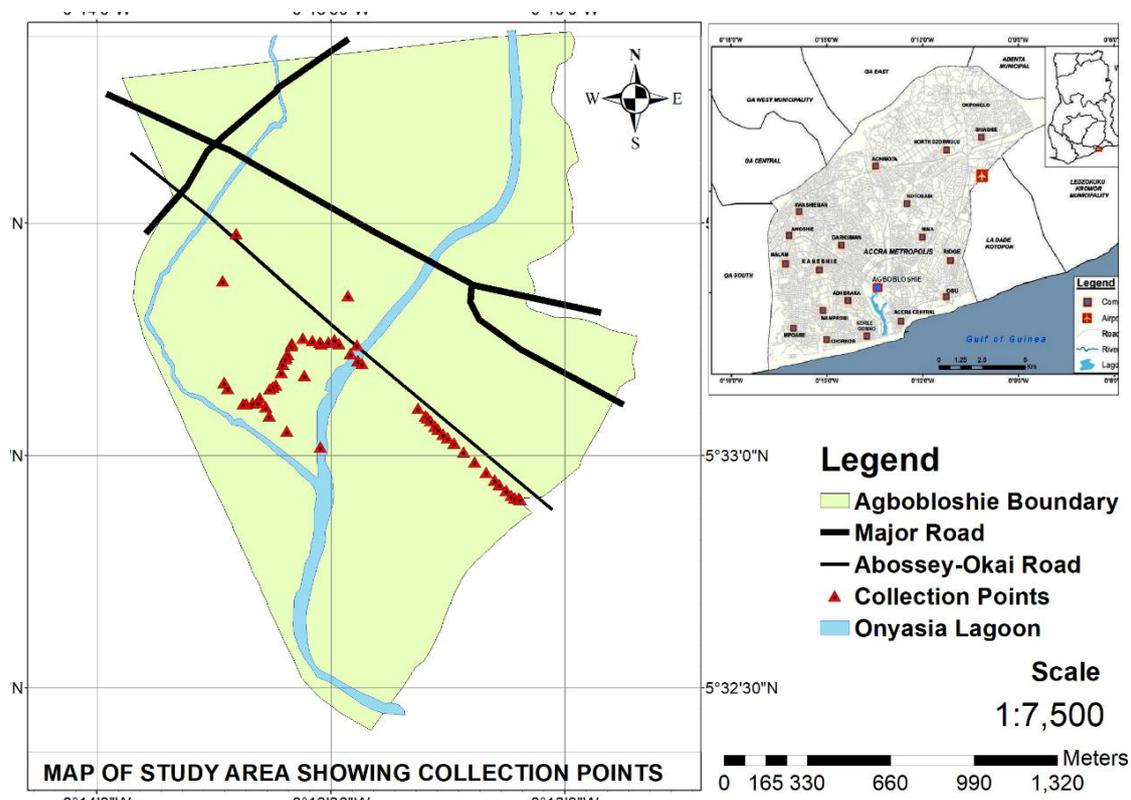
93

## 94 **2. Materials and methods**

### 95 *2.1. Study area*

96 This study was conducted at the Agbogbloshie E-waste dumpsite, also known as the  
97 Agbogbloshie Scrap Market in Accra, Ghana (Fig. 1). This site has for decades  
98 remained a dumping ground for waste products of imported EEE goods mainly from  
99 Western Europe [13]. Reports in 2013 indicate that 75% of electronic goods arriving  
100 at the main port of Ghana, Tema end up at Agbogbloshie and about 129,000 tons of

101 E-waste is generated at the site annually [14]. Agbobloshie has one of Accra's largest  
 102 food markets and about 40,000 residents live in the wider locality of Sodom and  
 103 Gomorrah, one of the main areas in Agbobloshie [14]. This location in Agbobloshie  
 104 is purely slum and home to many scrap dealers and informal recyclers of E-wastes.  
 105 The site is the main center for large scale recovery of materials from E-wastes and has  
 106 been regarded as one of the largest and most polluted in the world [13, 15]. The main  
 107 mode of operation at the site includes manual disassembly of obsolete electrical and  
 108 electronic products to retrieve metals which include copper and aluminum. Brigden et  
 109 al. [13] estimated that 40,000 - 250,000 people are at risk from the toxic fumes that  
 110 engulf the community as a result of the burning of used electrical appliances. The  
 111 fumes are known to cause major health complications. The water and soil from the  
 112 site are contaminated with increased concentrations of lead, plastic softeners and  
 113 dioxins which are carcinogenic.



**Fig. 1** Map of the study area showing sampling sites

116

## 117 *2.2. Experimental process*

118 The experimental process followed three main steps: (i) Determination of the physico-  
119 chemical properties of the AC, (ii) Determination of Adsorption property of the AC,  
120 and (iii) Application to samples from the polluted E-waste site.

121

### 122 *2.2.1. Source of activated carbon*

123 The cashew nut shell-based AC is one of the several ACs produced at the Climate-  
124 Environmental Research and Technology (CLERET) Laboratory, which is one of the  
125 research and development (R&D) umbrellas of Explore Scientific Innovations  
126 Limited, Ghana. CLERET Laboratory primarily focuses on developing AC cleaner  
127 production technologies. The products are generated based on optimization techniques  
128 appropriate for climate/environmental remediation and other science research, as well  
129 as several industrial applications. CLERET Laboratory is also a climate  
130 geoengineering setup aimed at developing technologies to mitigate greenhouse gas  
131 forcing of climate emanating primarily from industrial emissions.

132 In brief, the cashew nut shell-based AC was produced using physical  
133 activation, which essentially consisted of two main stages [16]: (i) Thermal pyrolysis  
134 (carbonization) of the raw material to elemental carbon in one ton stainless steel  
135 capacity reactor, with the inner and outer jackets lagged with fiber glass to minimize  
136 heat escape from the reactor. The wood-fired reactor for the pyrolytic process was  
137 carried out between 800-1000 °C, monitored by a digital temperature probe and a  
138 pyrometer, which measure core temperatures up to 1,500 °C; and (ii) oxidizing gas  
139 generated by wood-fired steam boiler, monitored by an analog temperature gage at  
140 160 °C under 7.5 atmospheres operating conditions with an analog pressure gage

141 reading to a maximum of 25 atmospheres. The activation temperature by the reactor  
142 operated between 500-600 °C. The high pressure gradient established between the  
143 steam boiler and the reactor, which expelled the steam from the former to the latter.  
144 The carbon was activated for 30 minutes, after which the activation pressure became  
145 exhausted, dropping below one atmosphere. To be consistent with experimental  
146 design and to ensure production quality, three replications were made for the two-  
147 stage process. For each replicate, 50 kg of the raw material were used.

148

#### 149 *2.2.2. Polluted samples collection*

150 The soil samples for the experiment were scooped from marked spots of selected sites  
151 at a depth of 0-15 cm using a soil auger. The collected samples were put together to  
152 form a composite sample. Three replicates were taken from each site making a total of  
153 six soil samples from the study site. The samples were put into transparent zip-locked  
154 plastic bags, labelled and transported to the laboratory for analysis. The samples were  
155 air-dried for four days, grinded into fine powder and sieved with a 2 mm sieve to  
156 remove coarse components. The resultant soil was sub-sampled for the heavy metal  
157 analysis.

158

#### 159 *2.2.3. Physico-chemical properties of the activated carbon based on particle size-* 160 *powdered activated carbon (PAC) and granular activated carbon (GAC)*

##### 161 *pH, electrical conductivity and temperature*

162 The pH was determined with the standard method ASTM 3838-80. The ASTM  
163 standard determination of pH is based on chemical reactions between the constituents  
164 of the AC and its non-carbonaceous constituents and the adsorbate containing fluid.  
165 Ten grams of the AC were weighed into a beaker and 50 ml of distilled water were

166 added. The mixture was stirred for 10 minutes to ensure proper dissolution of the  
167 sample, left for one hour for the suspended particles to settle and later filtered. The pH  
168 meter was first calibrated with standard buffer solution of pH 4.0 and 7.0. The  
169 electrode was then immersed into the solution and the pH and electrical conductivity  
170 readings were taken and recorded. The temperature of the solution was also recorded.

171

#### 172 *Bulk density*

173 A graduated cylinder was calibrated and used for the estimation of the bulk density.  
174 The cylinder was packed with the sample and compacted. The density was calculated  
175 using Eq. (1) as indicated by Meteku [17].

$$176 \quad \text{Bulk density (gcm}^3\text{)} = \frac{\text{Mass (g)}}{\text{Volume (cm}^3\text{)}} \quad (1)$$

177

#### 178 *Particle size determination*

179 By general purpose classification and based on physical properties, two types of  
180 activated carbons, i.e. powdered activated carbon (PAC) and granulated activated  
181 carbon (GAC) were produced for the study. The GAC was generated using a high-  
182 powered roller mill / hammer mill with specific mesh size. The GAC was  
183 approximately 2.0 – 4.0 mm in size corresponding to standard sieves [12, 18]. The  
184 PAC was obtained by grinding the GAC into powder using the crusher. The powdered  
185 AC was categorized into size ranges using sieves. Twenty grams of the PAC were  
186 weighed and placed on top of a set of six sieves with mesh sizes ranging from 2 mm  
187 to 71  $\mu\text{m}$ . The sieves were shaken using an aggregate stability machine for 3 minutes  
188 to allow the particles to separate into the various sieves according to their sizes. The  
189 weights of active carbon retained on each of the sieves and the bottom pan were

190 determined using ASTM STP 447B. Using the Eq. (2), the percentage weight of each  
191 category of particles retained in each sieve were computed [17].

$$192 \quad P(\%) = \frac{(S-R)}{S} \times 100 \quad (2)$$

193 Where  $P$  = percent of sample passing through the test sieve,  $R$  = weight of sample  
194 remaining on test sieve (g), and  $S$  = weight of sample used (g).

195

### 196 *Filtration rate determination*

197 After the treatment process with the digested sample and a known amount of activated  
198 carbon, the content was poured into a funnel with filter paper inserted. The filtration  
199 process was timed, that is, the time taken for all the liquid to drain through the filter  
200 paper. The filtration rate was determined using Eq. (3) [19]. After the filtrate rate  
201 determination, a vacuum filter was used in filtering in order to obtain a clear solution  
202 for further analysis.

$$203 \quad \text{Filtration rate}(m/s) = \frac{\text{Volume of liquid (ml)}}{\text{Time taken to drain}} \quad (3)$$

204

### 205 *2.3. Iodine number determination*

206 The porous structure or character of the AC produced was examined by the iodine  
207 number. The adsorption of aqueous iodine, a quick methodology for assessing the  
208 surface area of AC associated with pores greater than 1 nm was adopted in the  
209 characterization of the activated carbon produced [12, 20]. In determining the iodine  
210 number, 0.2 g of the AC was weighed into a dry flask and 40 ml of 0.1 N Iodine  
211 solution added. The mixture was swirled vigorously for 10 minutes and filtered using  
212 a Whatman No. 42 filter paper into a conical flask. Ten milliliters of the clear filtrate  
213 were taken into a conical flask; 2 ml of freshly prepared starch solution was added to  
214 the solution as an indicator and titrated with 0.05 N Sodium thiosulphate ( $\text{Na}_2\text{S}_2\text{O}_3$ )

215 until the pale yellow color of the iodine solution became colorless. The iodine number  
216 was determined using the Eq. (4) [12].

$$217 \quad \text{Iodine value (mg/g)} = \frac{(B-A) \text{ ml} \times 12.69 \times N}{\text{Weightt of sample (g)}} \quad (4)$$

218 Where  $B$  = titration of blank,  $A$  = titration of sample and  $N$  = normality of iodine (0.1  
219 N).

220

#### 221 *2.4. Preparation and analyses of soil samples*

222 A 1.0 g of each of the soil samples from the study site was measured into a digestion  
223 tube and digested with 10 ml of Ternary Solution (20 ml of  $\text{HClO}_4$ ; 500 ml of  $\text{HNO}_3$ ;  
224 50 ml of  $\text{H}_2\text{SO}_4$ ) on a hot plate at  $90^\circ\text{C}$  for 30 minutes to an hour until white fumes  
225 appeared. The digestion tube was removed from the hot plate and allowed to cool for  
226 some time and filtered into a 100 ml volumetric flask using a Whatman No. 42 filter  
227 paper. Distilled water was then added to the filtrate to make it to the 100 ml mark of  
228 the volumetric flask. PINAAcle 900T Perkin Elmer AAS was used to analyze the soil  
229 samples.

230

#### 231 *2.5. Application of activated carbon to samples from the polluted E-waste site*

232 Incremental weights (1 g, 2 g, 3 g, 4 g and 5 g) of the AC were applied to 50 ml  
233 leachates prepared from the polluted soil samples, with known initial concentrations  
234 of the metals (Cu, Pb, Cr, Cd and Fe) being investigated and kept for 24 hours. The  
235 adsorption of the metals from the leachates by the AC was determined after the 24  
236 hours; 20 ml of the samples (containing AC and leachates) were diluted to 100 ml and  
237 the respective metal contents after the treatment measured using AAS and the  
238 adsorption efficiency estimated using the Freundlich Adsorption Theorem [21] as  
239 indicated in Eq. (5).

240 
$$\text{Log } q_e = \text{log } k + (1/n) \text{ log } C_e \quad (5)$$

241 where;

- 242 •  $q_e$  is the amount of adsorbate (pollutant) adsorbed per AC dosage.
- 243 •  $C_e$  is the equilibrium concentration of adsorbate (pollutant) in water.
- 244 •  $k$  and  $(1/n)$  are empirical constants (Freundlich parameters).
  - 245 i.  $k$  is a value which is equal to the intercept where a larger value of  $k$
  - 246 indicates good adsorption efficiency for the particular AC.
  - 247 ii.  $1/n$  is the value of slope of the plot of  $\text{log } q_e$  versus  $\text{log } C_e$ , a larger value of
  - 248  $1/n$  indicates a more effective adsorption.

249

250 The Freundlich's adsorption efficiency is expressed from the graph as  $X/m = K_f C_e^{1/n}$ .

251 Using the adsorbance obtained based on Beer Lambert's Law, the concentrations were  
252 calculated and the responses of the standards used to determine the exact performance  
253 of the machine and accurate values of each element. Calculations of the  
254 concentrations of heavy metals were done using Eq. (6) [17].

255 
$$\text{Metal (mg/kg)} = \frac{\text{Conc. of analytical measurement} \times \text{Volume of extraction}}{\text{Weight of sample (g)}} \quad \text{Eq. (6)}$$

256

## 257 2.6. Statistical analysis

258 Principal Component Analysis (PCA) and the Analysis of Variance (ANOVA) were  
259 used to test the efficiency and difference of the ACs. Differences in the treatments  
260 were tested using Least Significant Difference Test (LSD). Significant differences  
261 were reported at p-values of  $\leq 0.05$ . Graphical representations in the forms of charts  
262 were used to illustrate results from the laboratory analysis and test results.

263

264

### 265 **3. Results and discussion**

#### 266 *3.1. Properties of the activated carbon*

##### 267 *3.1.1. Physical properties*

268 The temperature, pH, electrical conductivity, bulk density, iodine number and  
269 filtration rate of the activated carbons used (GAC and PAC) in the study are presented  
270 in Table 1. Temperature of the AC ranged from 26.90 to 27.30 °C with a mean of  
271  $27.10 \pm 0.15$  °C. Mean temperatures recorded for the GAC and PAC were  $27.30 \pm$   
272  $0.01$  °C and  $27.10 \pm 0.00$  °C, respectively. The AC generally had alkaline properties  
273 with mean pH values of  $9.60 \pm 0.00$  and  $9.55 \pm 0.07$  for the GAC and PAC,  
274 respectively. The bulk density on other hand was  $0.43 \pm 0.01$  for the GAC and  $0.41 \pm$   
275  $0.01$  for the PAC. The GAC had higher temperature, pH and bulk density than the  
276 PAC whereas the PAC had higher electrical conductivity, iodine number and filtration  
277 rate. The electrical conductivity ranged from 154.00 to 435.00  $\mu\text{S}/\text{cm}$  and mean  
278 values were  $431.50 \pm 0.71$  and  $435.00 \pm 0.00$   $\mu\text{S}/\text{cm}$  for GAC and PAC, respectively.  
279 The mean iodine number and filtration rate were  $719.14 \pm 19.43$  mg/g and  $0.11 \pm$   
280  $0.15$ , respectively.

281

282 **Table 1** Descriptive statistics of the physical properties of the GAC and PAC

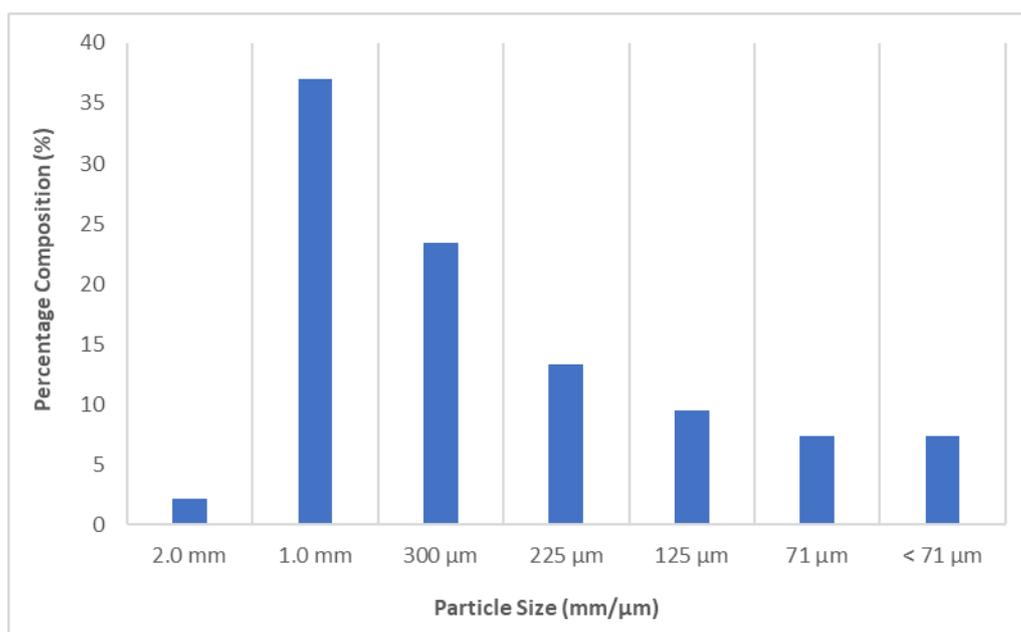
| Parameter                       |                                 | N | Mean   | Std. Deviation | Std. Error | 95% Confidence Interval |             | Minimum | Maximum |
|---------------------------------|---------------------------------|---|--------|----------------|------------|-------------------------|-------------|---------|---------|
|                                 |                                 |   |        |                |            | Lower Bound             | Upper Bound |         |         |
| Temperature (°C)                | Granular activated carbon (GAC) | 3 | 27.30  | 0.0071         | 0.0050     | 27.23                   | 27.36       | 27.29   | 27.30   |
|                                 | Powdered activated carbon (PAC) | 3 | 27.10  | 0.0000         | 0.0000     | 27.10                   | 27.10       | 27.10   | 27.10   |
|                                 | Total                           | 6 | 27.10  | 0.1493         | 0.0528     | 26.97                   | 27.22       | 26.90   | 27.30   |
| pH                              | Granular activated carbon (GAC) | 3 | 9.60   | 0.0000         | 0.0000     | 9.60                    | 9.60        | 9.60    | 9.60    |
|                                 | Powdered activated carbon (PAC) | 3 | 9.55   | 0.0707         | 0.0500     | 8.91                    | 10.19       | 9.50    | 9.60    |
|                                 | Total                           | 6 | 7.56   | 2.1520         | 0.7609     | 5.76                    | 9.36        | 5.50    | 9.60    |
| Electrical conductivity (µS/cm) | Granular activated carbon (GAC) | 3 | 431.50 | 0.7071         | 0.5000     | 425.15                  | 437.85      | 431.00  | 432.00  |
|                                 | Powdered activated carbon (PAC) | 3 | 435.00 | 0.0000         | 0.0000     | 435.00                  | 435.00      | 435.00  | 435.00  |
|                                 | Total                           | 6 | 294.20 | 148.6599       | 52.5592    | 169.92                  | 418.48      | 154.00  | 435.00  |
| Bulk density                    | Granular activated carbon (GAC) | 3 | 0.43   | 0.0071         | 0.0050     | 0.36                    | 0.49        | 0.42    | 0.43    |
|                                 | Powdered activated carbon (PAC) | 3 | 0.41   | 0.0071         | 0.0050     | 0.34                    | 0.47        | 0.40    | 0.41    |
|                                 | Total                           | 6 | 0.44   | 0.0285         | 0.0101     | 0.41                    | 0.46        | 0.40    | 0.48    |
| Iodine (mg/g)                   | Granular activated carbon (GAC) | 3 | 730.26 | 0.0071         | 0.0050     | 730.19                  | 730.32      | 730.25  | 730.26  |
|                                 | Powdered activated carbon       | 3 | 742.96 | 0.0071         | 0.0050     | 742.89                  | 743.02      | 742.95  | 742.96  |

|            |                                 |   |        |         |        |        |        |        |        |
|------------|---------------------------------|---|--------|---------|--------|--------|--------|--------|--------|
|            | (PAC)                           |   |        |         |        |        |        |        |        |
|            | Total                           | 6 | 719.14 | 19.4284 | 6.8690 | 702.90 | 735.38 | 698.49 | 742.96 |
| Filtration | Granular activated carbon (GAC) | 3 | 0.18   | 0.2036  | 0.1440 | -1.65  | 2.01   | 0.03   | 0.32   |
|            | Powdered activated carbon (PAC) | 3 | 0.20   | 0.2348  | 0.1660 | -1.91  | 2.31   | 0.04   | 0.37   |
|            | Total                           | 6 | 0.11   | 0.1461  | 0.0517 | -0.13  | 0.23   | 0.03   | 0.37   |

283

284 3.1.2. Particle sizes

285 Percentage composition of the various particle sizes of the AC produced is presented in Fig.  
286 2. The composition of particles by size was in the order: 1 mm > 300 μm > 225 μm > 125 μm  
287 > 71 μm > (< 71 μm) > 2 mm. Particles size of 1 mm, 300 μm and 225 μm dominated  
288 (73.8%). PAC consisted of finer carbon particles of 0.177 mm mesh size (95 – 100%). GAC  
289 defined as the AC being retained on a 0.297 mm mesh size, ranged in sizes 8×20, 20×40 or  
290 8×30 for liquid phase applications and 4×6, 4×8 or 4×10 for vapor phase applications. A  
291 20×40 GAC thus consists of particles capable of passing through a standard U.S Mesh Size  
292 No. 20 sieve (0.84 mm) (specified as 85% passing) but retained by a Standard Mesh Size No.  
293 40 sieve (0.42 mm) (specified as 95% retained). Powdered or fine granules less than 1.0 mm  
294 in size with an average diameter between 0.15 and 0.25 mm are the most active carbons due  
295 to their large surface to volume ratios and small diffusion distances. GAC on the other hand  
296 has lower external surface. Diffusion of the adsorbate is therefore a key factor in the use of  
297 GAC for adsorption. GACs are commonly used for adsorption of gas and vapour as a result  
298 of their high diffusion rate.



299

300

**Fig. 2** Size composition of the activated carbon

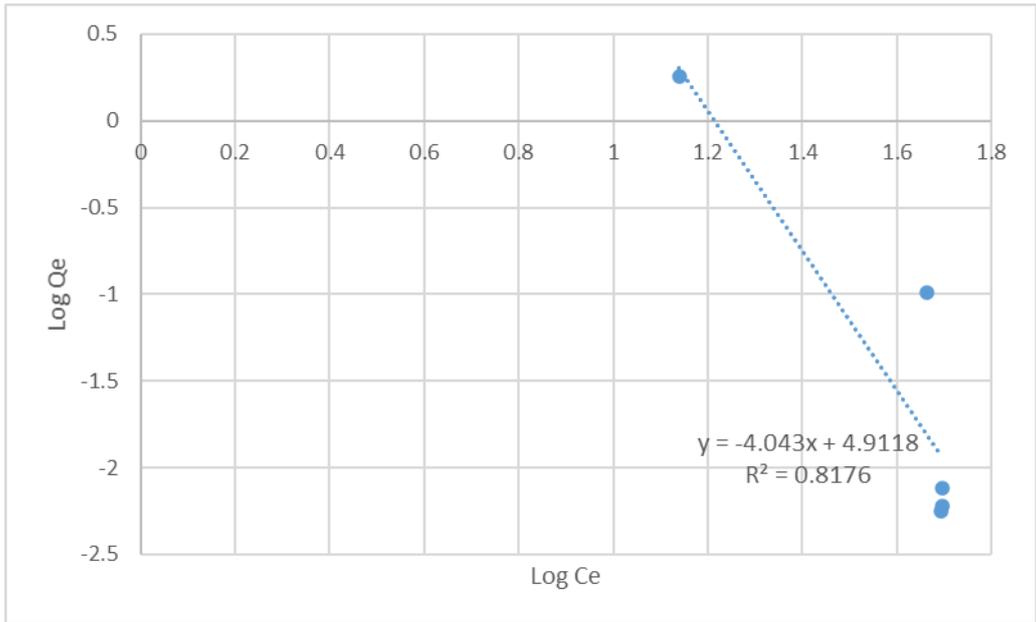
301

302 *3.1.3. Adsorption isotherm parameters*

303 The adsorption isotherms for copper (Cu), iron (Fe) cadmium (Cd), chromium (Cr), and lead  
304 (Pb) are presented in Figs. 3 – 7. The occurrence of the metals adsorption from the treated  
305 samples is indicated by the straight-line plot. From the graphs, the coefficients of  
306 determination ( $R^2$ ) are a good indication of the quality of adsorption of the heavy metals by  
307 the activated carbon. Higher  $R^2$  values imply higher adsorption rates and Table 2 shows the  
308 adsorption rates obtained. Adsorption isotherm measures the amount of substance (in this  
309 case heavy metal) adsorbed per unit weight of adsorbent (AC) to adsorbent amount remaining  
310 in the sample solution [21]. Adsorption isotherm experiment was conducted to determine the  
311 feasibility and efficiency of an adsorption treatment for the removal of the heavy metals using  
312 the cashew-based AC. The quality of the adsorption of specific heavy metal by the AC which  
313 is shown by the graph of adsorption isotherm is determined by the coefficient of  
314 determination ( $R^2$ ), and to a large extent the slope of the linear plot.

315 From the results, the  $R^2$  for the tested metals range from the least value of 0.7511 for  
316 Cd to a maximum of 0.9754 for Pb. The values of the  $R^2$  were in the order: Pb > Fe > Cr >  
317 Cu > Cd. The value of  $1/n$  was obtained from the slope of the linear plot while the  $K_f$  were  
318 obtained by taking the antilog value of  $\log C_e$ . Large adsorption constant ( $K_f$ ) values are  
319 indicative of greater adsorption capacity while the slope ( $1/n$ ) measures the strength of the  
320 activated carbon used. It can therefore be concluded that all the metals (copper, iron,  
321 cadmium, chromium, lead) tested could be reduced in the samples by the cashew-based  
322 activated carbon.

323

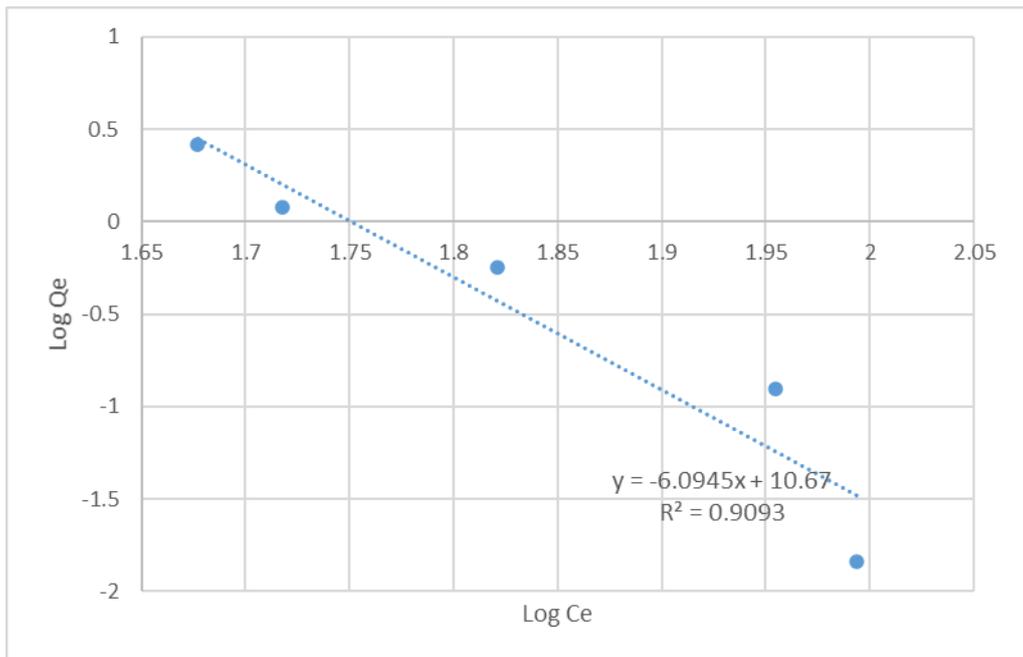


324

**Fig. 3** Adsorption isotherm for copper

325

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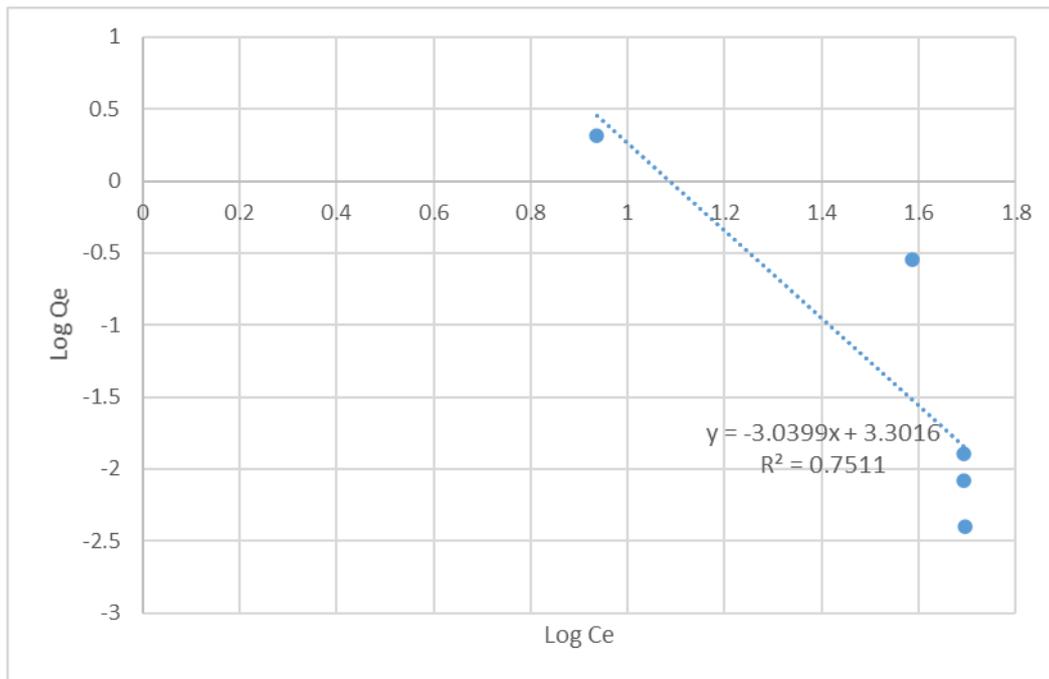


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**Fig. 4** Adsorption isotherm for iron

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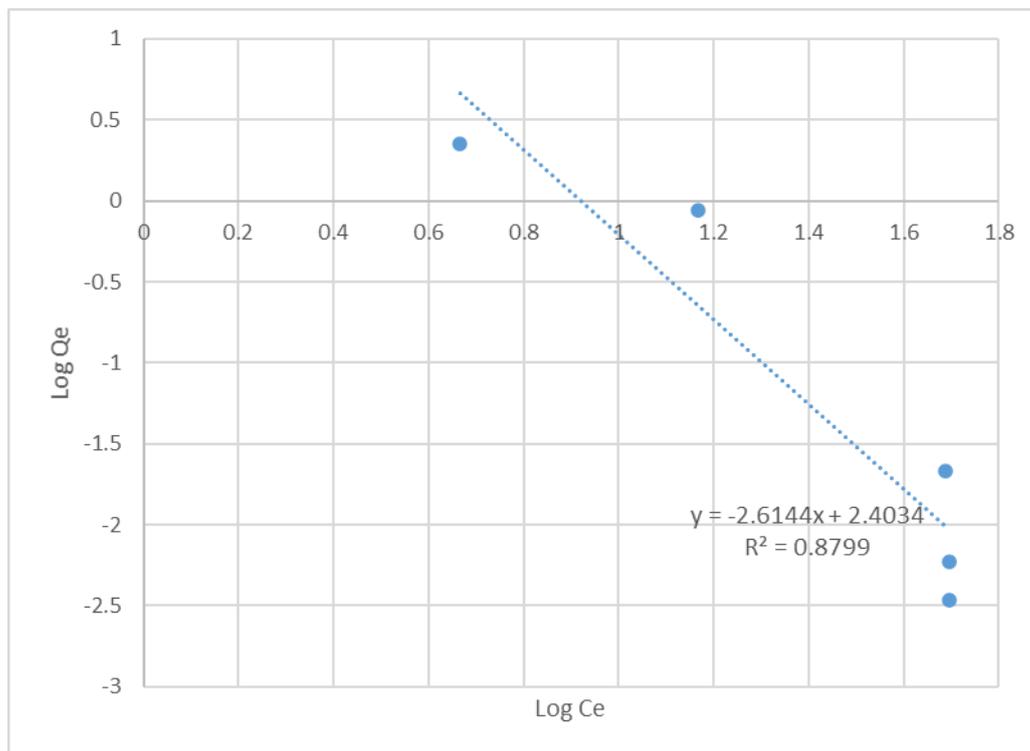


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332

**Fig. 5** Adsorption isotherm for cadmium

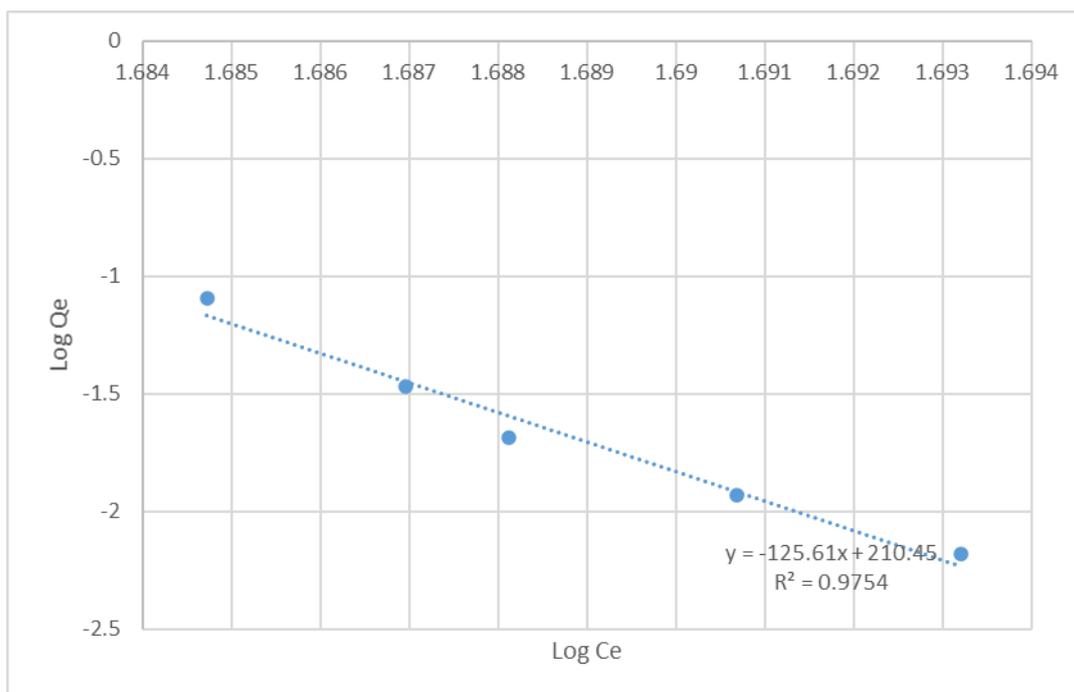


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335

**Fig. 6** Adsorption isotherm for chromium



336

337

**Fig. 7** Adsorption isotherm for lead

338

**Table 2** Summary of the adsorption isotherms for the metals considered

| Type of adsorbent | Slope  | Intercept ( $K_f$ ) | $R^2$  | Equation                        |
|-------------------|--------|---------------------|--------|---------------------------------|
| Copper            | 4.043  | 81620.6             | 0.8176 | $X/m = 81620.6 Ce^{4.043}$      |
| Iron              | 6.0945 | $4.67e^{10}$        | 0.9093 | $X/m = 4.67e^{10} Ce^{6.0945}$  |
| Cadmium           | 3.0399 | 2002.63             | 0.7511 | $X/m = 20002.6 Ce^{3.039}$      |
| Chromium          | 2.6144 | 253.16              | 0.8799 | $X/m = 253.16 Ce^{2.4034}$      |
| Lead              | 125.61 | $2.82e^{210}$       | 0.9754 | $X/m = 2.82e^{210} Ce^{125.61}$ |

340

### 341 3.2. Levels of metals in the soil samples

#### 342 3.2.1. Metal levels in untreated soil samples

343 Fig. 8 shows the mean metal concentrations of the soil samples before treatment with the

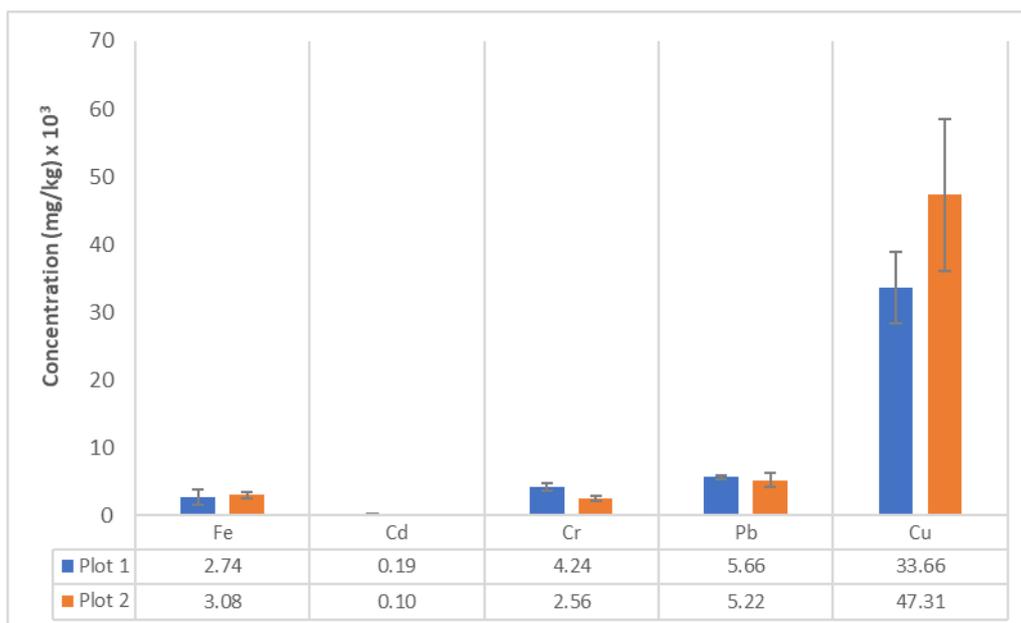
344 activated carbon. Iron recorded mean concentrations of  $2740 \pm 1.08$  and  $3083.67 \pm 0.45$

345 mg/kg for plots 1 and 2, respectively. Mean Pb concentrations in the untreated soil samples

346 were respectively 5657.33 mg/kg and 5218.67 mg/kg for plots 1 and 2. The mean  
347 concentration of Pb at both plots 1 and 2 exceeded the WHO/FAO acceptable maximum limit  
348 of 50.00 mg/kg for soils [22]. Comparatively, these concentrations were several times higher  
349 than those reported near similar E-waste recycling sites in Ibadan, Nigeria [23] and in Guiyu,  
350 China [24]. Mean Cu levels were  $33663.33 \pm 5.2888$  and  $47313.33 \pm 11.2324$  mg/kg,  
351 respectively for plots 1 and 2. These concentrations also exceeded the acceptable limit of 100  
352 mg/kg. Similarly, the mean concentrations of Cd ( $194.20 \pm 0.09$  and  $97.17 \pm 0.01$  mg/kg) and  
353 Cr ( $4237.33 \pm 0.59$  and  $2561 \pm 0.33$  mg/kg) for the plots 1 and 2 respectively, exceeded the  
354 WHO/FAO acceptable levels for soils [22]. These results are consistent with that of Yeboah  
355 [9] who indicated that the concentrations of heavy metals measured at Agbogbloshie were  
356 significantly higher than that of the EPA in Canada and Dutch environmental standards.

357         Copper and lead constituted the two major heavy metals in the soil samples prior to  
358 the application of the carbons. Cadmium, chromium and lead recorded comparatively higher  
359 concentrations in all the soil samples from plot 1. The concentrations of the metals in the soil  
360 samples were in the order: Cu > Pb > Cr > Fe > Cd. The increased levels of heavy metals  
361 contamination can be attributed to the burning of E-waste materials such as used computers,  
362 refrigerators, cables, batteries, among others. Using the Eigen values extracted from the PCA,  
363 nearly eighty five percent (84.6%) of the total variation in the dataset can be explained by  
364 three components, namely Pb, Fe and Cr (Table 3). Lead contributed the highest (33.9%),  
365 followed by iron (27.5%) and chromium (23.2%) with Eigen values 1.697, 1.373 and 1.159,  
366 respectively. This finding from the PCA confirms the order of metals from the adsorption  
367 isotherms using the  $R^2$  values.

368



369

370

**Fig. 8** Mean concentrations of metals before treatment

371

372 **Table 3** Varimax rotated factor loadings and communalities of soil metals

|                        | PC 1   | PC 2   | PC 3   | Commonalities |
|------------------------|--------|--------|--------|---------------|
| Copper                 | .799   | .470   | -.122  | .874          |
| Iron                   | -.238  | .814*  | .133   | .737          |
| Cadmium                | .541   | -.622  | -.241  | .738          |
| Chromium               | -.125  | -.286  | .930*  | .962          |
| Lead                   | .833*  | .143   | .451   | .917          |
| Eigen value            | 1.697  | 1.373  | 1.159  |               |
| Variance (%)           | 33.940 | 27.454 | 23.174 |               |
| Cumulative Percent (%) | 33.940 | 61.394 | 84.569 |               |

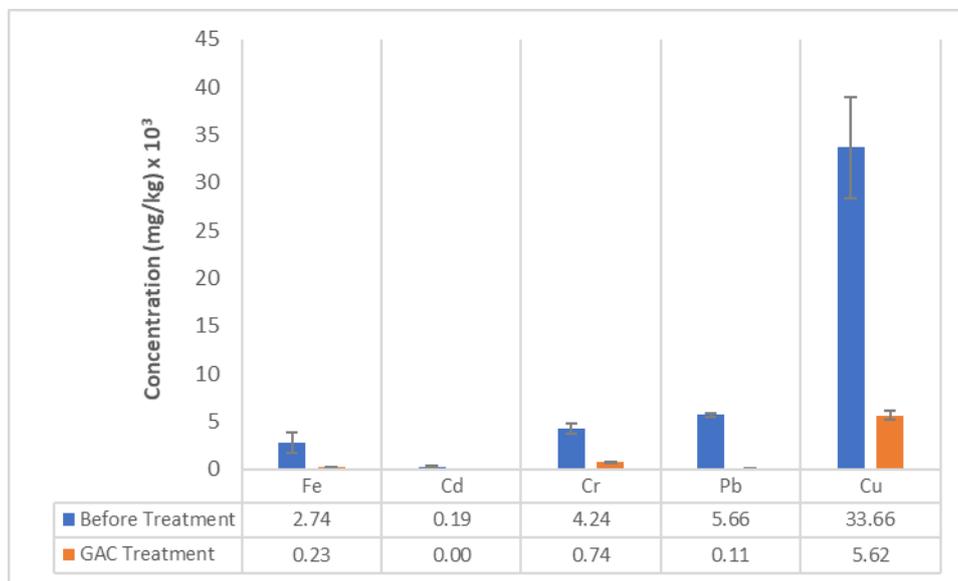
373 \* *Significant values*

374

### 375 3.2.2. Metal concentrations in treated samples

376 Figs. 9 and 10, respectively show the significant detoxification effect of the GAC on the  
 377 metals considered. The results show a significant reduction in the concentrations of all the  
 378 metals in the samples of both plots after treatment with GAC. The adsorption trend remains  
 379 similar for the two plots 1 and 2 when PAC treatment was applied (Figs. 11 and 12).

380 Cadmium removal recorded the highest efficiency (100%) for both GAC and PAC treatments  
 381 in the two plots while chromium removal recorded the lowest efficiencies with both  
 382 treatments (75.85% for GAC and 87.19% for PAC). The order of the metal concentration in  
 383 terms of their removal efficiency from the polluted soil is: Cd > Pb > Cu > Fe > Cr for GAC  
 384 and Cd > Pb > Fe > Cu > Cr for PAC (Table 4). Comparatively, powdered AC recovered  
 385 higher metal concentrations from the soils and had better adsorption rates than granular AC.  
 386 This can be attributed to the fact the PAC have greater surface areas due to their nature which  
 387 enhances adsorption of the metals considered.

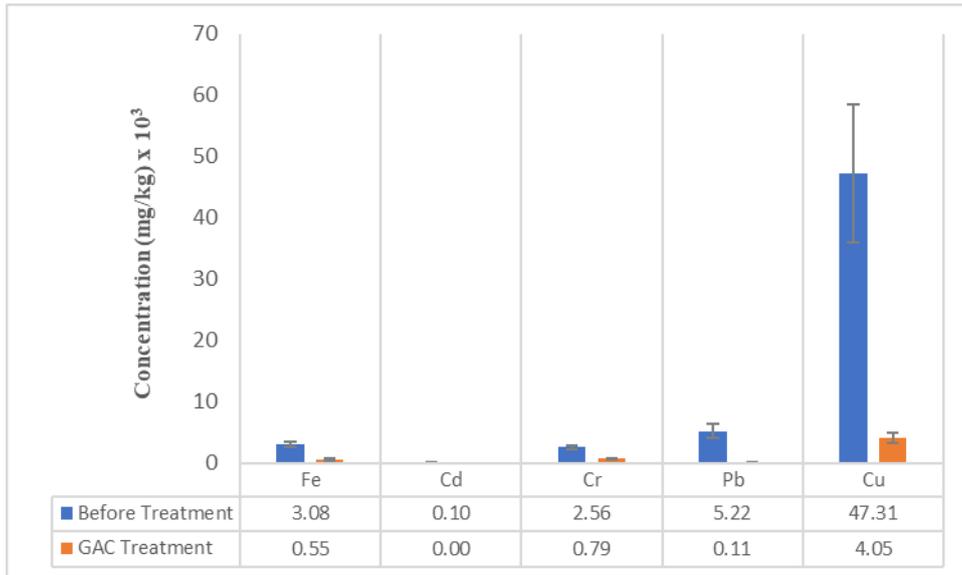


388

389

**Fig. 9** Mean metal concentrations of plot 1 samples treated with GAC

390

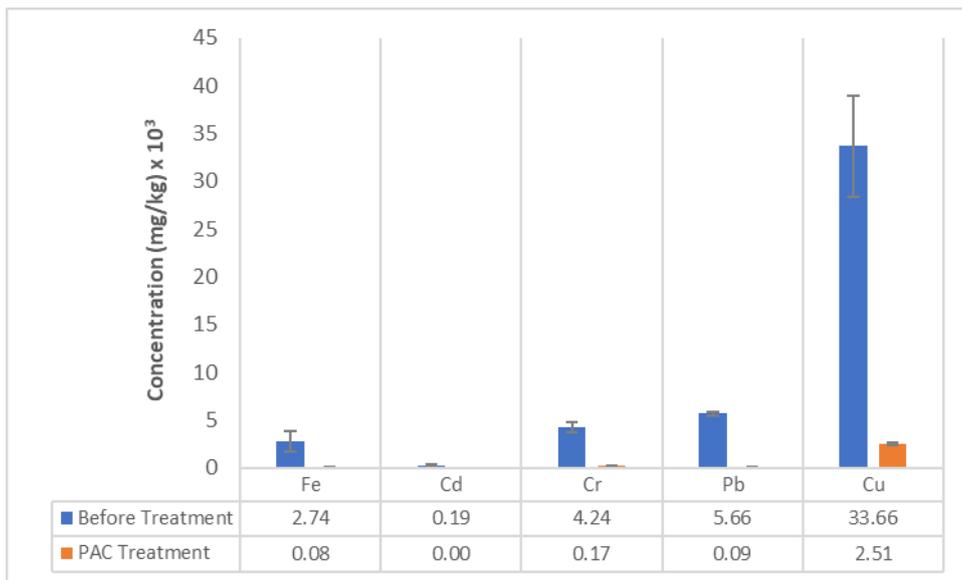


391

392

**Fig. 10** Mean metal concentrations of plot 2 samples treated with GAC

393

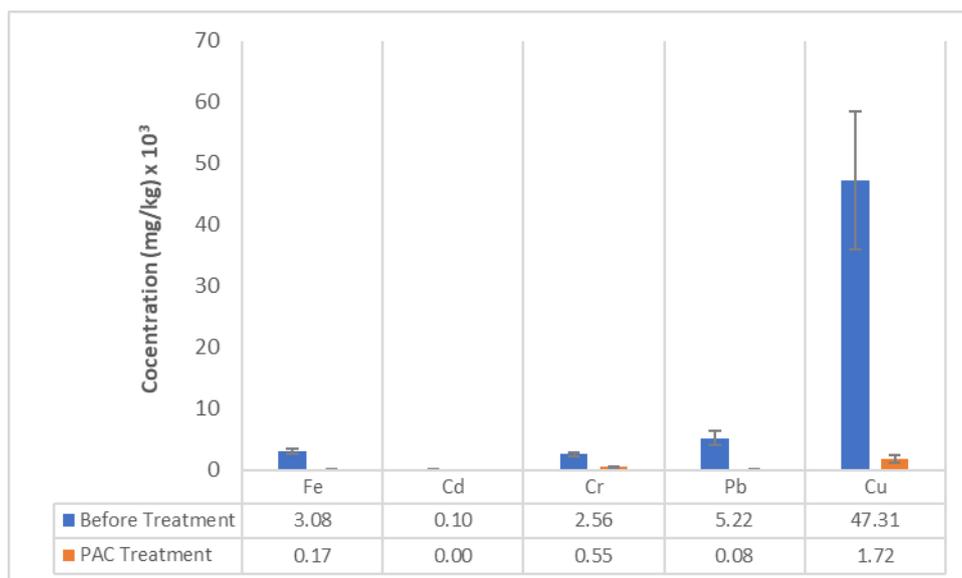


394

395

**Fig. 11** Mean metal concentrations of Plot 1 samples treated with PAC

396



**Fig. 12** Metal concentrations of Plot 2 samples treated with powdered AC

397

398

399

400 **Table 4** Mean adsorption rates for the metals

| Carbon type          | Adsorption rate (%) |        |       |       |       |
|----------------------|---------------------|--------|-------|-------|-------|
|                      | Fe                  | Cd     | Cr    | Pb    | Cu    |
| Granular AC (Plot 1) | 91.44               | 100.00 | 82.47 | 87.98 | 83.29 |
| Granular AC (Plot 2) | 82.11               | 100.00 | 69.22 | 97.89 | 91.45 |
| Overall rate (GAC)   | 86.78               | 100.00 | 75.85 | 92.94 | 87.37 |
| Powdered AC (Plot 1) | 96.93               | 100.00 | 96.00 | 98.43 | 92.55 |
| Powdered AC (Plot 2) | 94.47               | 100.00 | 78.38 | 98.46 | 96.37 |
| Overall rate (PAC)   | 95.70               | 100.00 | 87.19 | 98.45 | 94.46 |

401

### 402 3.3. Effects of particle size and iodine number on adsorption rates

403 Iodine Number is used in reference to the mass of iodine adsorbed (in milligrams) per gram

404 of carbon at a residual iodine level of 0.02 N. It is a relative measure of the porosity, a helpful

405 approximation of surface area for different types of AC and the fundamental parameter for

406 determining the performance of AC [20]. Mao et al. [25] reported that the typical iodine

407 number of high-grade AC is usually greater than 1000 mg/g. In this study, the GAC's iodine

408 number was 730.25 mg/g while that of the powdered AC was 742.95 mg/g, indicating that the

409 AC was of a good quality. The iodine number of the GAC (composed of larger particles) was  
410 approximately 1.71% lower than that of PAC (composed of smaller particles). Although  
411 higher iodine numbers are indicative of higher degrees of activation, the connection between  
412 iodine number and surface area cannot be established. It differs with changes in raw material  
413 generating the carbon, processing conditions, and also pore volume distribution. Thus, there  
414 was a clear trend linking particle size and iodine number to the adsorption efficiency of both  
415 granular raw carbon and granular AC.

416 The PAC showed higher percentages of adsorption of all the metals (Fe, Cr, Pb, Ni,  
417 and Cu) compared to the granular form. The conversion of the carbon into the powdered form  
418 (smaller particle sizes) through grinding thus may have resulted in greater adsorption capacity  
419 through improvements in iodine number. The iodine numbers of the activated carbon  
420 increased by 2.7% from 730.25 to 742.95 mg/g after conversion from granular to powdered  
421 activated carbons. Similarly, the electrical conductivity improved slightly by 0.93% for the  
422 activated carbon being converted into powdered form. The increase in iodine numbers in the  
423 powdered carbons is as a result of improved activation reactions as smaller particles result in  
424 greater penetration by potassium hydroxide (KOH) for increased activation reactions [25].  
425 However, the improvements in the iodine numbers did not translate into significant variations  
426 in the adsorption capacities between the granular and powdered activated carbons in this  
427 study.

428

#### 429 *3.4. Adsorption effects of the cashew nut shell-based activated carbon*

430 All the two AC types; GAC and PAC, showed adsorption effects on the heavy metals in the  
431 soil samples tested. The GAC and PAC were efficient in adsorbing the heavy metals from the  
432 contaminated soil samples. In all the cases, Cd was below detection limit after treatment. The  
433 combined adsorption rates/adsorption efficiencies of the heavy metal ions by the respective

434 ACs for all the treatments were in the order Cd > Pb > Fe > Cu > Cr. In analyzing the effects  
 435 of the treatments in the adsorption of the heavy metals, the randomized completely block  
 436 design (RCBD) using Analysis of Variance was adopted. The design eliminates any known  
 437 source of external factors or variations that could influence the treatments. Both blocking and  
 438 treatments had significant effects on the adsorption of the heavy metals (Table 5). The  
 439 analyses further indicated that the treatment had a statistically significant detoxification effect  
 440 at 95% confidence interval ( $p \leq 0.05$ ) on the heavy metals in the E-waste sample. The  
 441 treatment is thus responsible for the overall mean adsorption rate of 93% of the heavy metals  
 442 from the E-waste sample. The Randomized Completely Block Design (RCBD) using analysis  
 443 of variance was used to test the efficiency of the different ACs. The LSD showed that no  
 444 significant difference existed in the adsorption capacities of the powdered and granular  
 445 activated carbons though the powdered carbon had a slightly better performance in removing  
 446 the heavy metals from the soil.

447

448 **Table 5** Blocking and treatment effects

| Tests of Between-Subjects Effects |                         |    |             |        |      |  |
|-----------------------------------|-------------------------|----|-------------|--------|------|--|
| Source                            | Type III Sum of Squares | df | Mean Square | F      | Sig. |  |
| Corrected Model                   | 18.533 <sup>a</sup>     | 5  | 3.707       | 5.349  | .000 |  |
| Intercept                         | 67.500                  | 1  | 67.500      | 97.403 | .000 |  |
| Treatment                         | 18.533                  | 4  | 4.633       | 6.686  | .001 |  |
| Block                             | 24.933                  | 1  | 24.933      | 6.686  | .005 |  |
| Error                             | 3.467                   | 5  | .693        |        |      |  |
| Total                             | 46.933                  | 10 |             |        |      |  |
| Corrected Total                   | 53.456                  | 11 |             |        |      |  |

a. R Squared = 0.959 (Adjusted R Squared = 0.932)

449

450

451 **4. Conclusions**

452 The study focused on the potential use of cashew nut shell-based AC for remediation of soils  
453 from E-waste polluted site from Agbogbloshie in Accra, Ghana. The AC was produced using  
454 physical activation techniques and characterized based on bulk density, particle size, iodine  
455 number, EC, porosity, and pH. Results from the application of the AC to the polluted soil  
456 sample from Agbogbloshie indicates that the AC has significant detoxification effect on  
457 heavy metals (lead, iron, copper, chromium and cadmium) in the soil collected from the E-  
458 waste polluted area. At 95% confidence interval ( $p \leq 0.05$ ), the AC is responsible for the  
459 overall elimination of 93% of the heavy metals.

460 Specifically, the GAC significantly removed the heavy metal contents of the E-waste  
461 polluted soil with percent removal efficiency in the order: Cd (100%) > Pb (93%) > Fe (87%)  
462 > Cu (87%) > Cr (76%) whereas the PAC had in this order: Cd (100%) > Pb (98%) > Fe  
463 (96%) > Cu (94%) > Cr (87%). Their adsorption isotherms depict that PAC and GAC are  
464 good adsorbents and have the potential to be used for other polluted environmental settings.

465

466

467 **Availability of data and materials**

468 All data generated or analyzed during this study are kept by the corresponding author and  
469 will be provided upon request.

470

471 **Competing interests**

472 The authors declare they have no competing interests.

473

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476 authors.

477

478 **Authors' contributions**

479 The first author conceived, designed the experiment, directed and supplied the activated  
480 carbon for the study. The second author performed the field and laboratory studies. All  
481 authors assisted in data analysis, interpretation and contributed to the writeup. All authors  
482 reviewed and approved the final manuscript.

483

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# Figures

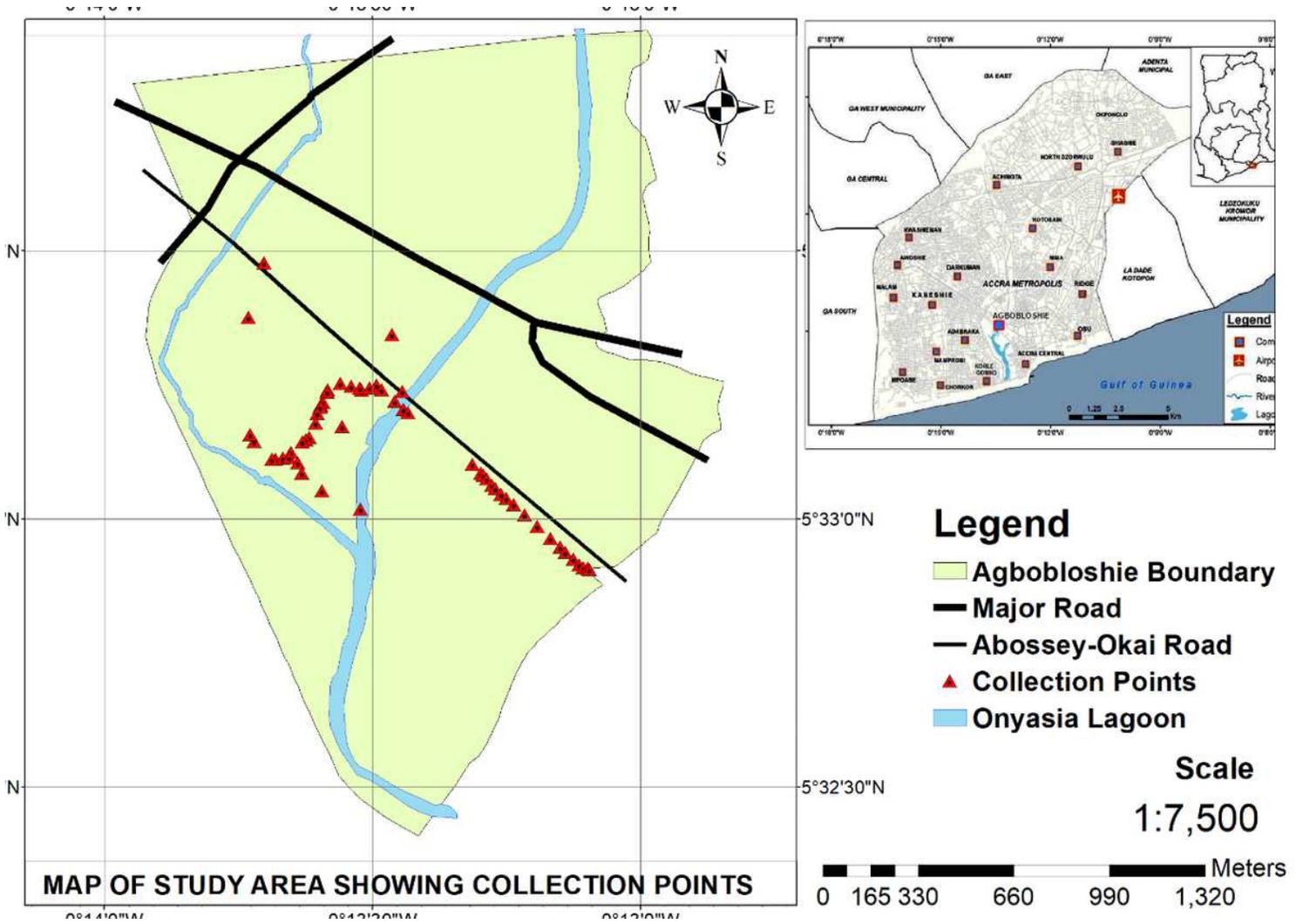
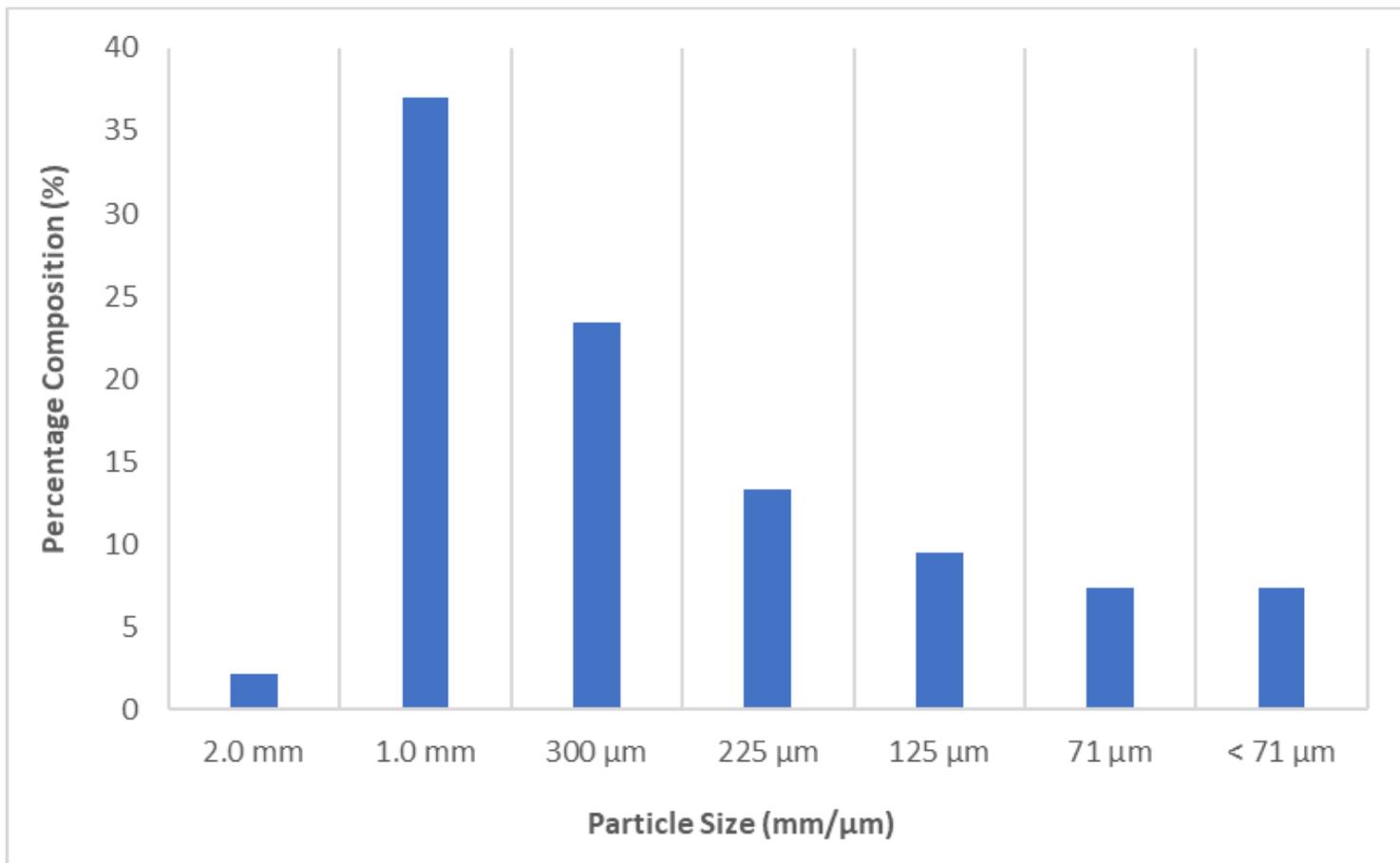


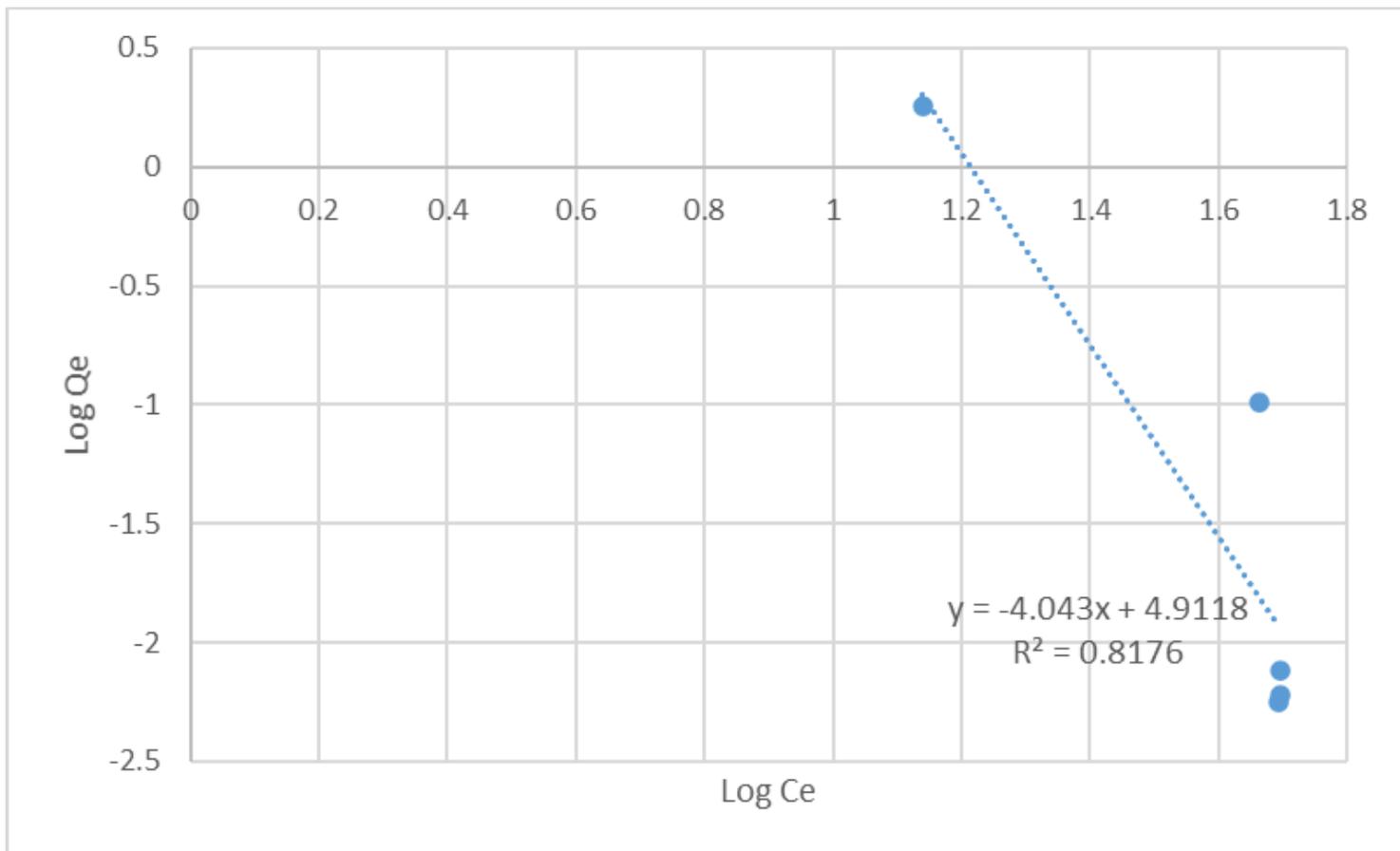
Figure 1

Map of the study area showing sampling sites



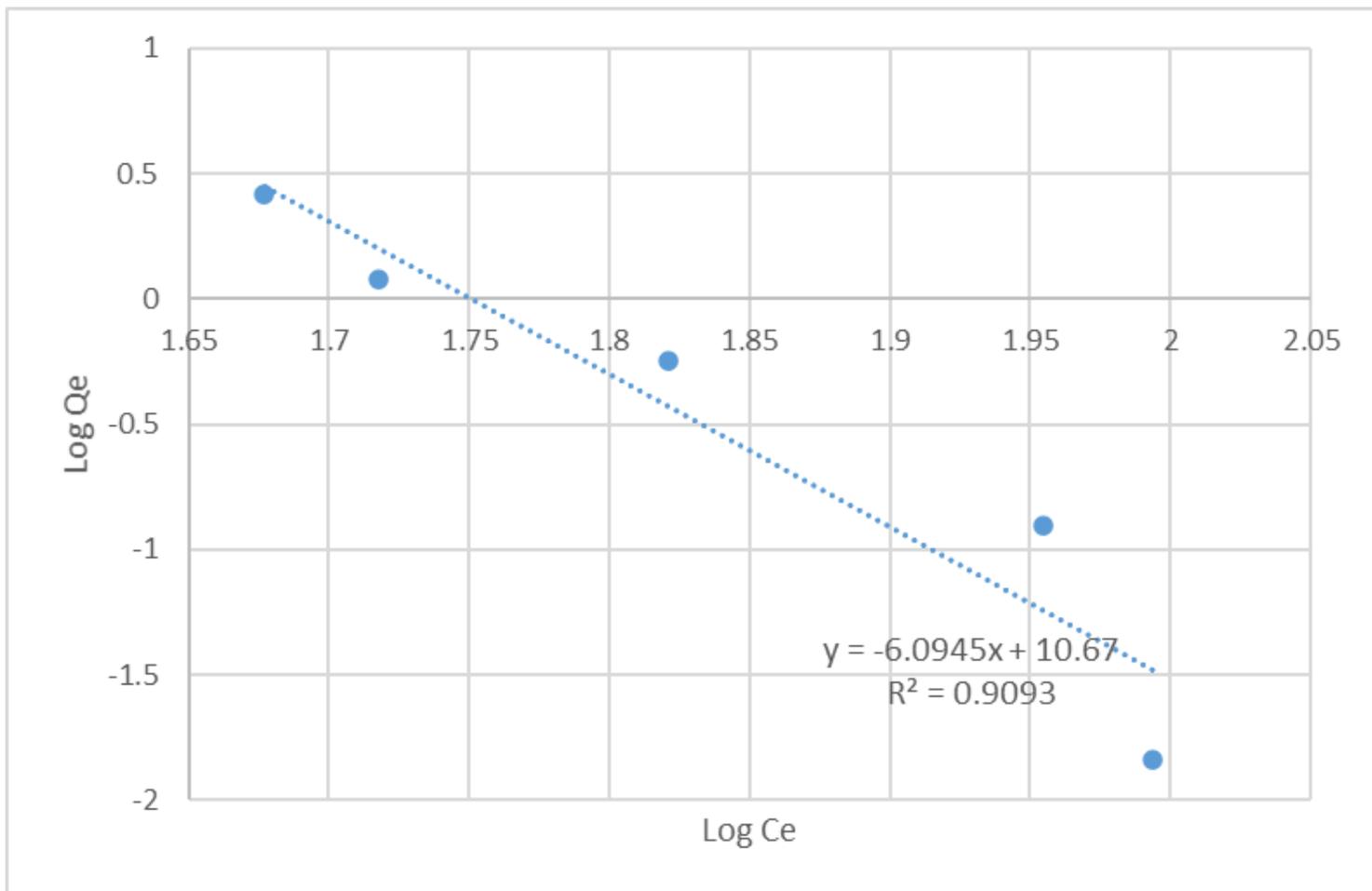
**Figure 2**

Size composition of the activated carbon



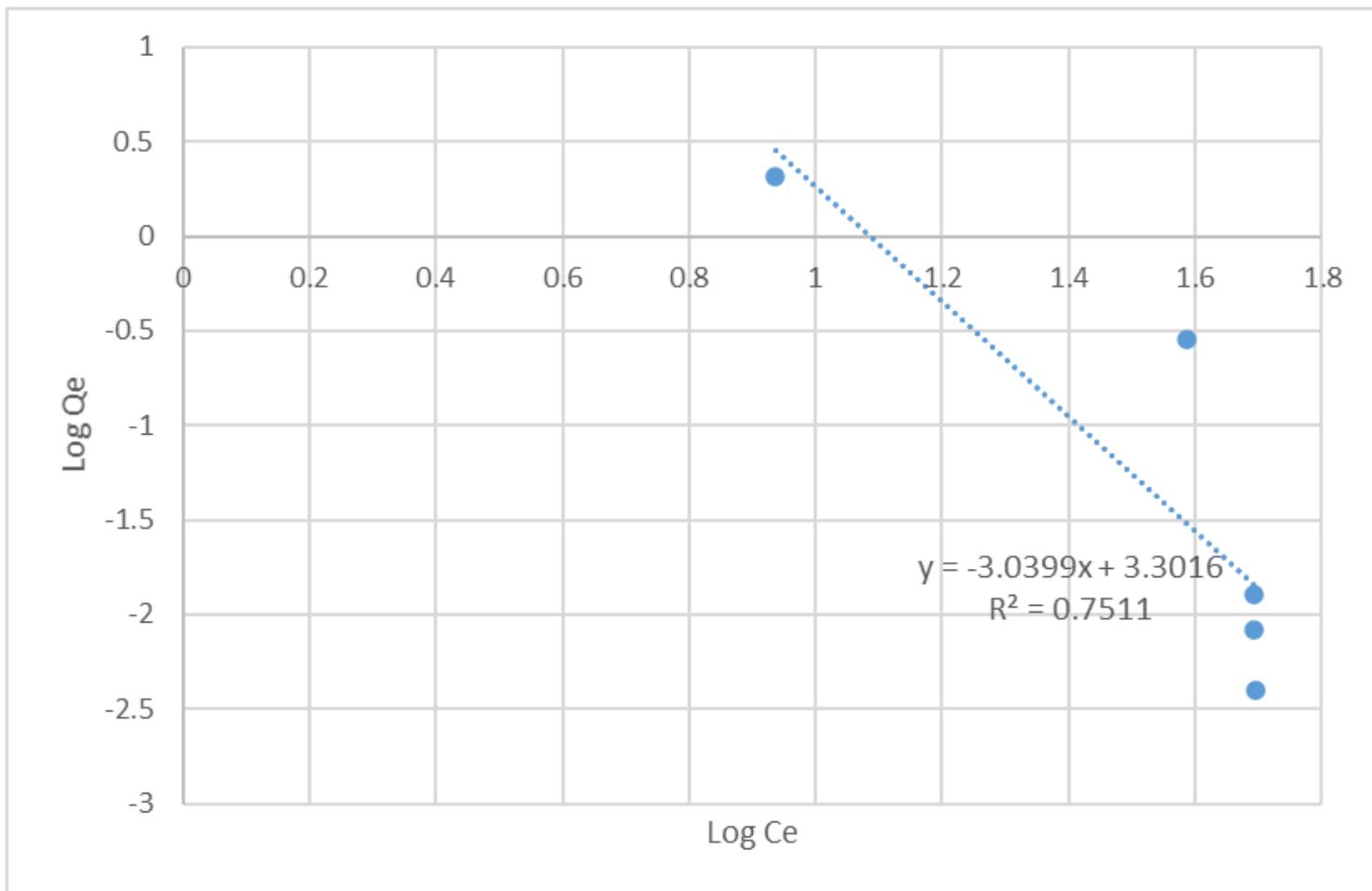
**Figure 3**

Adsorption isotherm for copper



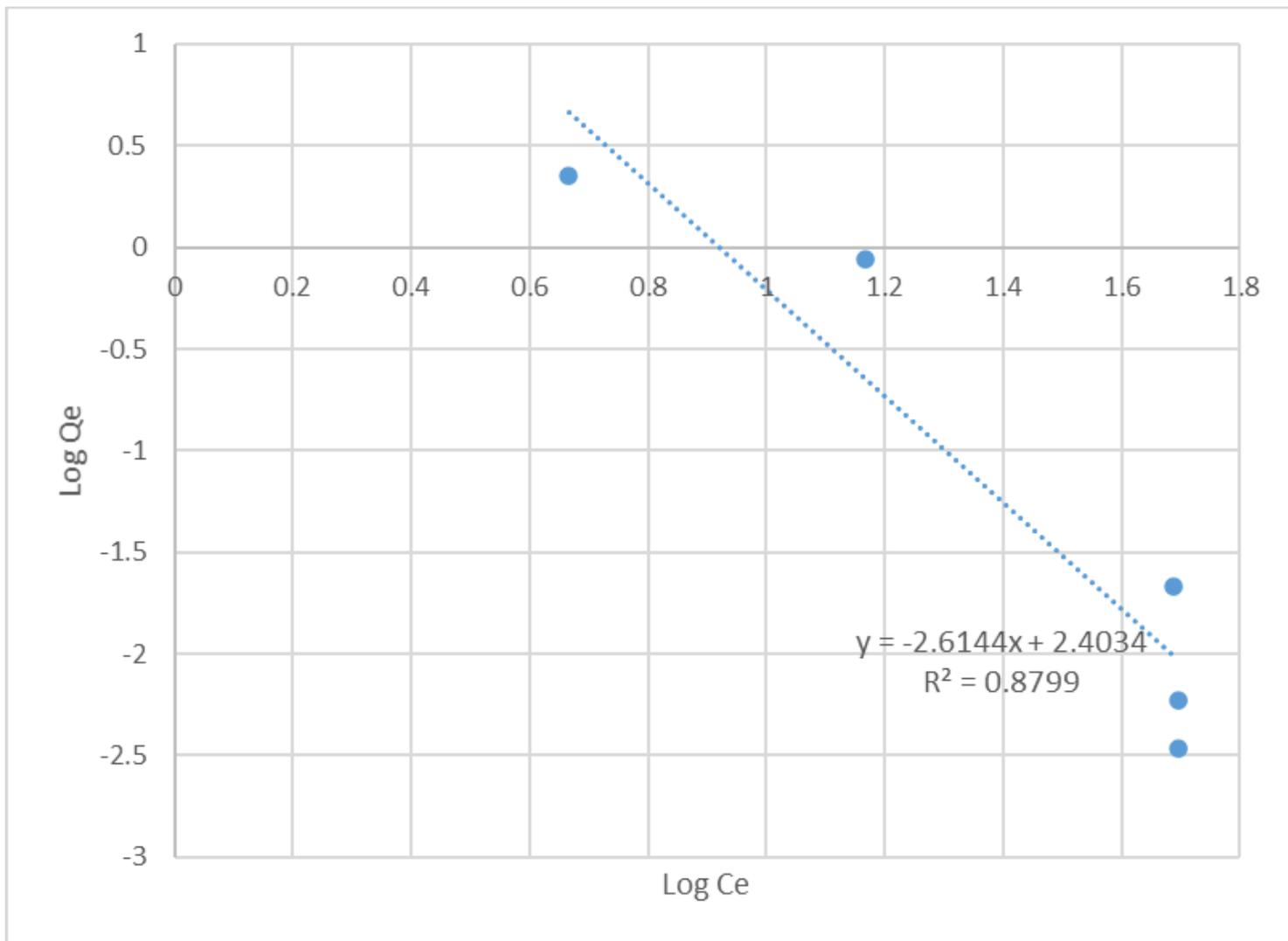
**Figure 4**

Adsorption isotherm for iron



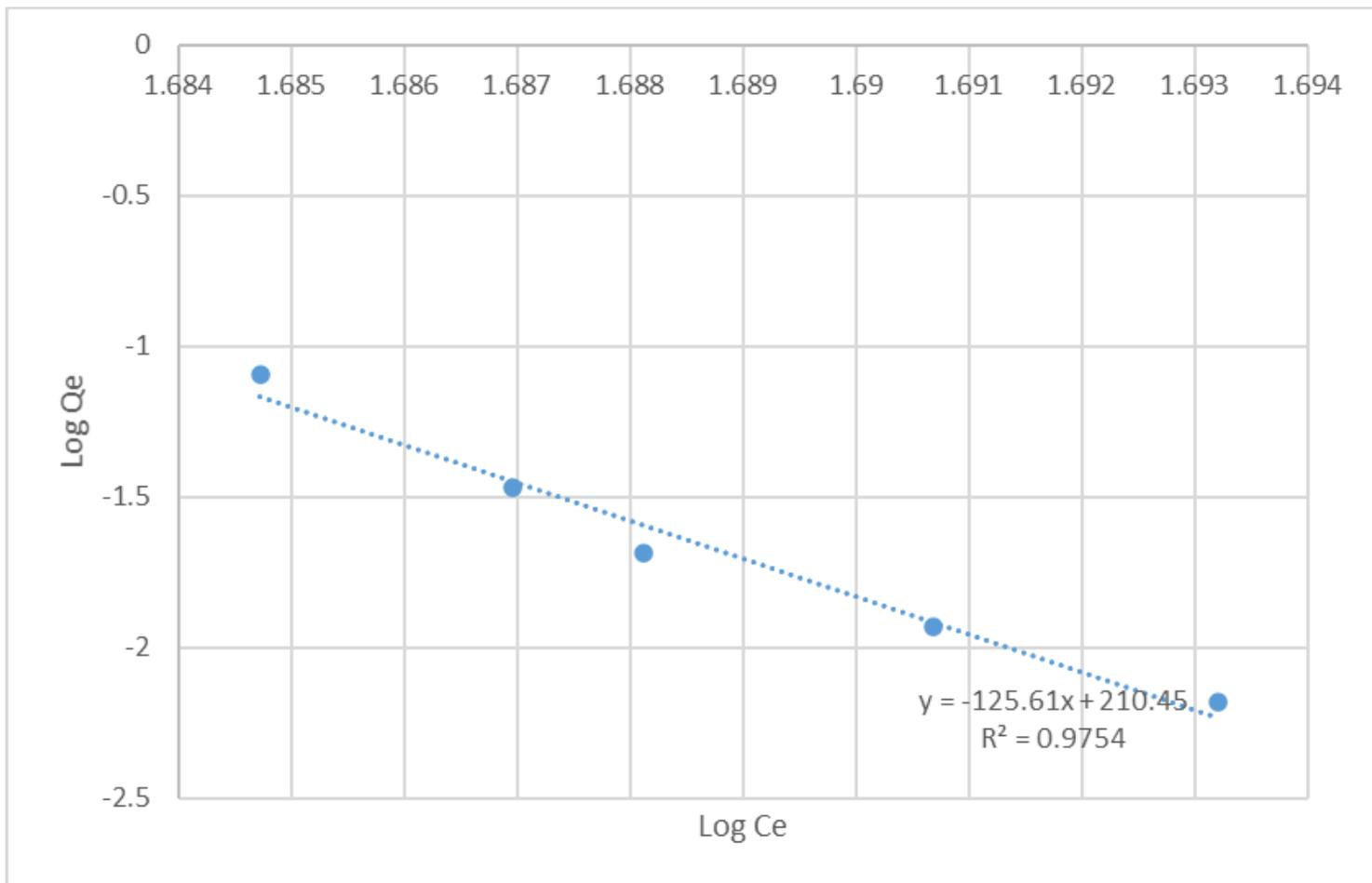
**Figure 5**

Adsorption isotherm for cadmium



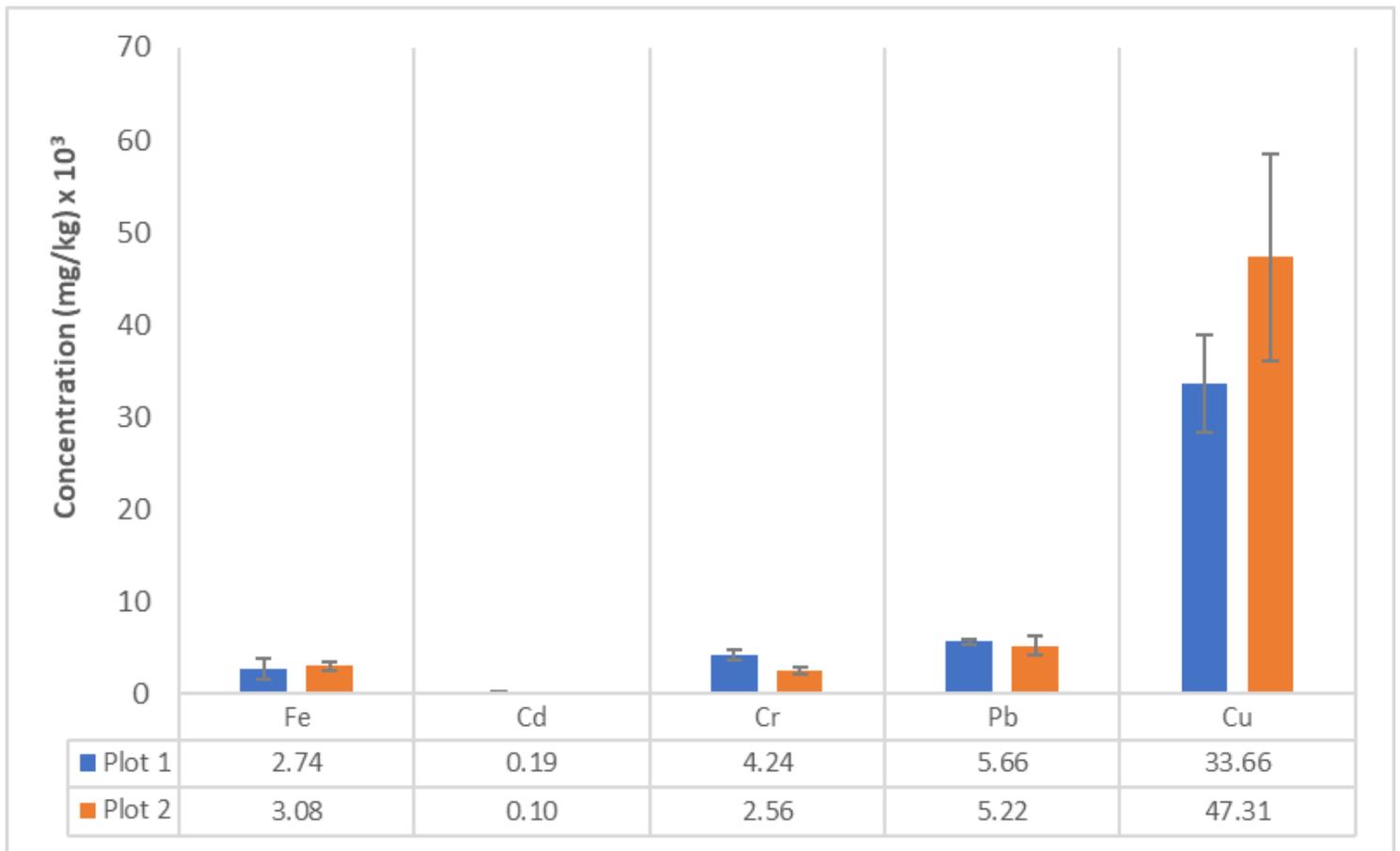
**Figure 6**

Adsorption isotherm for chromium



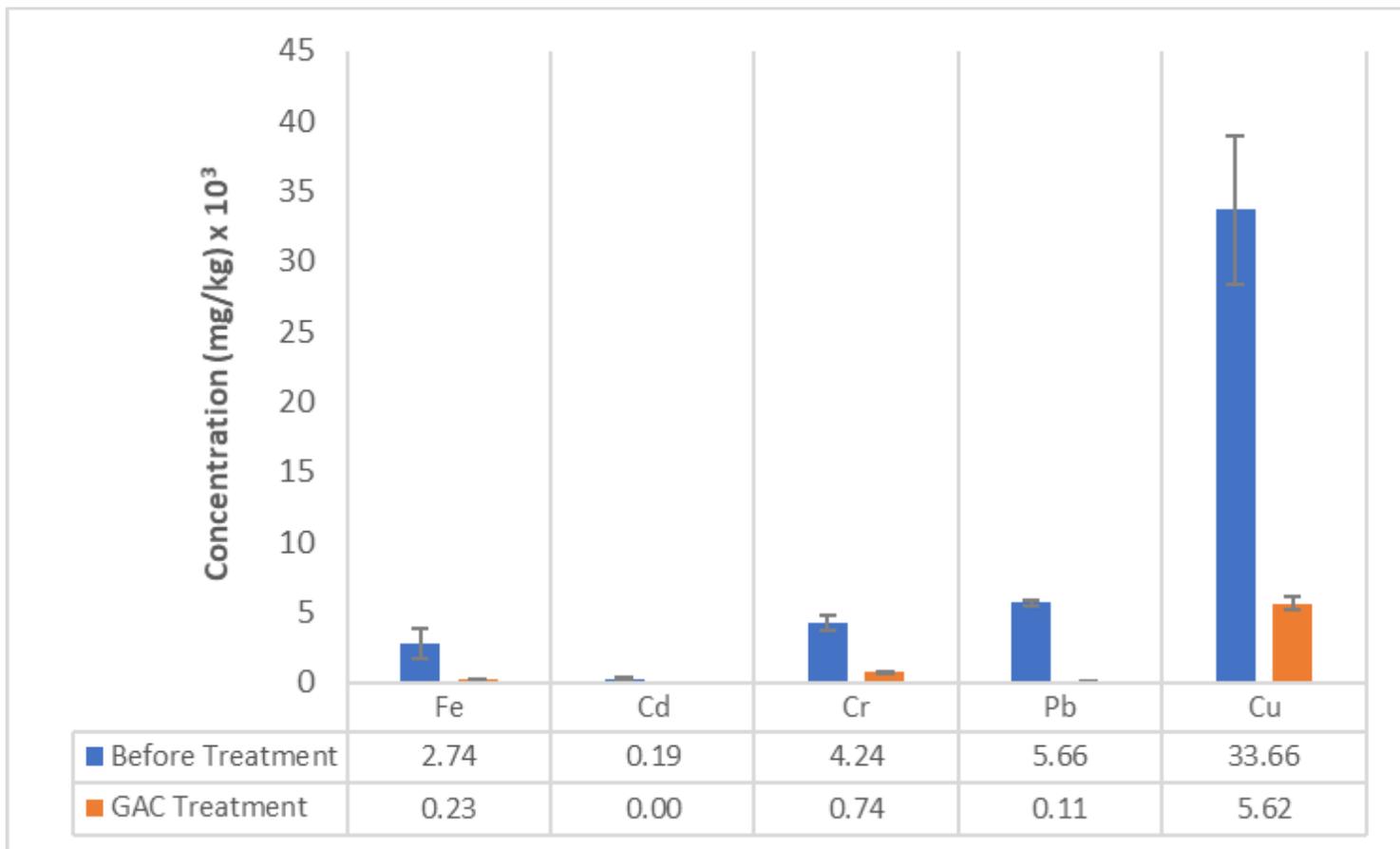
**Figure 7**

Adsorption isotherm for lead



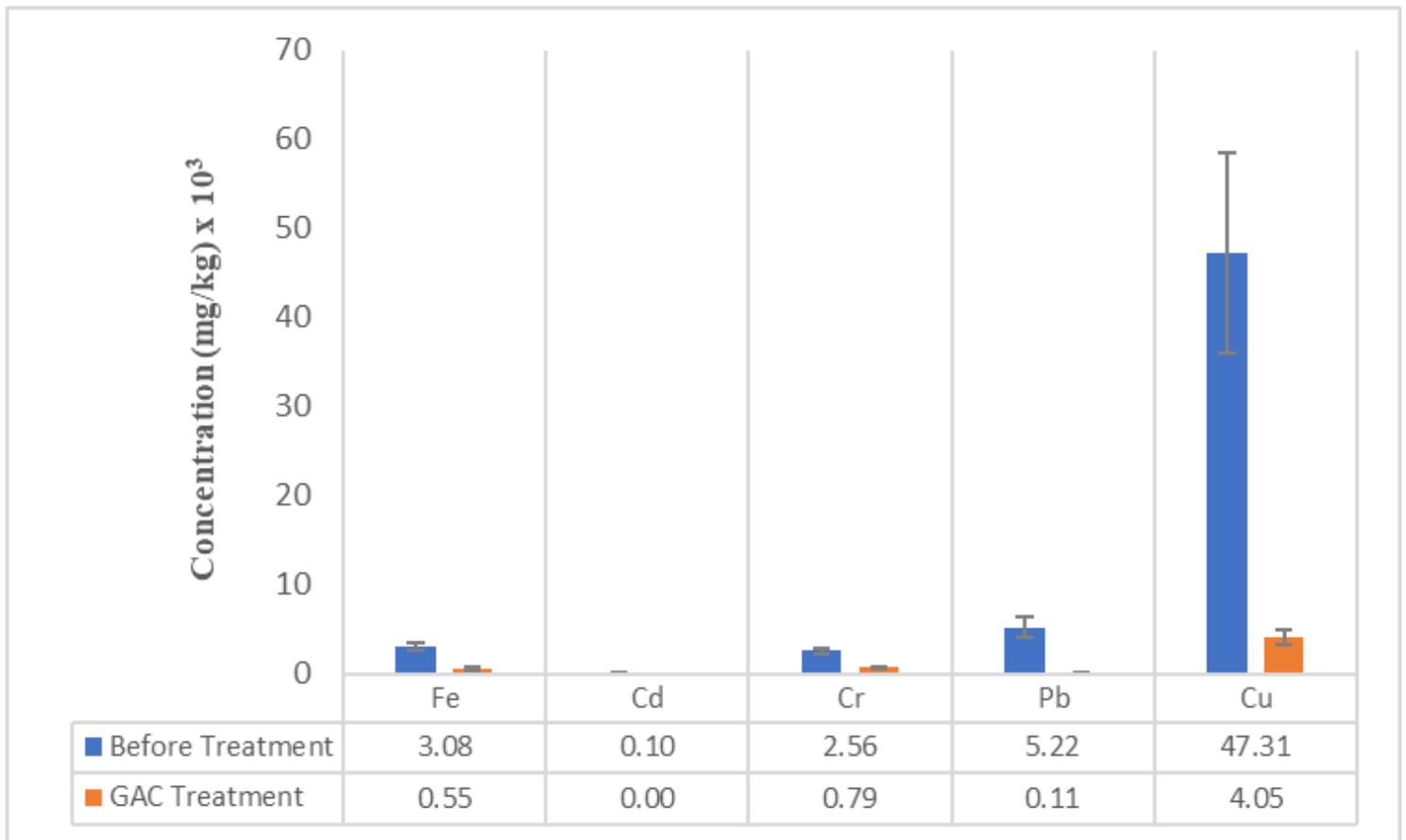
**Figure 8**

Mean concentrations of metals before treatment



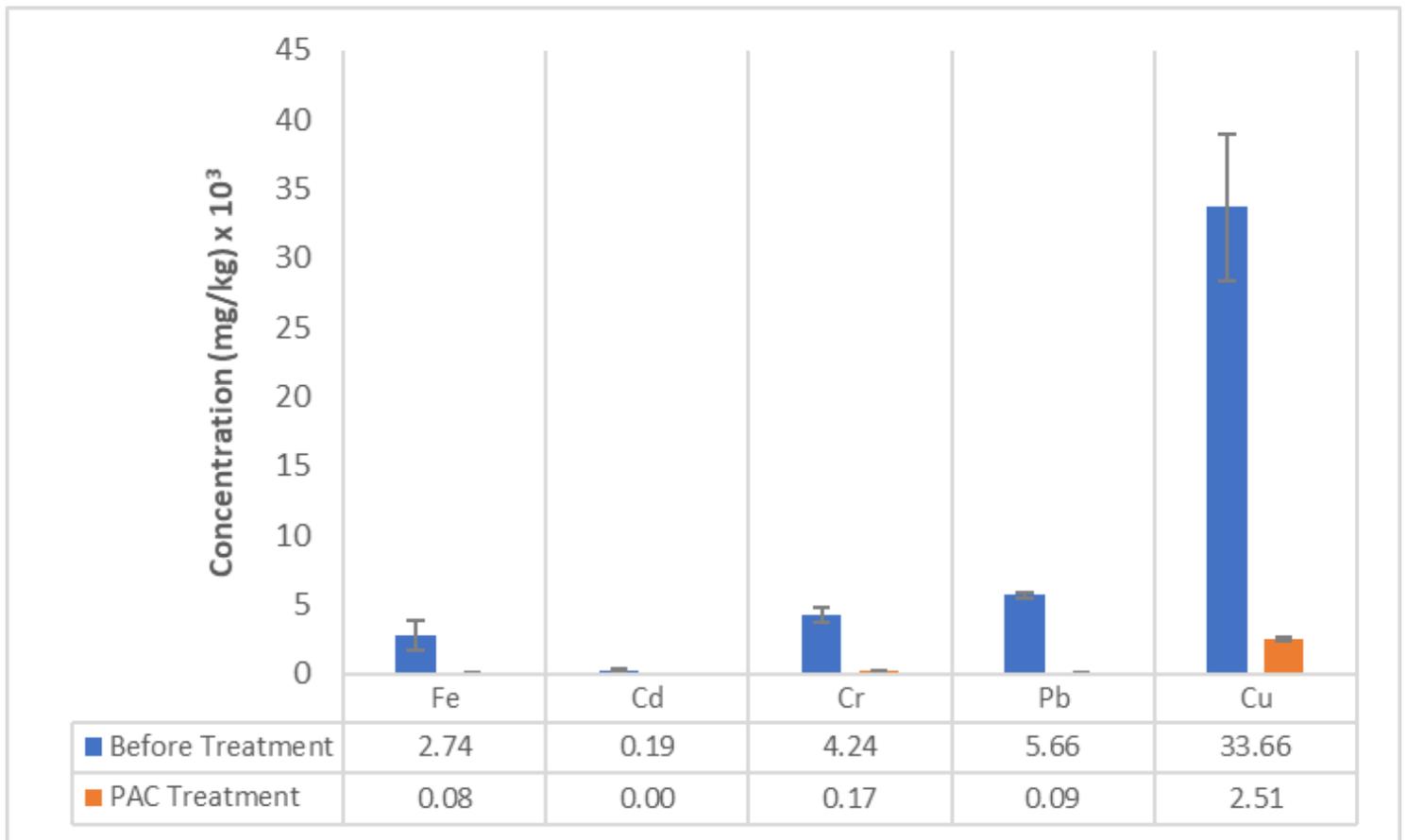
**Figure 9**

Mean metal concentrations of plot 1 samples treated with GAC



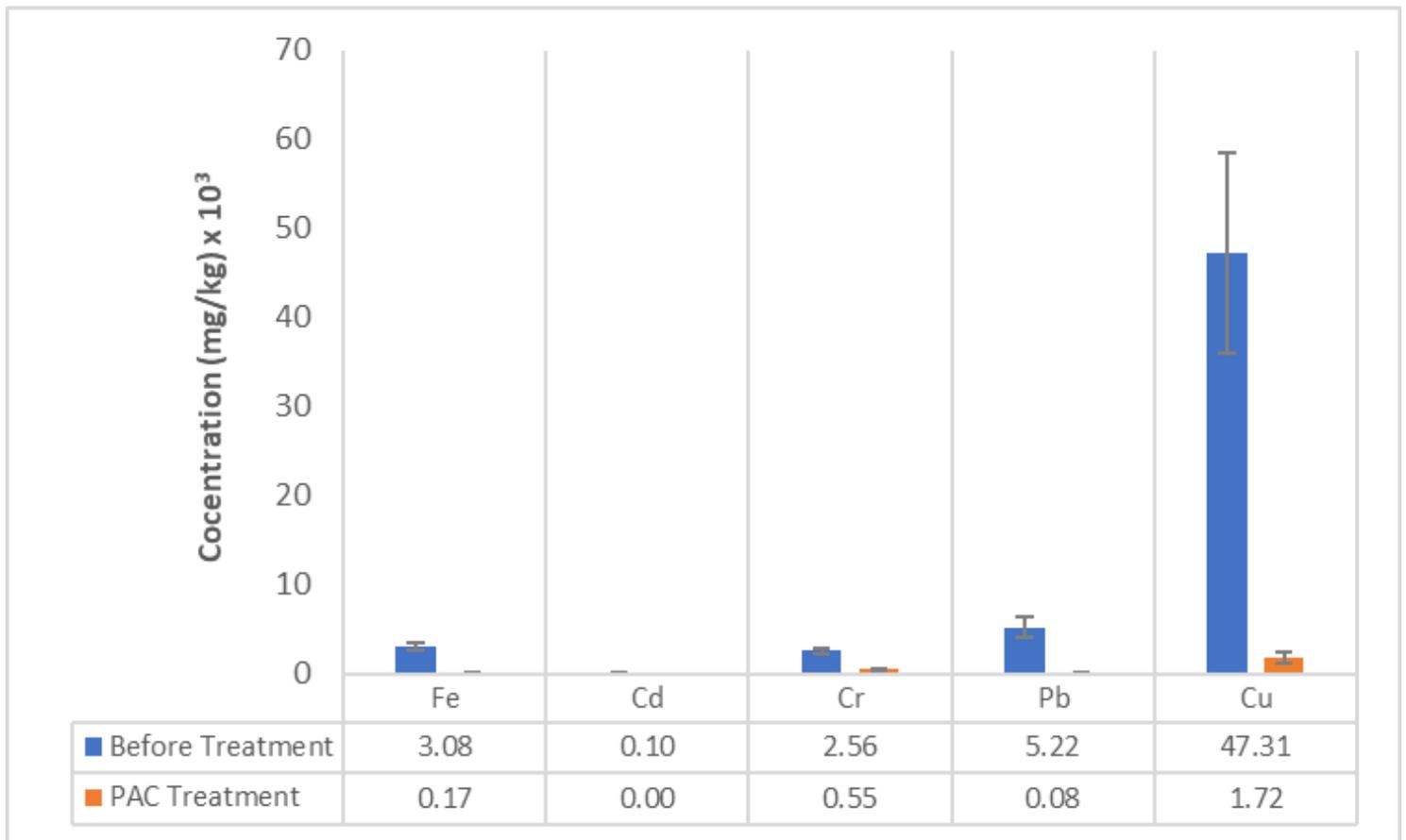
**Figure 10**

Mean metal concentrations of plot 2 samples treated with GAC



**Figure 11**

Mean metal concentrations of Plot 1 samples treated with PAC



**Figure 12**

Metal concentrations of Plot 2 samples treated with powdered AC