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Research Article

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Posted Date: September 23rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10908841/v1>

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Additional Declarations: No competing interests reported.

Column Studies on Biosorption of Metal Ions in Contaminated Surface Water and Leachate

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Abstract

The removal of major and trace metal ions in real-contaminated urban surface water from the Nakivubo channel and leachate from the Kampala Capital City disused landfill in Kiteezi, Central Uganda, was studied in fixed-bed columns using biosorbents derived from *Coffea canephora* husks and *Musa spp.* peels as an alternative to conventional water treatment methods. The maximum bed capacity, metal removal efficiency, and equilibrium metal uptake were determined, and breakthrough curves were then plotted for selected major and trace elements. The sorption capacities of selected elements major and trace metal ions increased with increasing treated volume without saturation of the biosorbents after 1450 – 2250 minutes runtime at flow rates of 3mL/min for Nakivubo channel water and 2.5mL/min for Kampala city landfill leachate. Experimental data from the fixed-bed columns were fitted to the Thomas ($0.808 \leq R^2 \leq 0.989$) and Adams-Bohart ($0.811 \leq R^2 \leq 0.987$) models. Correlation coefficients ($0.75 < r < 0.99$) of residual elements with dissolved organic matter indicated that they were associated. A total of 134.9µg/g of trace metals and 1215.1µg/g of major elements were adsorbed onto *coffea canephora* husks whereas 1.58µg/g of trace metals and 1761.5µg/g of major elements were adsorbed onto *musa spp.* peels. The biosorbents suitably removed ions in the order; $Cd^{2+} > Ba^{2+} > Zn^{2+} > Pb^{2+} > Cu^{2+}$, from contaminated surface water and landfill leachate. The *Coffea canephora* husks and *Musa spp* peels biosorbents demonstrated potential

in removing contaminant ions in minute concentrations from real wastewater samples in continuous fixed-bed columns.

Key words: Adams-Bohart model, bed capacities, biosorbents, landfill leachate, surface water, Thomas model, metal ions

1.0 Introduction

The amount of usable freshwater in the global hydrologic cycle is 22,000 cubic miles, which accounts for 7 ppm of the total water on Earth.(Rodell et al., 2018) This implies that although water is available, it is a scarce resource globally. On the other hand, freshwater resources are prone to contamination from natural and anthropogenic sources, including industrial discharges, agricultural runoff, domestic waste, and natural disasters.(Gu et al., 2023; Mirdashtvan et al., 2021; Yang et al., 2021) These contaminants include chemicals, pharmaceuticals, emerging contaminants like per- and polyfluoroalkyl substances, biological agents, and physical pollutants. (Zamora-Ledezma et al., 2021). The presence of these contaminants poses a substantial threat to both ecological and human health, disrupting aquatic ecosystems, accumulating in the food chain, and leading to severe health issues such as cancer, endocrine disorders, and developmental problems. (Wang et al., 2024) Moreover, the introduction of trace levels of heavy metals into drinking water poses a significant threat to human health, potentially leading to various diseases, including nervous system damage, kidney failure, hypertension, diabetes, and growth inhibition. (Kotnala et al., 2025a; V. Singh et al., 2024a)

Naturally, elements exist in the earth's crust in stable forms of ores, oxides, sulfides, carbonates, phosphates, and hydroxides with very low water solubilities. Moreover, their speciation also depends on their complexation with soluble organic matter, which is influenced by pH changes. (Han et al., 2025) The toxic trace metals are mobilized by natural phenomena of weathering and volcanic activity, although these contribute very little contamination compared to the expansive anthropogenic activities. Anthropogenic activities range from the combustion of fossil fuels, sewage sludge, and waste dumpsite leachates, to the wear and tear of machinery, to mining, smelting, and processing industries, which are usually conducted with little or no pretreatment, compromising water quality and endangering life systems. (Basu et al., 2025; Kotnala et al., 2025b) These metals, originating from industrial processes, mining activities,

and agricultural practices, can contaminate water sources, posing significant risks to human health through the consumption of contaminated water and food. (Moghimi Dehkordi et al., 2024; Xu et al., 2024) The anthropogenic pollution of water with toxic trace metals occurs locally but has global effects, necessitating remediation of contaminated water, wastewater, landfill leachate, and groundwater. Whereas some trace metals are essential micronutrients, their widespread increase due to human activities, such as industrial processes and agricultural practices, has significantly altered their biogeochemical cycles and introduced them into ecosystems at harmful levels. (McComb et al., 2014) These toxic metals are biologically nondegradable and tend to accumulate in living organisms, leading to various illnesses and disorders. The presence of heavy metals in water systems is particularly alarming because of their potential to cause long-term health issues, including cardiovascular, reproductive, and neurological disorders, as well as various types of cancer. (Galasso et al., 2025; Mustapha et al., 2026)

Among various pollutants present in surface water, inorganic species of heavy metals and their metalloids are of major concern, as they are difficult to remove owing to their smaller ionic sizes, complex forms, very low concentrations in high volumes, and competition with non-toxic inorganic species. (Hama Aziz et al., 2023; Maithani et al., 2023; P. K. Singh et al., 2024) The intricate behavior of heavy metals in aquatic environments involves complex interactions with water, sediments, and aquatic organisms, where metals can exist in various forms, influencing their bioavailability and toxicity. (Osae et al., 2026; Sharma et al., 2025; V. Singh et al., 2024b) Toxic trace metals cause detrimental health effects in ecosystems and humans through either long-term exposure to low concentrations or short-term exposure to high levels. Therefore, there is a need to reduce and remove heavy metal contaminants from wastewater, surface runoff, landfill leachate, and contaminated groundwater to protect the precious water resource and ensure public health. As such, various trace-metal remediation technologies, including chemical precipitation, adsorption, evaporation, electrochemical treatment, solvent extraction, membrane separation, reverse osmosis, and ion exchange, have recently been reported to reduce environmental levels and counteract the deleterious effects of trace metals by remediating contaminated water. (Jimoh et al., 2026; Qasem et al., 2021; Saleh et al., 2022; Shofia et al., 2025) However, the majority remain economically unviable or environmentally unrealistic for the remediation of metal ions at minute concentrations. Consequently, there is a growing need

for cost-effective, environmentally friendly methods to remove heavy metals from contaminated water. (Bhagat & Giri, 2021)

The aim of this study was to examine the performance of *Coffea canephora* husks and *Musa* spp. peels in fixed-bed column studies for removing toxic trace ions, Pb^{2+} and Cd^{2+} , from real contaminated surface water from an urban stream (Nakivubo channel) and from Kampala city landfill leachate (Kiteezi). The biomass investigated was *Coffea canephora* husks and *Musa* spp. (cooking banana) peels in their untreated form. Banana peels from cooking are sometimes used as fodder for domestic animals, and coffee husks are used as bedding in poultry houses. Nevertheless, the production of this agricultural waste in Uganda exceeds their reuse, thereby creating a waste burden in municipalities. The column dynamics have been investigated using the Thomas and Adams-Bohart models, with the possibility of scaling up the conditions to fit field treatment systems.

2.0 Materials and methods

2.1 Preparation of biosorbents

Coffea canephora husks and *musa spp* peels are common waste agricultural materials in Uganda where they pose a waste burden due to minimal reapplication. The banana peels were obtained from roadside markets where cooking bananas were peeled before steaming; the coffee husks were acquired from coffee processing industries in farming districts; and the quartz sand used as a control in the column studies was obtained from the shores of Lake Victoria in Entebbe. The plant materials were prepared in the laboratory to a diameter of 2 mm according to the previous method (Bakyayita et al., 2019) whereas the sand was washed and oven-dried before use in the columns.

2.2 Preparation of reagents and biosorbates

Biosorbates were surface water grab samples collected from Nakivubo channel and Kampala landfill leachate in Kiteezi 1m from the peripheral at depths within 0.5m of the surface at selected sampling sites. The samples were collected from the sample sites in 20 L plastic jerricans that had been prewashed 3 times with the sample water prior to collection. The field measurements of pH, temperature and EC were taken at the point of collection of the samples. All the chemicals used in this study were of analytical reagent grade and obtained from J.T. Baker H, Deventer, Holland. The initial pH of the contaminated surface water and landfill

leachate was adjusted to the required value, pH 4.5, using drops of 2 M HCl and 2 M NaOH just before pumping the water through the columns at $25 \pm 2^\circ\text{C}$. The influent was sampled as well as the effluent at regulated intervals over a period of 36 hours, and repeated with an adjusted flow rate. The water samples were filtered through $0.20\mu\text{m}$ filters into polypropylene bottles with a drop of concentrated HNO_3 before being analyzed for residual metal ions, whereas those for DOC and anions analysis were not acidified but cooled before being transferred to the analytical laboratory at SGU and KTH, respectively. The water samples were taken in duplicate to ensure $\pm 0.5\%$ reproducibility of the experimental data.

2.3 Fixed-bed column studies

Figure 1 represents the schematic diagram of the fixed bed sorption system used this study. Packed-bed column studies were conducted at room temperature in plastic columns with a length of 43cm and an internal diameter of 2cm. The columns were packed to 43cm bed height with dry biomass: 240g for quartz sand in column 1, 60g for *Musa spp.* in column 2, and 50g for *Coffea canephora* in column 3. Column 1 was a control column in which sorption of the trace metals was not or at least not expected. The biomass was underlain and overlain with thin layers of fine glass wool to prevent loss of biosorbent and the column was closed with a plastic stopper with plastic tubing. The void space was determined as 58cm^3 for sand, 88cm^3 for *musa spp* and 99.8cm^3 for *Coffea canephora*. The columns were configured in an up-flow arrangement and the flow of water through the tubes was done via the peristaltic pump assisted by atmospheric pressure. The contaminated water was pumped upwards to avoid channeling in the columns, which would occur due to gravity in a downward flow. The contaminated water container was set at a level of 50cm above the column inlet points. Therefore, atmospheric pressure and the peristaltic pump assisted the upward flow of water through the biomass at controlled rates. The water flow rates were adjusted throughout the experiment to achieve an average flow rate for each medium within the desired range: 2.0 ± 0.1 – 3.0 ± 0.2 mL/min for surface water from the Nakivubo channel and 3.5 ± 0.2 mL/min for Kampala city landfill leachate from Kiteezi. The influent pH was set at 4.5 for all contaminated water samples, while the effluent samples collected periodically were measured and recorded at the time of sampling. 20 effluent samples were collected at varying intervals from the Nakivubo Channel over a period of 46 hours. The column studies were performed in duplicate for Nakivubo Channel at flow rates of 2.0 ± 0.1 mL/min and 3.0 ± 0.2 mL/min to vary the column resident time of the contaminated water. The column studies were conducted once for Kiteezi

landfill leachate; moreover, 10 effluent samples were collected at intervals over 22 hours. The effluents for ICPMS metal analyses were collected and filtered through 0.4µm filters into polypropylene sample bottles and acidified with two to three drops of concentrated nitric acid for the Nakivubo channel. The effluent samples for ICPMS analysis from the columns used for remediation of Kiteezi landfill leachate were black water; therefore, they were pre-treated to produce a clear supernatant without total destruction of the organic matter. To 50 mL of the treated leachate effluents, 1 mL of nitric acid and 5 drops of 30% hydrogen peroxide were added to a plastic tube. The plastic tubes were closed and placed in a constant temperature water bath at 60°C for 30 minutes. Precipitation of the organic matter occurred, and the clear supernatants were filtered through 0.4µm filters into plastic sample bottles. All samples for DOC and anion analysis were not pretreated with acid, but were cooled until analysis was done.

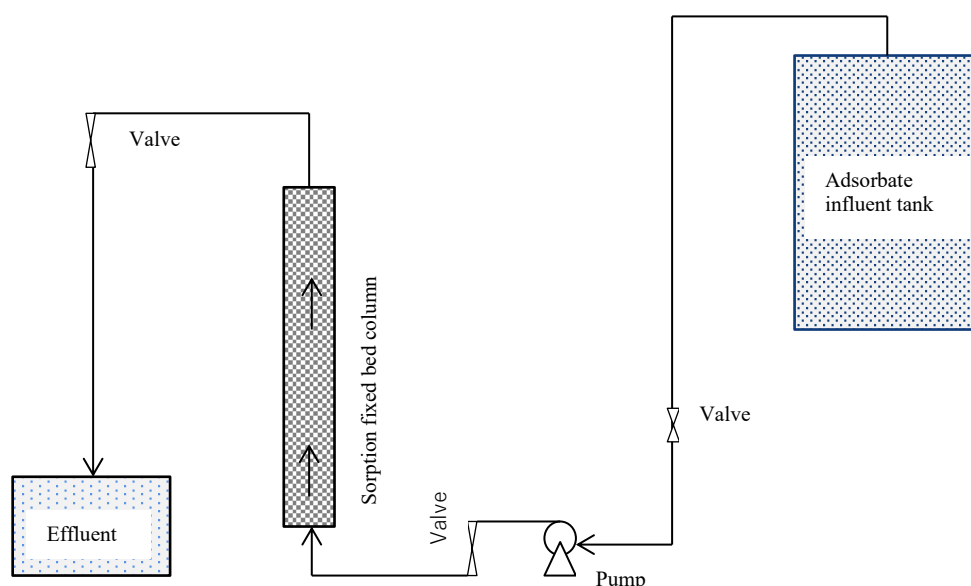


Figure 1: Schematic flow diagram of fixed bed system onto biosorbents

The effluent volume was calculated using the following equation:

$$V_{eff} = Qt_{total} \quad (1)$$

Where, V_{eff} is effluent volume collected, ml; Q is the volumetric flow rate, ml/min; t_{total} is the total flow time (min).

The maximum bed capacity for a given flow rate and initial concentration is given by equation 2:

$$q_{total} = \frac{Q \int C_{ad} dt}{1000} \quad (2)$$

Where q_{total} is the maximum bed capacity, mg; Q is the inlet flow rate, ml/min; C_{ad} is adsorbed metal concentration, ppm. The value of integral is obtained from the area under the curve of adsorbed metal concentration versus time.

The total amount of metal ions sent to the column is given by the following equation:

$$M_{total} = \frac{C_0 Q t_{total}}{1000} \quad (3)$$

Where, M_{total} is the total amount of metal ions sent to the column, gm; C_0 is the initial metal ion concentration, ppm; Q is the volumetric flow rate, ml/min; t_{total} is the total flow time, min.

Total percentage of metal ions removed is given by the following equation:

$$\% \text{ Removal} = \frac{q_{total}}{M_{total}} 100 \quad (4)$$

Where, q_{total} is the maximum bed capacity, mg; M_{total} is the total amount of metal ions sent to the column, mg.

The equilibrium metal ions uptake in the column is given by the following equation:

$$q_{eq} (xp) = \frac{q_{total}}{x} \quad (5)$$

Where, $q_{eq} (xp)$ is the equilibrium metal uptake, mg/gm; x is the amount of biosorbent in the column, gm.

2.4 Modeling of fixed-bed column studies

The sorption performance of the metal ions through the columns was analyzed using the Thomas and Adams-Bohart models from the concentration ratio, $C_t/C_0 > 0.1$, that is, 10% breakthrough until $C_t/C_0 > 0.9$ that is, 90% breakthrough for the metal ions under study, considering safe water quality standards and the operating limit of the mass transfer zone in a column. (Hu et al., 2024; Ibrahim et al., 2021) Experimental data from fixed-bed column studies can serve as the basis for the design of full-scale column operations. Several models have been proposed to evaluate the efficiency and applicability of column models for operations at the field water treatment plant level. To design a full-scale column sorption operation, prediction of the breakthrough curve and sorbent capacity for the trace metal contaminant under a given set of process conditions is necessary. In the present study, sorption data from fixed-bed columns were analyzed using the Thomas and Adams-Bohart models.

2.5 Analysis of adsorption data by Thomas Model

Thomas model is based on the mass transfer model, which assumes that the trace metal ions migrate from the solution to the film around the particle and diffuse through the liquid film to the surface of the biosorbent, followed by intraparticle diffusion and adsorption onto biosorbent sorption sites. It is therefore assumed that the process follows the Langmuir kinetics of sorption-desorption with no axial dispersion. It states that the rate-determining step obeys 2nd-order reversible kinetics. (He et al., 2026; Thomas, 1944) The linear form of Thomas model for adsorption is:

$$\ln\left(\frac{C_0}{C_t} - 1\right) = \frac{k_{TH}q_0m}{Q} - k_{TH}C_0t \quad (6)$$

Where, C_0 is the initial metal ions concentration, ppm; C_t is the effluent metal ions concentration at time t ; k_{TH} is the Thomas model rate constant, mL/min.mg; q_0 is the maximum sorption capacity, mg/gm; m is the mass of biosorbent in the column, Q gm; is the inlet flow concentration, ml/min. The value of k_{TH} and q_0 are determined from the slope and intercept of the linear plots of $\ln(C_0/C_t - 1)$ versus t using values of the column experiments.

2.6 Analysis of adsorption data by Adams-Bohart Model

This model was established based on surface reaction theory and assumed that equilibrium is not instantaneous. Therefore, the rate of adsorption will be proportional to both the residual capacity of the activated carbon and the concentration of the sorbing species. (Bohart & Adams, 1920; Chu, 2020) The linear form of the Adams-Bohart model is given by the following expression:

$$\ln\left(\frac{C_t}{C_0}\right) = K_{AB}C_0t - K_{AB}N_0\left(\frac{z}{U_0}\right) \quad (7)$$

Where C_0 is the influent sorbate concentration, ppm; C_t is the effluent sorbate concentration at time t , ppm; z (cm) is the bed height, U_0 (cm/min) is the superficial velocity of the influent solution. N_0 (mg/L) is the maximum sorbent uptake per unit volume of the adsorbent column and K_{AB} (L/g min) is Adams-Bohart rate constant. The value of K_{AB} and N_0 are determined from the slope and intercept of a plot of $\ln\left(\frac{C_t}{C_0}\right)$ versus t . The Adams-Bohart model was applied to the experimental data to describe the initial part of the breakthrough curve.

3.0 Results and discussion

The results of the field measurements are presented in Table 1.

The temperature levels for the surface water and landfill leachate were above the mean value, $25 \pm 2^\circ\text{C}$ for the shallow groundwater sources in Kampala. The high temperatures are

characteristic of microbial activity typical of landfill leachate and surface water heavily polluted with organic matter. The pH of surface water was near neutral but above the mean value for shallow groundwater in Kampala (5.6 ± 1.4), whereas that of landfill leachate was due to biodegradation of organic waste and oxidation processes that dissipate a lot of heat. The electrical conductivity levels were above the guideline value of $1000 \mu\text{S}$, indicating that the surface water and landfill leachate contained inorganic contaminants that were highly dissociated in solution.

Table 1. Field measurements for water characteristics

Water source	Temperature ($\pm 1^\circ\text{C}$)	Electrical Conductivity ($(\pm 5 \mu\text{S})$)	pH ± 1.4
Nakivubo channel	28	1723	5.60
Kiteezi landfill leachate	30	51000	8.44

The remediation of real contaminated natural surface water from an urban stream (Nakivubo channel) and Kampala city landfill leachate from Kiteezi was done using a continuous-flow system with *Coffea canephora* husks and *Musa spp.* peels biosorbents; therefore, no adjustments were made to the initial metal concentrations, although the flow rate was in the range of 2.5–3 ml/min and the bed height was 43cm. The flow rate used in this study was consistent with the 2 mL/min employed in several column studies. (Thongdamrongtham et al., 2026) which was reported to be low enough to allow greater contact time between the adsorbate and sorbent particles, as well as to enable effective intraparticle diffusion and higher removal efficiency. The results in Table 2 show that *C. canephora* and *Musa spp.* had high void space, good bed density, and particle density, indicating that the sorbate–sorbent interaction was high during the continuous-flow experiments, thereby enabling effective removal of the contaminant ions.

Table 2: Column details for the columns used in the continuous flow studies

Biomass	Mass (g)	Bed volume (cm^3)	Bed height (cm)	Void space (cm^3)	Effective volume (cm^3)	Bed density (g/cm^3)	Particle density (g/cm^3)
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<i>Coffea canephora</i> husks	50	527.8	43	98	429.8	0.095	0.116
<i>Musa spp</i> peels	58	527.8	43	84	443.8	0.11	0.131
Quartz sand	240	527.8	43	60	467.8	0.455	0.513

Figure 2 shows breakthrough curves of selected elements' adsorption onto *coffea canephora* husks (a and b) and *musa spp.* peels (c and d) for landfill leachate. The breakthrough curves were good for most ions although sorbent exhaustion was only achieved in a few isolated cases. The sorption of trace metals; cobalt and nickel showed better curves than lead and cadmium whereas zinc and calcium showed anomalous behaviour. The landfill leachate was a complex mixture of various elements which indicated that simultaneous sorption onto the sorbent materials other than the target trace metals occurred. The best performance of *Coffea canephora* husks in the removal process for contaminant ions in landfill leachate was observed for Cd, Zn, Pb, Na and Fe. The breakthrough curves of selected elements' adsorption onto *Musa spp. peels* for landfill leachate indicated that Zn, Ca, K, and Mg followed anomalous behavior during the removal of contaminant ions. The best performance of *Musa spp.* peels in the removal process for contaminant ions in landfill leachate was observed for Ni, Cu, Pb, Cd, K, Cr, Na and Fe. Treatment of contaminated water through the continuous flow systems is more effective when the external mass transfer and intra-particle diffusion control the process for higher residence time of the sorbate ions. From the breakthrough curves for *coffea canephora*, the breakthrough time t_b could be established when $C_e = 0.2C_i$ where C_e is the effluent concentration and C_i is the influent concentration of the contaminant was generally below 30 minutes whereas the t_e , the exhaustion time could be deduced when $C_e = 0.9C_i$ ranged between 5.5 and 35 hours. On the other hand, the breakthrough curves for *musa spp.* showed that t_b was below 30 minutes and that t_e ranged between 1 and 27 hours. In some cases, the breakthrough time could not be deduced due to an anomalous characteristic of the uptake of elements, whereas the exhaustion time in several cases was beyond the runtime of the experiments. This implied that the biosorbents, where no exhaustion time was beyond the runtime, were not saturated and could present higher sorption performance. On the other hand, the breakthrough curves in Figure 2 show that the sorption of Zn and Ca onto biosorbents from *Coffea canephora* husks and *Musa*

spp. peels followed a different mechanism from that followed by other trace and major elements, which could be surface complexation, other than the ion exchange mechanism.

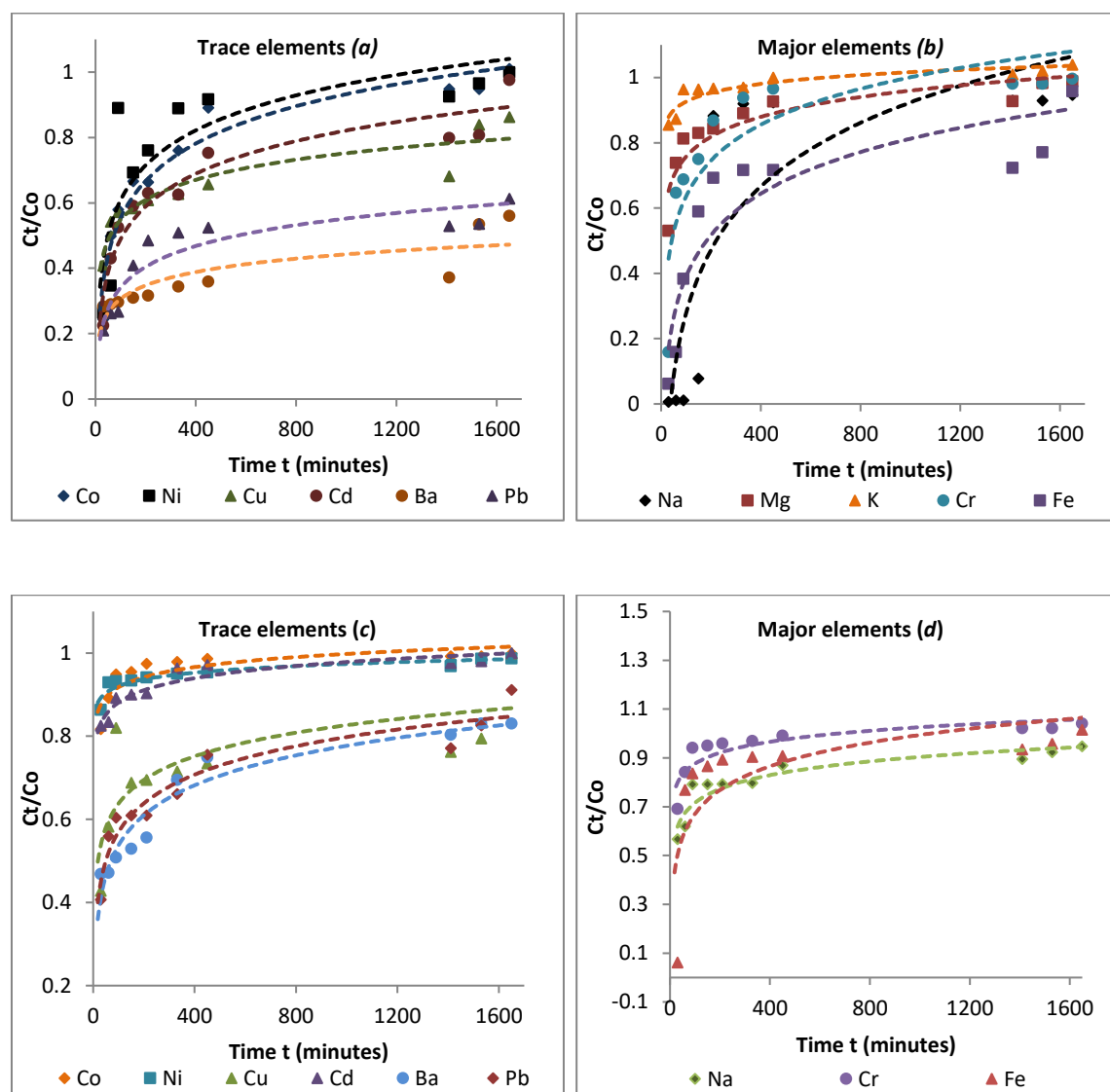


Figure 2: Breakthrough curves of selected elements' adsorption onto *coffea canephora* husks (a and b) and onto *musa spp* peels (c and d) for landfill leachate

Figure 3 shows breakthrough curves for selected elements adsorbed onto *Coffea canephora* husks for water from the Nakivubo channel. The breakthrough curves were good for the major ions: Na, Mg, Ca, Mn, and Fe, although sorbent exhaustion was achieved for Na, Mg, and P. The breakthrough curves for sorption of trace metals, Zn, Cd, and Pb, were anomalous, whereas Cu had a normal breakthrough curve. The contaminated Nakivubo channel water was a complex mixture of various elements, except that it had lower DOC than the landfill leachate. Simultaneous sorption onto the sorbent materials, other than the target trace metals, was

311 observed in Nakivubo channel water, although better removal of contaminant elements was
312 observed with landfill leachate. The best performance of *Coffea canephora* husks in the removal
313 of contaminant ions from landfill leachate was observed for Cd, Zn, Pb, Na, and Fe. For selected
314 elements' adsorption onto *musa spp.* peels, the breakthrough curves for the major ions, Na, Mg,
315 Ca, Mn, and Fe were good. The breakthrough curves showed that *Coffea canephora* husks had
316 a strong affinity for Pb, Cd, and Zn, while *Musa spp.* peels had a strong affinity for P, Zn, Cd,
317 and Pb; moreover, the other elements studied showed weak attachment, suggesting a separate
318 adsorption mechanism. Indeed, various sorption mechanisms operate simultaneously to varying
319 degrees depending on biomass, functional groups, and experimental conditions (Chojnacka et
320 al., 2005; Przybylska-Balcerek et al., 2026). In addition, differences in sorption mechanisms
321 for various ions can be attributed to differences in atomic weight, electronegativity, ionic radii,
322 and binding energies.

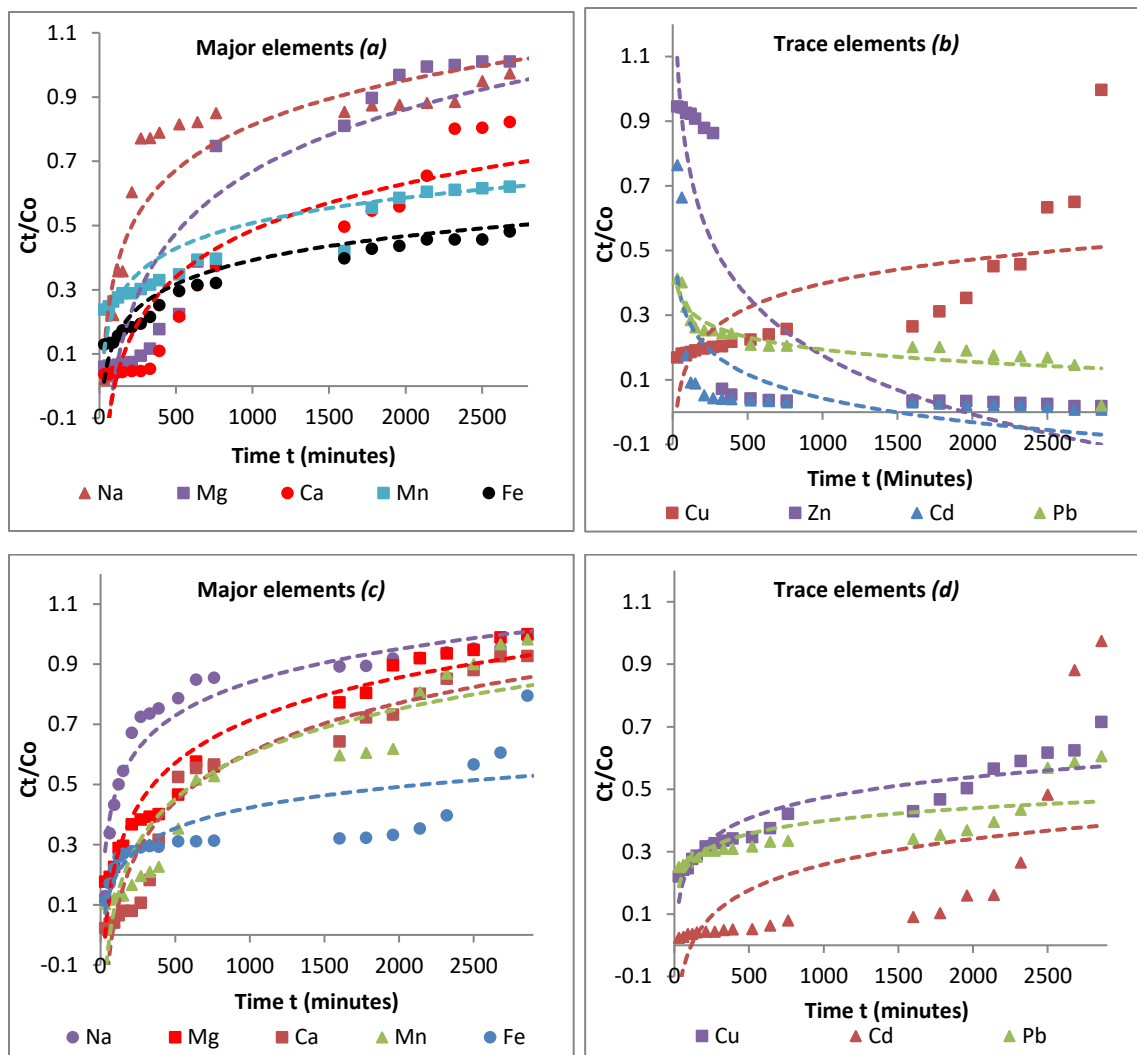


Figure 3 Breakthrough curves of selected elements' adsorption onto *coffea canephora* husks (a and b) and onto *musa spp* peels (c and d) for contaminated surface water from Nakivubo channel

A comparison of breakthrough curves in Figure 3 for sorption onto *Coffea canephora* husks and *Musa spp.* peels respectively showed that major elements sorbed better onto *coffea canephora* husks whereas trace elements sorbed better onto *musa spp.* peels. More of the major elements were removed from the contaminated water than trace elements. The breakthrough curves for *coffea canephora*, revealed that the breakthrough time t_b was generally below 30 minutes whereas the t_e , the exhaustion time ranged between 32 and 47 hours. On the other hand, the breakthrough curves for *musa spp.* showed that t_b was below 30 minutes and that t_e ranged between 41 and 50 hours.

In several cases where the exhaustion time was not realized, the biomass was not saturated, which meant that there were more binding sites available for sorption. The behaviour of the

columns in this study was similar to that reported by (Syeda et al., 2025) metal ions of all species, multi-component dynamic adsorption systems, bind to binding sites in the initial stages of column operation, but the metals of lower affinity are progressively displaced, leading to early breakthrough. The low initial concentrations of trace metal contaminant ions resulted in extended breakthrough curves, indicating a larger treated volume of surface water and landfill leachate, as low concentration gradients slow transport due to a small mass transfer coefficient. The Thomas model was applied to the kinetic data for treated landfill leachate and surface water for the continuous flow sorption systems of *coffea canephora* husks and *musa spp.* peels. The flow rates for contaminated surface water and landfill leachate were 3ml/min and 2.5ml/min respectively. To determine the parameters of the Thomas model; sorption capacity, q_{eq} , the rate constant, k_{Th} and the regression coefficient, R^2 were calculated from the linear plots of $\ln \left(\frac{C_0}{C_t} - 1 \right)$ versus time t and results are presented in Table 3. The Thomas model applied better to sorption data for remediation of contaminated surface water, with regression coefficients (R^2) between 0.808 and 0.982, than to sorption data for treated landfill leachate, with regression coefficients (R^2) between 0.813 and 0.989. The high k_{TH} values implied that those ions needed shorter time for sorption whereas low k_{TH} values meant that those ions were sorbed slowly. The values of k_{TH} in this study were in the same range and comparable to those in the report by (Vázquez et al., 2009). The q_e values for Zn were higher, whereas those of Cu and Pb were lower than those reported by (Vázquez et al., 2009) . The Thomas model fitted the sorption data for the removal of contaminant ions from landfill leachate and surface water; therefore, it suitably predicts the fixed-bed column adsorption processes for biosorbents derived from *Coffea canephora husks* and *Musa spp.* peels. The good fit of the experimental data to the Thomas model indicated that external and internal diffusion were not the limiting steps.

Table 3 Thomas model parameters for treated landfill leachate and Nakivubo channel water

Treated Landfill leachate				
<i>Coffea canephora husks</i>				
Elem ent	C_0 (ppm)	q_e (mg/g)	k_{TH} (L/min.. mg)	R^2

Cr	0.320	0.071	2.84×10^{-2}	0.818
Mg	29.463	136.5	1.73×10^{-4}	0.815
Ni	0.336	1.418	2.26×10^{-2}	0.849
Cd	0.0066	0.0598	8.3×10^{-1}	0.813
Pb	0.1479	2.546	2.3×10^{-2}	0.802
Ba	0.3704	21.79	2.16×10^{-3}	0.989
	<i>Musa spp. peels</i>			
Cr	0.320	1.5	2.75×10^{-2}	0.818
Co	0.1199	1.83	4.84×10^{-2}	0.827
Cd	0.0066	0.0833	7.25×10^{-1}	0.947
Ba	0.3704	1.437	8.37×10^{-3}	0.972
Zn	2.0738	7.095	8.2×10^{-4}	0.871
	Quartz sand			
Cd	0.0066	0.0003	4.47	0.937
Pb	0.1479	0.926	2.16×10^{-2}	0.840
Co	0.1199	0.347	9.01×10^{-2}	0.842

Ni	0.336 0	8.33	3.87 x 10 ⁻³	0.84 365
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384 **Table 4** Thomas model parameters for treated surface water from Nakivubo channel

Treated Nakivubo channel water				
	<i>Coffea canephora husks</i>			
Element	C ₀ (ppm)	q _e (mg/g)	k _{TH} (L/min.. mg)	R ²
Zn	0.685 4	12.8	1.55 x 10 ⁻²	0.81 4
Cu	0.018 5	24.8	3.79 x 10 ⁻²	0.98 2

Mg	7.715	48	4.67 x 10 ⁻⁴	0.95 0
Ca	28.97 1	2630	7.25 x 10 ⁻⁵	0.89 6
Mn	0.761	77.5	7.88 x 10 ⁻⁴	0.95 8
Fe	2.711	337	2.95 x 10 ⁻⁴	0.81 8
<i>Musa spp. peels</i>				
Mg	7.715	228	2.2 x 10 ⁻⁴	0.94 1
Ca	28.97 1	1830	6.56 x 10 ⁻⁵	0.86 1
Mn	0.761	41.6	2.37 x 10 ⁻³	0.92 5
Cu	0.018 5	0.959	5.95 x 10 ⁻²	0.88 6
Cd	0.001 0	0.137	1.25	0.86 4
Pb	0.008 1	1.36	3.78 x 10 ⁻²	0.82 8
Zn	0.685 4	14.9	1.49 x 10 ⁻²	0.92 5
Quartz sand				
Zn	0.685 4	11.4	4.23 x 10 ⁻³	0.95 6
Ba	0.883 3	24.2	9.06 x 10 ⁻⁴	0.83 1
Cu	0.018 5	0.068	2.16 x 10 ⁻²	0.91 9

Cd	0.001	0.069	5.75 x 10 ⁻¹	0.91 5
Ca	28.97 1	1650	3.45 x 10 ⁻⁵	0.88 2

385
386 The Adams-Bohart model was applied to the kinetic data for treated landfill leachate and
387 surface water for the continuous flow sorption systems of *coffea canephora* husks and *musa*
388 *spp.* peels biosorbents. The flow rates for contaminated surface water and landfill leachate were
389 3 mL/min and 2.5 mL/min, respectively. The values of adsorption capacity of the biosorbents
390 N_0 , the Adams-Bohart rate constant, K_{AB} , and the regression coefficient, R^2 were calculated
391 from the linear plots of $\ln\left(\frac{C_t}{C_0}\right)$ versus t and the results are presented in Table 4. The results
392 show that the model predicted the sorption performance of the biosorbents for contaminant ions
393 from the landfill leachate and surface water.

394 Table 5 Adams-Bohart model parameters for treated landfill leachate

Treated Landfill leachate				
	<i>Coffea canephora</i> husks			
Elem ent	C ₀ (ppm)	N ₀ (mg/g)	K _{AB} (L/min.. mg)	R ²
Ba	0.37	3.405	1.62 x 10 ⁻³	0.98 7
Ca	320	65.18	1.36 x 10 ⁻⁵	0.98 1
	<i>Musa spp. peels</i>			
Ba	0.37	1.077	3.25 x 10 ⁻³	0.97 6
Cd	0.007	0.0013	6.04 x 10 ⁻¹	0.86 6
Zn	2.074	5.558	4.82 x 10 ⁻⁴	0.89 1

Ca	370	64.82	1.35×10^{-5}	~~398~~ 396
Mg	29.46 3	46.57	3.39×10^{-5}	~~397~~ ~~398~~ 399
	Quartz sand			400
Fe	9.232	2.515	1.08×10^{-5}	~~401~~ 402
Mg	29.46 3	1.255	1.7×10^{-5}	~~403~~ 404
K	142.6 2	18.37	1.4×10^{-6}	~~405~~ 406
Cu	0.311	0.802	1.61×10^{-3}	~~407~~ ~~408~~ 409
Ni	0.336	0.982	2.98×10^{-4}	~~410~~ 411

412

413

Table 6 Adams-Bohart model parameters for treated water from Nakivubo channel

Treated Nakivubo channel water				
	<i>Coffea canephora husks</i>			
Element	C ₀ (ppm)	N ₀ (mg/g)	K _{AB} (L/min..m g)	R ²
Zn	0.685 4	0.2404	8.46×10^{-3}	0.81 1
Ba	0.883 3	0.0103	4.08×10^{-3}	0.88 4
Cu	0.018 5	0.3263	2.7×10^{-2}	0.97 9
Ca	28.97 1	148.1	1.24×10^{-4}	0.92 7

Mg	7.715	35.73	4.41×10^{-4}	0.967
Fe	2.711	19.80	5.16×10^{-4}	0.942
Mn	0.761	7.751	9.2×10^{-4}	0.941
<i>Musa spp. peels</i>				
Ca	28.971	114.6	1.52×10^{-4}	0.906
Mn	0.761	3.822	3.15×10^{-3}	0.985
Mg	7.715	38.86	2.07×10^{-4}	0.888
Ba	0.8833	12.92	1.59×10^{-3}	0.910
Cd	0.001	0.0155	1.15	0.849
Zn	0.6854	0.4233	5.84×10^{-3}	0.888
Pb	0.0081	0.1392	4.97×10^{-2}	0.813
Cu	0.0185	0.0395	4.33×10^{-2}	0.893
Quartz sand				
Cu	0.0185	0.4031	1.08×10^{-2}	0.936
Zn	0.6854	9.449	2.04×10^{-3}	0.938
Cd	0.001	0.0325	5.75×10^{-1}	0.919
Ba	0.8833	16.37	6.79×10^{-4}	0.815

Ca	28.97 1	47.35	2.07 x 10 ⁻⁶	0.869
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The model applied more to the sorption data of remediated surface water with regression coefficient, R^2 values between 0.811 and 0.985, than the data for treated landfill leachate with regression coefficient, R^2 values between 0.87 and 0.987. The Adams-Bohart model predicted the sorption performance of the biosorbents in the continuous flow system studied for contaminated surface water. When the Adams-Bohart model applies to experimental results, it can be concluded that the overall system kinetics were dominated by external mass transfer. (Bohart & Adams, 1920; Chu, 2020; Syeda et al., 2025; Vázquez et al., 2009) The analysis of the performance of biosorbents in the removal of selected contaminant ions from Kiteezi landfill leachate was done. The values of the total amount of elements, M_{total} in the contaminated water influent to the columns, total amount sorbed, q_{total} , sorption capacity, $q_{\text{eq(max)}}$ and percentage removal were calculated and the results are presented in Table 5. The results show that the percentage removal was high in the remediation of Nakivubo channel water but it was better for flow rate 3ml/min than for flow rate 2ml/min for both *coffea canephora* husks and *musa spp.* peels. The $q_{\text{eq(max)}}$ values for trace metals were 117 $\mu\text{g/g}$ and 103.8 $\mu\text{g/g}$ at a flow rate of 3ml/min, whereas at a flow rate of 2ml/min, the values were 2.27 $\mu\text{g/g}$ and 10.14 $\mu\text{g/g}$ for sorption onto *Coffea canephora* husks and *Musa spp.* peels respectively. The total values for the $q_{\text{eq(max)}}$ for trace metals' sorption capacities for the biomass studied showed that *coffea canephora* husks performed better than *musa spp.* peels in removing trace metals, whereas *Musa spp.* was better in removing major elements from contaminated surface water. The sorption of trace metals onto biomass was compared to that of major elements in the remediation of landfill leachate and the results indicated that major elements were removed in preference to trace elements. A total of 134.9 $\mu\text{g/g}$ of trace metals, compared to 1215.1 $\mu\text{g/g}$ of major elements, were adsorbed onto *Coffea canephora* husks, whereas 1.58 $\mu\text{g/g}$ of trace metals, compared to 1761.5 $\mu\text{g/g}$ of major elements, were adsorbed onto *Musa spp.* peels. The results indicated that the materials had higher affinities and preferences for major elements than trace elements, which is supported by the observation that light metal ions such as Na, K, Ca and Mg, common in wastewater and landfill leachate exert co-ion effects on the uptake of contaminant metal ions such as Pb, Cd, Zn and Cu.

443 Table 7: The removal of selected elements from real contaminated water by *coffea*
444 *canephora* husks and *musa spp* peels biosorbents under various conditions

Biomass	Flow rate (ml/min)	Cation	M _{total} (μg)	q _{total} (μg)	q _{eq(max)} (μg/g)	% Removal
Surface water from Nakivubo Channel						
<i>Coffea canephora</i> husks	3	Cu	1.664	1.384	0.028	83.2
		Zn	5880	5769	115.4	98.1
		Cd	8.949	8.88	0.178	99.2
		Pb	73.42	71.87	1.437	97.9
		Ba	7579	7420	148.4	97.9
<i>Musa spp</i> peels	3	Cu	1.664	1.298	0.022	78
		Zn	6251	6019	103.8	96.3
		Cd	0.094	0.091	0.002	96.8
		Pb	0.725	0.544	0.009	75
		Ba	79.5	78.62	1.356	98.9
Landfill leachate from Kiteezi, Kampala						
<i>Coffea canephora</i> husks	2.5	Zn	8554	6724	134.5	78.6
		Cd	0.497	0.385	0.008	77.5
		Pb	11.09	8.762	0.175	79
		Ba	27.78	19.92	0.398	71.7
		Na	57910	57505	1150	99.3
		Fe	692	650	13	93.9
		Zn	155.5	71.55	1.234	46
		Cd	0.497	0.087	0.002	17.5
		Pb	11.09	6.59	0.114	59.4

<i>Musa spp</i> peels	2.5	Ba	27.78	14.78	0.255	53.2
		Na	57910	25075	432.3	43.3
		Fe	38082	6018	103.8	15.8

The various elements in the real contaminated water caused competitive and synergistic effects on sorption of the elements, as discussed in earlier studies by Bakayita et al., 2015), where it was reported that both Cd^{2+} and Pb^{2+} ions' sorption onto *Coffea canephora*, *Cyperus papyrus* and *Musa spp.* was suppressed by the presence of other metal ions in the competitive media.

The values of residual elements in treated landfill leachate were highly correlated with the values of DOC in the remediated solutions as the results presented in Table 6 show. The DOC in treated landfill leachate was very high; 767 – 1455 mg/L for *coffea canephora* and 710 – 1187 mg/L for *musa spp.*, therefore, correlation studies were done to determine the relation between the residual elements and the dissolved organic carbon. The results presented in Table 5 showed that both the major and trace elements were associated with the DOC in the treated water. The correlation coefficients' values for effluent through *coffea canephora* husks were in the range 0.75 – 0.95 whereas for *musa spp.* peels they were between 0.82 – 0.99.

Table 8 Correlation coefficients, r for selected residual elements with the DOC in the treated landfill leachate

Na	Mg	P	K	Ca	Cr	Fe	Co	Ni	Cu	Zn	Cd	Ba	Pb
<i>Musa spp peels</i>													
0.99	0.87	0.82	0.89	0.92	0.97	0.91	0.87	0.97	0.82	0.97	0.86	0.91	0.98
<i>Coffea canephora husks</i>													
0.75	0.95	0.93	0.92	0.29	0.9	0.87	0.97	0.89	0.89	0.84	0.92	0.85	0.82
Quartz sand													
0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92

The results in Table 8 suggest that, in remediated water with high DOC, some elements associated with DOC may not be available for sorption onto biosorbents. The trends in the levels of DOC in water treated with the *coffea canephora* husks and *musa spp.* Peel's biosorbents were analyzed, and the results are presented in Figure 4. The results show that continuous flow treatment systems greatly reduced the DOC in treated landfill leachate for both

biosorbents from 1400 to 720 mg/l, although the levels were higher than the allowable level of 2.0 mg/l for wastewater.

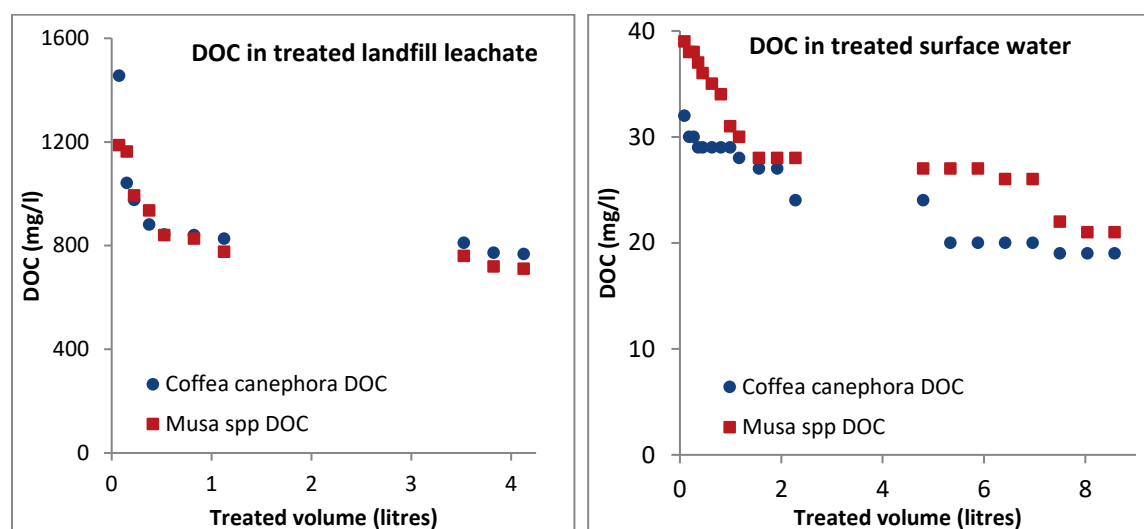


Figure 4 Variation of DOC with treated volume for remediated landfill leachate and surface water from Nakivubo channel

For treated surface water, DOC levels were reduced from 40 to 20 mg/l with both biosorbents, but remained above the allowable level of 2.0 mg/l for wastewater. Unlike landfill leachate, which had very high DOC, the DOC in treated surface water was relatively lower, although still above contamination levels. The use of biosorbents for the remediation of contaminated water should be combined with other methods for DOC removal to attain the allowable levels in wastewater.

From the plots of q_{total} versus treated volume of landfill leachate shown in Figure 5, *Coffea canephora* graphs showed that the levels of major elements adsorbed decreased with treated volume, whereas for trace elements, there was an increase in total adsorbed amount. The q_{total} values for *musa spp.* peels showed that trace elements sorption could be followed and was in the order: Ba > Zn > Pb > Cu > Cd ($\mu\text{g/g}$).

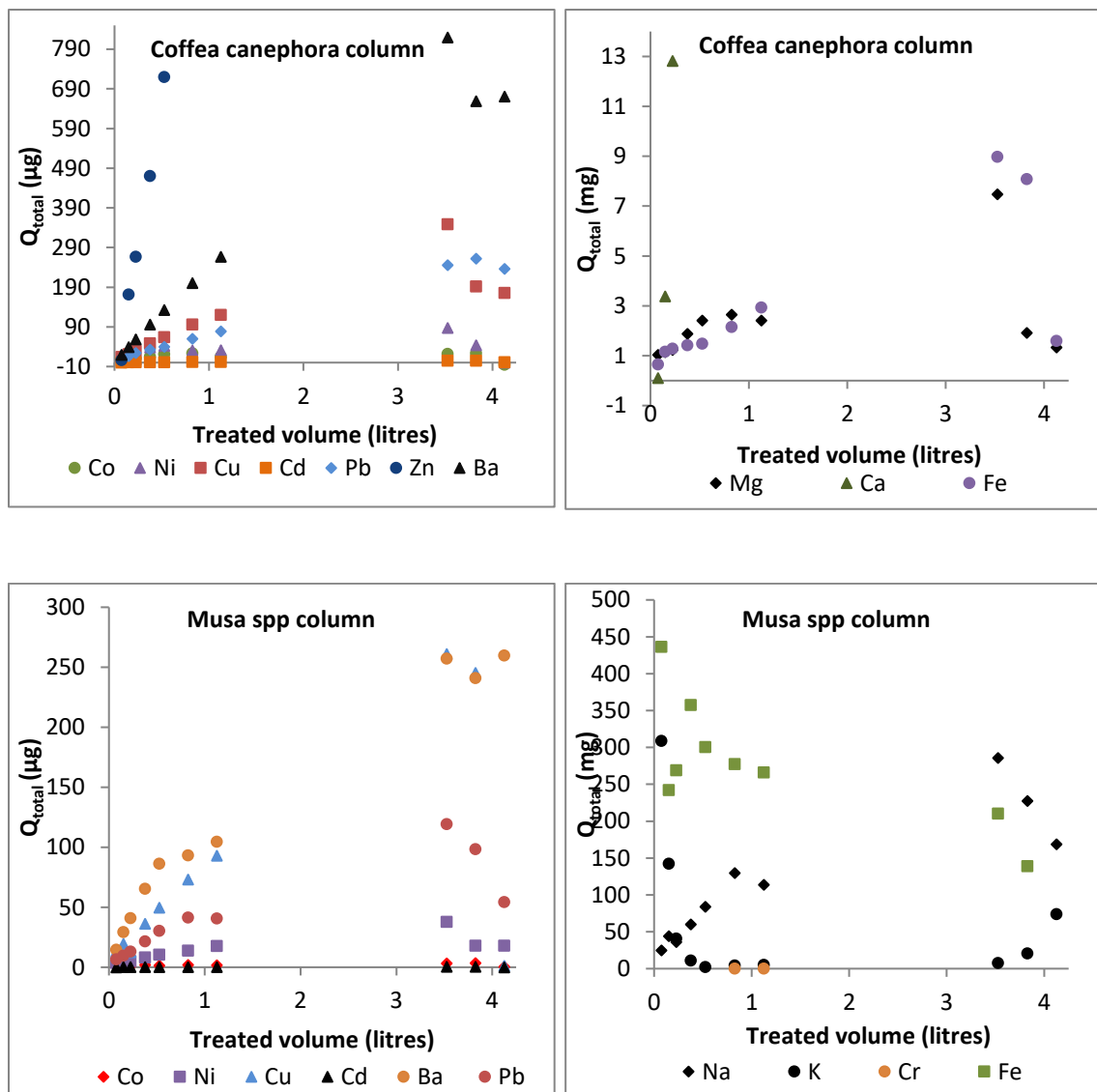


Figure 5 Adsorption capacity Q_{total} for selected elements onto *coffea canephora* husks and onto *musa spp* peels from landfill leachate

There was a tendency for the major elements P, Mg, and Ca to leach from *Musa spp.* peels into the treated water, indicating an ion-exchange mechanism in addition to other adsorption mechanisms. For the remediation of contaminated surface water, the q_{total} variations for selected elements with treated volume were plotted in Figure 6. The order in which major elements were adsorbed was: $Ca > Na > K > Mg > Fe$ (mg/g), whereas for the trace elements, the order of sorption was: $Zn > Ba > Cu > Pb > Cd$ (μg/g). The contaminated surface water and landfill leachate contain different amounts of cations, which may influence the biosorption of the metal ions being studied. The trends in q_{total} versus treated volume in this study are comparable to

those reported by Loutseti et al. (2009) for the sorption of Cu and Cd onto microalgae, where 180mg Cd/g and 160mg Cu/g of biomass were observed after treatment with 1650 mL of metal solution.

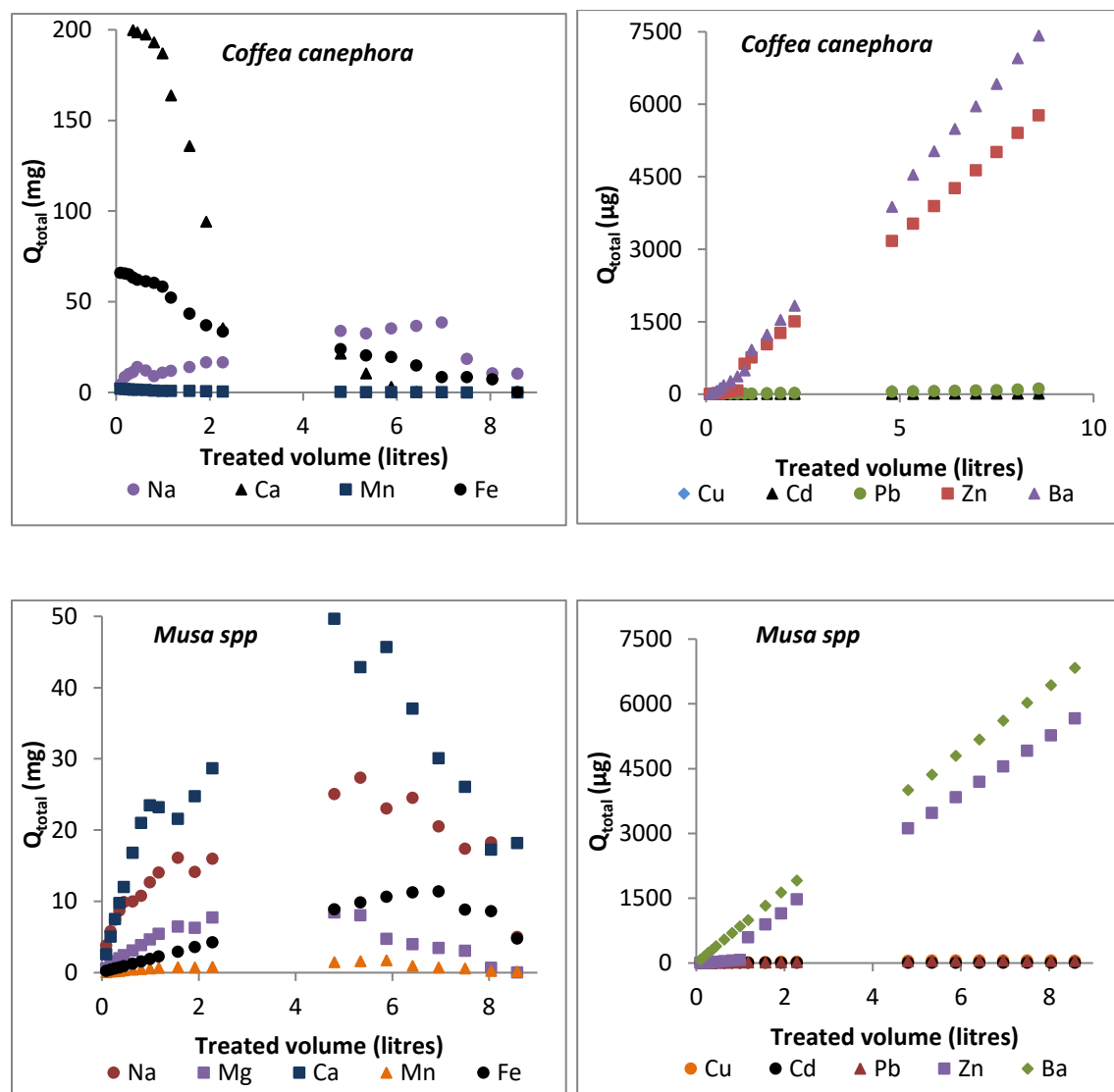


Figure 6 Adsorption capacity Q_{total} for selected elements onto *coffea canephora* husks and onto *musa spp.* peels from contaminated surface water

Conclusion

Continuous flow through fixed-bed columns using real contaminated surface water and landfill leachate was performed to scale up the application in field treatment plants for the removal of trace metal contaminants under specific operating conditions. The *Coffea canephora* husks and *Musa spp.* peels were studied as alternative biosorbents for the removal of Cd^{2+} and Pb^{2+} ions

from contaminated surface water from the Nakivubo channel and from Kampala landfill leachate from Kiteezi. The various organic and inorganic species in the surface water and landfill leachate resulted in competitive sorption effects on the uptake of trace metals onto the biosorbents. The major elements had co-ion effects on the sorption of trace elements from the aqueous media. The breakthrough curves followed a characteristic S-shape profile, although uptake was slow due to low initial contaminant concentrations. Under moderate flow rates, 2.5 – 3 mL/min, the biosorbents removed substantial amounts of major and trace elements from solution in the ranges: 75 – 99.2% for both biosorbent columns for surface water and for landfill leachate, 46.9 – 99.3% for the *Coffea canephora* column, and 17.5 – 59.4% for *Musa spp* column. In several cases, the exhaustion time was not realized, and the materials were not saturated. The experimental results from the fixed-bed columns were modeled using the Thomas and Adams-Bohart models, indicating that several sorption mechanisms were operating simultaneously, as is typical of real environmental samples. The residual elements were associated with dissolved organic carbon, indicating that DOC removal would reduce contaminant levels. The total values were high, indicating that repeated treatment of the contaminated water would subsequently reduce contaminant levels to allowable levels. For sustainability purposes, sorption–desorption studies need to be carried out to authenticate the low-cost biosorbent's removal of organic and inorganic contaminant species from surface water, wastewater, surface runoff, and landfill leachate.

Acknowledgements

The authors extend their gratitude to the sponsors and the staff of Kungliga Tekniska Högskolan, Makerere University, Kabaale University, and Kyambogo University for their collaboration and support in all capacities during these studies.

Funding

This study was funded by the Royal Swedish Government through the Swedish International Development Cooperation Agency (Sida), in a bilateral research collaboration with Makerere University, Uganda.

Ethics declarations

Ethics approval and consent to participate

Not applicable.

549 **Consent to publication**

550 Not applicable.

551

552 **Competing interests**

553 The authors declare no competing interests.

554

555 **Data Availability Statement**

556 The datasets generated during and/or analysed during the current study are available from the
557 corresponding author on reasonable request.

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