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Research Article

Column Study for Adsorption of Copper and Cadmium Using Activated Carbon Derived from Sewage Sludge

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Among the water-polluting substances, heavy metals stand out due to their carcinogenic and toxic effects on the creatures and environment. This study aimed to scrutinize the effectiveness of sewage sludge-based activated carbon in the removal of copper and cadmium from aqueous solutions in column study. Detection of breakthrough curves and related parameters was conducted by varying bed depths (3, 6, and 9 cm). The solution with an initial metal concentration (IMC) of 100 ppm was pumped to the column at a flow rate of 2 mL/min. In the process of copper removal, the breakthrough points for depths 3 cm, 6 cm, and 9 cm were achieved at 10 min, 15 min, and 60 min, respectively, whereas breakthrough points of similar depths in cadmium removal process were achieved at 5 min, 10 min, and 30 min, respectively. Adsorption kinetics were analyzed using the Adams–Bohart, Yoon–Nelson, and Thomas kinetics models. The Adams–Bohart model described only the initial part of breakthrough curves. The Thomas model represented the adsorption process with coefficients of determination (R^2) ranging between 0.90–0.95 for cadmium removal and 0.89–0.96 for copper removal, while the coefficients of determination of Yoon–Nelson ranged between 0.89–0.94 for cadmium and 0.95–0.97 for copper. Yoon–Nelson was fitted well with copper removal data, while removal of cadmium data was best described by the Thomas model. This study demonstrated that using sewage sludge-based activated carbon to remove heavy metals is an alternative, more cost-effective option to reach the objectives of sustainable development.

1. Introduction

Pollution caused by industrial and anthropogenic activities is one of the major challenges of this century [1]. The environmental pollution concept is referred to the deficit in the environmental process of the ecosystem caused by contamination of its components, either atmosphere, soil, or aquatic system [2]. However, heavy metals are one of the most common environmental polluting substances, particularly copper and cadmium, which at high concentrations are toxic and detrimental to the environment due to their carcinogenic and nonbiodegradable features [3, 4]. Yet, although copper at low concentration is an essential metal for the growth of plants [5], excessive copper is associated with many health and environmental problems [6]. Nowadays, copper is the most abundant and wildly prevalent heavy metal used in many industrial activities such as metal finishing, electroplating, and plastics [7]. There is a continuous increase in the amount of heavy metals present in wastewater; therefore, many techniques are used to remove them, such as electrocoagulation (EC), adsorption using synthetic and natural adsorbents, magnetic field implementation, advanced oxidation processes, and membranes. However, choosing the most applicable and efficient techniques is very critical and depends on many factors [8]. Adsorption is an efficient and polishing technique to remove heavy metals, but the manufacturing of granular and powdered activated carbon is an expensive process [9]; therefore, using low-cost adsorbents is a promising technique in removing a wide range of pollutants [10]. However, different types of waste materials, such as nutshell [11], bagasse [12], wood, sawdust, and tea leaf, have been used as precursors to produce activated carbon as adsorbent [13]. The key features which evaluate the efficiency of any adsorbent are its adsorption capacity, structural, and physical properties. Among a wide variety of starting waste materials, sewage sludge has been reported to produce an effective low-cost adsorbent due to its carbonaceous property [14, 15]. The adsorption process is usually carried out in batch studies, fixed-bed column studies, fluidized bed continuous studies, or moving beds. However, among continuous studies, a fixed-bed column is preferred due to its feasibility, efficiency, and low-cost process [16]. The process in column studies is described by a breakthrough curve [17]. Breakthrough curves are modeled using the data from the adsorption experiments. Additionally, many models were generated to investigate the breakthrough profiles and explain the dynamic adsorption behaviour of heavy metals, such as the Adams–Bohart, Yoon–Nelson, and Thomas models [18]. The purpose of this study is to assess the efficiency of sewage sludge-based activated carbon for the removal of copper and cadmium ions from aqueous solutions under different operation runs in column studies.

2. Materials and Methods

2.1. Preparation of the Adsorbent. Sewage sludge-based activated carbon, prepared in a previous study [1], with a surface area of 377.7 m^2/g, was used as an adsorbent in this study. Stock solutions (1000 ppm) of cadmium Cd^{2+} and copper Cu^{2+} were prepared using cadmium nitrate Cd $(NO_3)_2$ and copper nitrate Cu $(NO_3)_2$ [2]. Afterward, different concentrations of Cd^{2+} and Cu^{2+} were prepared by diluting the stock solution to the desired concentrations [3]. All the chemicals used were of analytical grade. The specific surface areas were measured by the BET equation based on the Brunauer–Emmett–Teller method using N_2 adsorption/desorption isotherm. Table 1 illustrates the adsorption data to determine BET.

2.2. Column Studies. Column study was conducted in downflow fixed-bed column (1.5 cm diameter), packed with activated carbon at 3 cm, 6 cm, and 9 cm. Glass wool was used at the bottom of the column to prevent the leaching of activated carbon and clogging of the drainage area. It was also placed on the top of the adsorbent bed to gently distribute the solution onto the adsorbent surface and to maintain a consistent flow. The initial concentrations of copper and cadmium solutions were fixed at 100 mg/L. pH was set at 5.0 using sodium hydroxide (NaOH) and hydrochloride acid (HCL). The optimum values of batch adsorption conditions were adopted in the column study. The solution was pumped into the column at a constant flow rate of 2 ml/min in a downflow direction by a peristaltic pump (Eyela Poller Pump, RP-1000). Effluents were collected every 5 min for the first hour and at intervals of half-hour for the remaining period until the concentration of metal ions in the effluents reached the exhaust point. Measurement of residual concentrations was conducted using a spectrophotometer (DR3900). The column study was conducted at room temperature, and all column experiments were performed in triplicate.

2.3. Calculation of Column Parameters. Important parameters, such as the total weight of metal adsorbed q_{total} (mg), volume of effluent treated V_t (ml), total mass of metal entering the column M (mg), concentration of metal adsorbed $C_{a\,d}$ and q_e (mg/g), and the total experimental uptake capacity, are determined using the plot of time (t) against C_t/C_0 according to equations (1) to (5), where C_t denotes outlet concentration, C_0 is the feed concentration, m is the mass of adsorbent in column (g), and Q is the flow rate (mL/min) [4].

$$q_{\text{total}} = \frac{Q}{1000}\int_{t=0}^{t=\text{total}} C_{a\,d}dt, \tag{1}$$

$$q_e = \frac{q_{\text{total}}}{m}, \tag{2}$$

$$V_t = Q * t_{\text{total}}, \tag{3}$$

$$m_{\text{total}} = C_0 * \frac{Qt}{1000}, \tag{4}$$

$$\text{total removal }\% = \frac{q_{\text{total}}}{m_{\text{total}}} * 100. \tag{5}$$

3. Modeling of Column Studies

Many models are used to analyze the column adsorption performance depending on regression coefficient (R^2) and the best fit of the straight line [5]. In this study, three models, Adams–Bohart, Yoon–Nelson, and Thomas, were applied to investigate the column adsorption process and performance.

3.1. Adams–Bohart Model. The ability of this empirical model is limited to the first part of the breakthrough curve [6]. Equation (6) represents the formula of the Adams–Bohart model. This model was initially applied to gas-charcoal adsorption, and thereafter, it applies to check the dynamic behavior of the column [7].

$$\ln\left(\frac{C_t}{C_0}\right) = k_{AB}C_0t - k_{AB}N_0\left(\frac{Z}{U_0}\right), \tag{6}$$

where k_{AB} (L/mg.min) stands for kinetic constant, whereas the depth is denoted by Z (cm) and N_0 (mg/L) symbolizes the maximum adsorption capacity. U_0 (cm/min) is designated for the linear velocity of the solution. Parameters of correlation coefficients (R^2) k_{AB} and N_0 can be determined using the graph of ln (C_t/C_0) versus t.

Table 1: Physical properties of the prepared activated carbon deduced from N_2 adsorption.

Surface area (m^2/g)				Pore size (nm)		Total pore volume (cm^3/g)
BET	Langmuir	t-plot micropore	t-plot external	Adsorption average pore diameter	Desorption average pore diameter (nm)	
377.7	542.7	102.1	275.36	5.04	4.8	0.28

3.2. Yoon–Nelson Model. One of the common and simple models which are wildly used to study the breakthrough curve behavior during the adsorption process is the Yoon–Nelson model. Parameters of k_{YN} and τ are calculated using

$$\ln\left(\frac{C_t}{C_0 - C_t}\right) = K_{YN}t - \tau K_{YN}, \quad (7)$$

where k_{YN} (L/min) stands for the rate of constant and the time required for 50% of the breakthrough curve is denoted by τ (min). A plot of ln $(C_t/(C_0 - C_t))$ versus time τ is used to calculate the model parameters of k_{YN} and τ from the slope and intercept, respectively. The calculated τ from the experiment was compared with the value obtained from the linear model [8].

3.3. Thomas Model. Thomas model is commonly used to study the process of the adsorption and predict the breakthrough curve in fixed bed column. It is based theoretically on Langmuir kinetic and the assumption that the driving force is subjected to second-order reversible rate kinetics [9, 10]. The linear form of the Thomas model is presented by

$$Ln\left(\frac{C_0}{C_t} - 1\right) = \frac{k_{TH}q_0 m}{Q} - \frac{k_{TH}C_0 t}{m}, \quad (8)$$

where $C_0, C_t, k_{TH}, q_0, m,$ and Q are the initial metal concentration, the final concentration or outlet concentration at time t, Thomas constant rate (mL/min.mg), the maximum uptake capacity (mg/g), adsorbent mass in the column (g), and the flow rate mL/min, respectively. The values of parameters k_{TH} and q_0 are found from the intercept and slope of the linear equation generated from the plot between t and ln $(C_0/C_t - 1)$.

4. Results and Discussion

Besides the bed depth, many factors have a great impact on the adsorption process, such as initial concentration, flow rate, and pH. However, the optimum values obtained from batch studies were applied, and bed depth was varied and investigated in this study.

4.1. Effect of Bed Depth on Breakthrough Curves of Copper Removal. Breakthrough curves were plotted by changing the three-bed depths (Z), 3, 6, and 9 cm, and keeping the flow rate and initial metal concentration (IMC) fixed at 2 mL/min and 100 mg/L, respectively. Table 2 shows the performance of the column under each depth. Results showed that the smaller the bed depth, the faster to achieve the breakthrough point. Depth of 3 cm, 6 cm, and 9 cm achieved the breakthrough points at 10, 15, and 60 min, respectively. This trend can be interpreted as follows: at the lowest bed depth, there are few numbers of adsorbent active sites; therefore, it requires a shorter time to achieve a breakthrough point [11].

Figure 1 shows the measured breakthrough curves for adsorption of copper onto activated carbon. It can be observed that the breakthrough time has different trends with different depths. Breakthrough at a depth of 9 cm took the longest time and higher adsorption capacity. This could be attributed to the availability of a large surface area and sufficient contact time [12]. Increasing the bed depth leads to the dominance of diffusion mass transfer over the axial dispersion; therefore, the breakthrough time increases [13].

Figure 2 shows the exhausting points for the three different depths. It is obvious that the higher the depth is, the longer time it takes to exhaust. Bed depth of 3 cm exhausted at time 510 min, bed depth of 6 cm exhausted at 600 min, and bed depth of 9 cm exhausted at 870 min. This can be attributed also to the higher number of adsorbent sites and larger surface area.

A similar observation was reported in the study of copper removal using coimmobilized activated carbon and *Bacillus subtilis* in fixed-bed studies [14]. In addition, a similar trend was observed in cadmium removal from wastewater using sunflower carbon calcium-alginate beads in column studies [15]. Sugar beet shreds were investigated in the removal of copper ions from aqueous solutions using the Box–Behnken design on three levels and three parameters. The shape of the breakthrough was asymmetrical S-shaped [16]. Kenaf fibres were also used to remove copper ions from an aqueous solution in a fixed-bed column. It was reported that breakthrough time and exhaustion time increased with the increase in bed depths [17].

4.2. Effect of Bed Depth on Breakthrough Curves of Cadmium Removal. Cadmium removal under three different depths (Z) was studied (refer to Table 3). It was found that, by increasing the bed depth, the breakthrough and exhausting times increased. Figure 3 shows the trend observed in cadmium adsorption. A similar observation was reported in the adsorption of cadmium into biogenic aragonite shell-derived adsorbents [18].

From Figure 4, it was found that depths of 3 cm, 6 cm, and 9 cm achieved exhausting points at 450 min, 540 min, and 840 min, respectively. This might be assigned to that in higher bed depth; there is more adsorbent which provides more active sites. Therefore, more time was required to achieve saturation.

Many researchers investigated the removal of cadmium using various adsorbents. Sunflower waste carbon calcium-alginate beads were investigated in adsorption and desorption of cadmium ion in fixed-bed studies. It was

Table 2: Performance of the column under different depths.

Z (cm)	Flow rate (mL/min)	IMC mg/L	Breakthrough time (min)	Exhausting time (min)	M_{total} (g)	Removal %	q_e (mg/g)
3	2	100	10	510	102	76.7	24
6	2	100	15	600	120	70.14	12.9
9	2	100	60	870	174	56.49	10

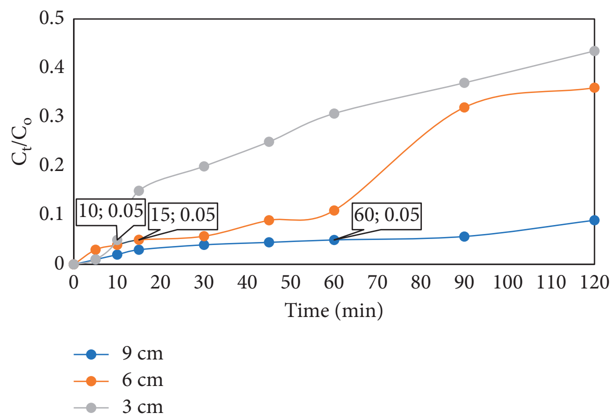

Figure 1: Breakthrough curve for adsorption of copper at different depths.

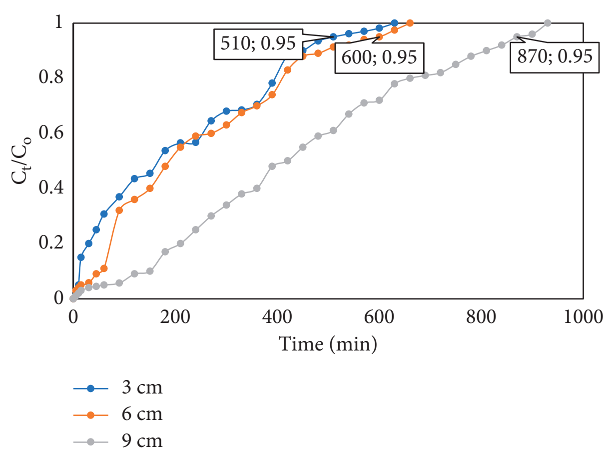

Figure 2: Exhausting points for copper adsorption at different depths.

Table 3: Column performance in cadmium removal at different bed depths.

Z (cm)	Flow rate (mL/min)	IMC mg/L	Breakthrough time (min)	Exhausting time (min)	M_{total} (g)	Removal %	q_e (mg/g)
3	2	100	5	450	90	71.41	28.6
6	2	100	10	540	108	70.93	11.75
9	2	100	30	840	168	64.2	11.02

reported that breakthrough curves, adsorption capacity, and exhaustion time increased with the increase in bed depths. This could be due to the availability of more binding sites at higher bed depths for sorption resulting in a higher mass transfer zone. Similar observations have been reported by Qu et al. [19].

4.3. Kinetics Models for Column Adsorption Studies. The required time to achieve a breakthrough point and the trend of the breakthrough curve are the dominant parameters in the investigation of fixed-bed column behavior. To decide which model is well fitted, correlation coefficients are used, where the higher coefficient indicates better fitting [20].

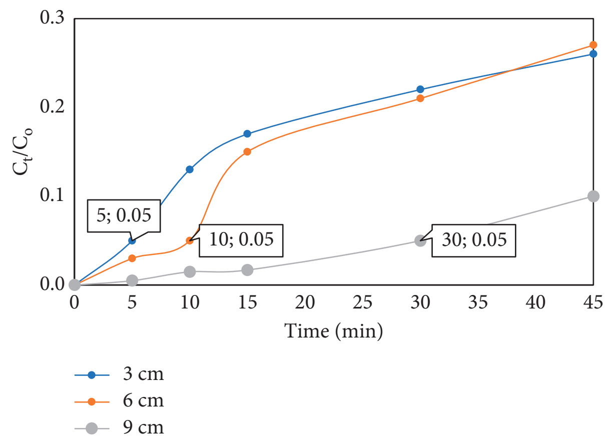

Figure 3: Breakthrough points for cadmium adsorption at different bed depths.

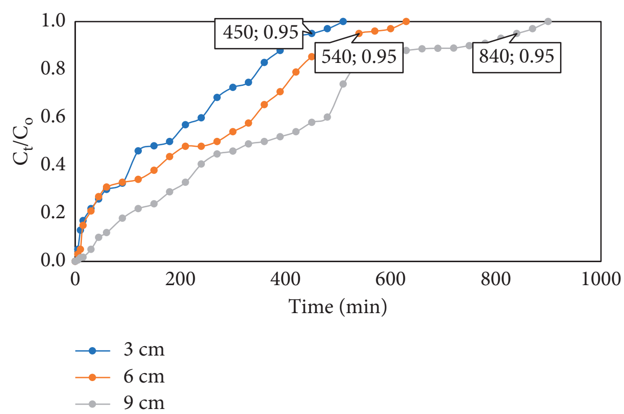

Figure 4: Cadmium removal exhausting time at different depths.

4.3.1. Modeling of Copper Removal by Adams–Bohart Model. In this model, some parameters are determined, such as adsorption capacity $\mathbf{N_o}$ and kinetics constant $\mathbf{K_{ab}}$ as listed in Table 4. It was found that the range of R^2 lay between 0.819 and 0.973, indicating that the model does not perfectly match the experimental data and confirming that the Adams–Bohart model is well suited to use only in the first part of the breakthrough curve (10–50% of saturation point) [12]. With increasing bed depth, adsorption capacity $\mathbf{N_o}$ continues to increase further. This is because longer bed depth contains more active sites and ensures longer contact time [21].

Figure 5 showcases the results from the carried experiments for the first 10% part of the breakthrough curve after fitting to the Adams–Bohart model equation. It can be clearly seen herein that the data for depths of 3 cm and 6 cm are located closely adjacent to trend lines in good agreement. However, for a depth of 9 cm, the points are not the best but relatively in reasonable agreement with the trend line.

4.3.2. Adams–Bohart Model for Cadmium Removal Experiments. The linear trends of the 10% of the initial part of breakthrough curve experimental data were fitted with the Adams–Bohart model equation as shown in Figure 6. The data for depth 3 cm, 6 cm, and 9 cm are located around the trend lines in good agreement. Therefore, the linear relationship can be justified.

The obtained parameters for cadmium removal from the Adams–Bohart model are listed in Table 5. The value of $\mathbf{k_{AB}}$ increases by an increase in bed height. The highest saturation concentration $\mathbf{N_0}$ of 1074.89 mg/L was obtained at depth 3 cm, and then it was decreased at depths of 6 cm and 9 cm to 516.071 mg/L and 956.43 mg/L, respectively. This is because of the availability of more active sites in higher depths [22]. However, R^2 ranged between 0.9 and 0.96, indicating a good quality of fitting.

4.3.3. Yoon–Nelson Model for Copper Removal. Yoon–Nelson model was also applied to investigate the behavior of copper adsorption in column studies. Figure 7 illustrates the results from this column study. The linear plots showcase a higher R^2 value, which suggests that the linear relationship is to be a good fit.

Parameters of this Yoon–Nelson model are listed in Table 6. $\mathbf{K_{YN}}$ and τ are calculated using the slope and intercept of the trend line resulting from the plot of ln $(C_t/C_0 - C_t)$ against time [23] as shown in Figure 7.

The longest 50% breakthrough time τ of 462.39 min was obtained at a bed depth of 9 cm, followed by 247.62 min, which was obtained at a bed depth of 6 cm. Then the shortest

Table 4: Kinetics of the Adams–Bohart model for copper removal.

Flow rate (mL/min)	Z (cm)	K_{ab} (L/min.mg)	N_o (mg/L)	Z/U	R^2
	3	0.00271	1259.25	2.655	0.988
2	6	0.00025	2440.74	5.31	0.966
	9	0.00014	3677.6	7.97	0.756

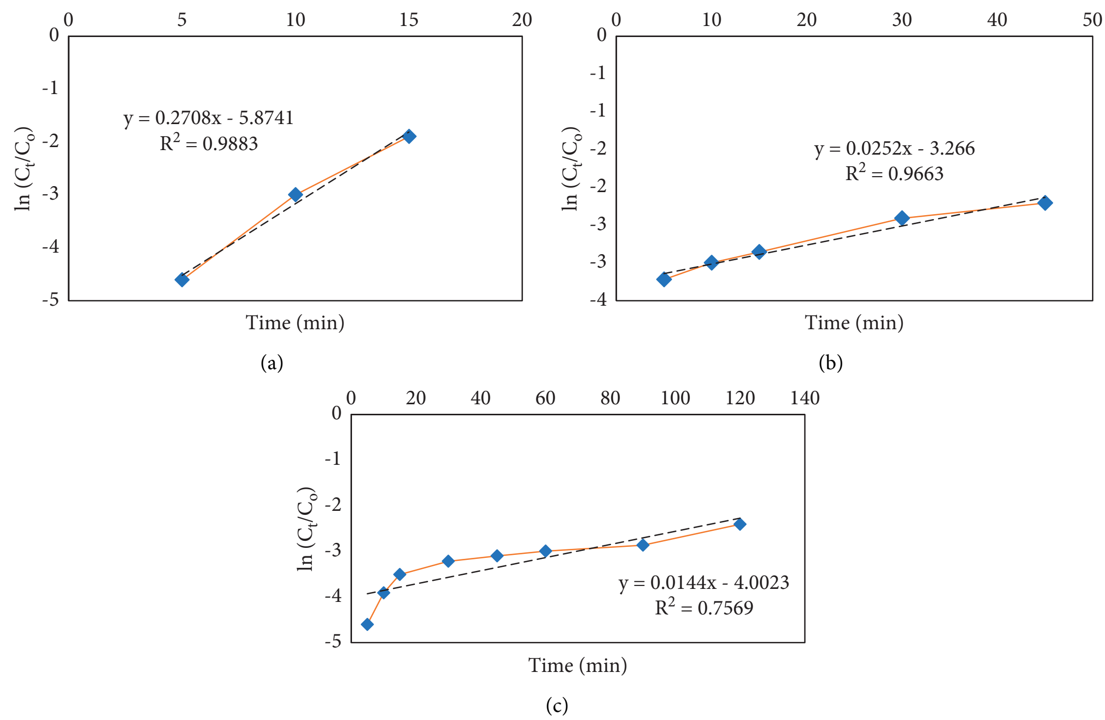

Figure 5: Adams–Bohart model linear form for copper removal at depths. (a) Bed depth of 3 cm. (b) Bed depth of 6 cm. (c) Bed depth of 9 cm.

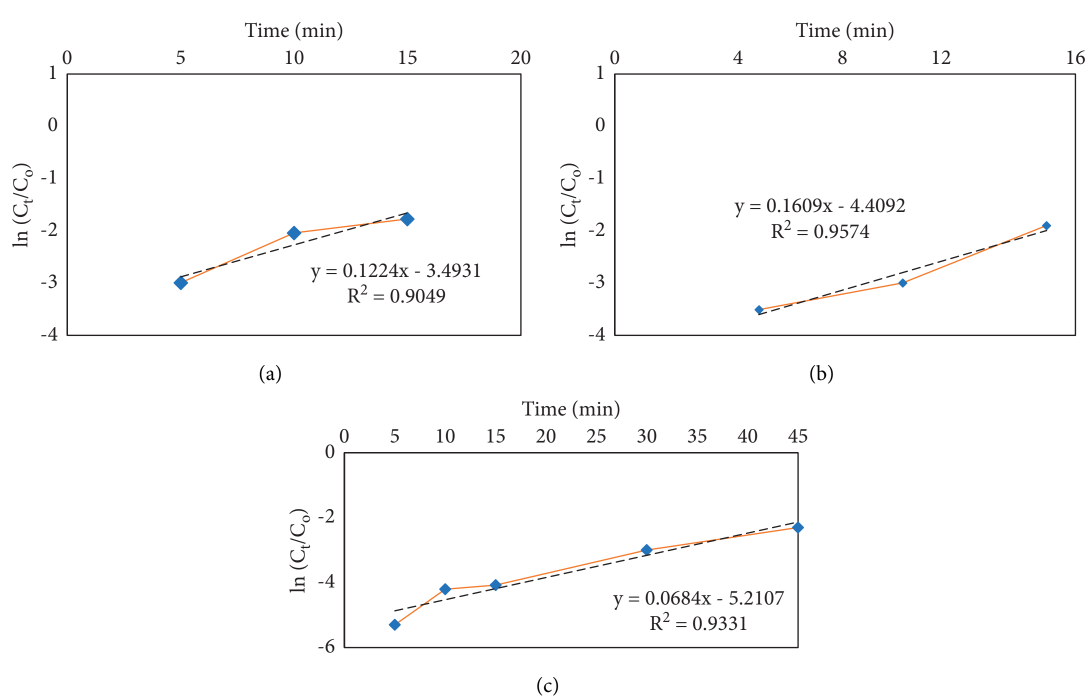

Figure 6: Adams–Bohart model linear form for cadmium removal. (a) For 3 cm. (b) For 6 cm. (c) Bed depth of 9 cm.

Table 5: Kinetics of the Adams–Bohart model for cadmium removal.

Flow rate (mL/min)	Z (cm)	k_{AB} (L/mg.min)	N_0 (mg/L)	Z/U	R^2
	3	0.001224	1074.89	2.655	0.9049
2	6	0.00161	516.071	5.31	0.957
	9	0.000684	956.43	7.965	0.933

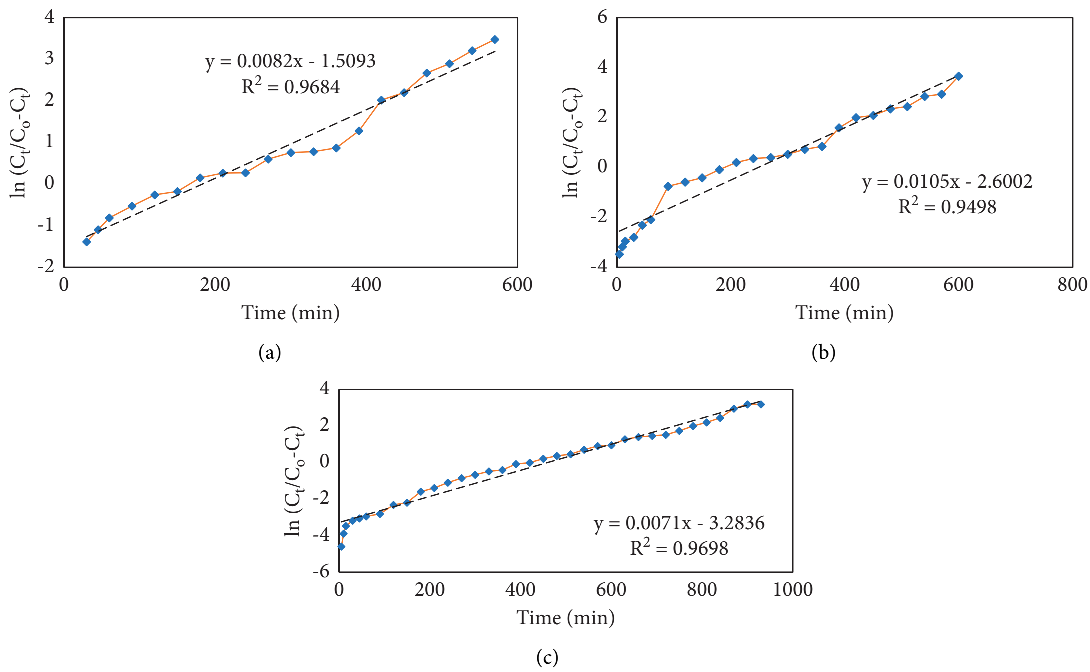

Figure 7: Yoon–Nelson plots for copper removal at different bed depths. (a) Bed depth of 3 cm. (b) Bed depth of 6 cm. (c) Bed depth of 9 cm.

Table 6: Yoon–Nelson parameters for copper removal.

Flow rate (ml/min)	Z (cm)	$\mathbf{K_{YN}}$ (L/min)	τ	R^2
	3	0.0082	184.06	0.97
2	6	0.006	247.62	0.95
	9	0.0036	462.39	0.97

50% breakthrough time τ of 184.06 min was obtained at 3 cm. It is obvious that, with an increase in bed depth, the 50% breakthrough time τ increases, whereas the rate constant $\mathbf{K_{YN}}$ decreases. The lowest $\mathbf{K_{YN}}$ of 0.0036 was obtained at depth 9 cm, followed by 0.006 obtained at depth 6 cm, and then the highest $\mathbf{K_{YN}}$ was obtained at a depth of 3 cm. Correlation coefficients R^2 with an ideal range of 0.95 to 0.97 confirm that the experimental data were well fitted with the Yoon–Nelson Model.

4.3.4. Yoon–Nelson Model for Cadmium Removal Experiments. The adsorption behavior of cadmium in column studies was also tested using the Yoon–Nelson model. $\mathbf{K_{YN}}$ and $\boldsymbol{\tau}$ are calculated using the slope and intercept of the trend line resulting from the plot of $\ln(C_t/(C_0 - C_t))$ against time as shown in Figure 8.

Parameters of this model are tabulated in Table 7. The longest 50% breakthrough time τ of 389.39 min was obtained at a bed depth of 9 cm, followed by 311.98 min, which was obtained at a bed depth of 6 cm. Then the shortest 50% breakthrough time τ of 157.27 min was obtained at 3 cm. It was obvious that, with an increase in bed depth, the 50% breakthrough time τ increases. Similar trend was reported in the modeling of adsorption of hexavalent chromium using *Phanera vahlii* fruit biomass-based activated carbon.

The results showed that the Yoon–Nelson rate constant $\mathbf{K_{YN}}$ was decreased from 0.0108 L/min to 0.0086 L/min with an increase of a bed depth from 3 cm to 6 cm. The lowest constant rate of 0.0074 was obtained at the highest bed depth of 9 cm. The correlation coefficients R^2 ranged between 0.87 and 0.94, confirming that the experimental data were fitted with the Yoon–Nelson model, and it can be used to explain overall kinetics in column studies.

4.3.5. Thomas Model for Copper Removal Experiments. The values of constant rate (k_{TH}) and adsorption capacity q_0 for the Thomas model for copper removal were determined

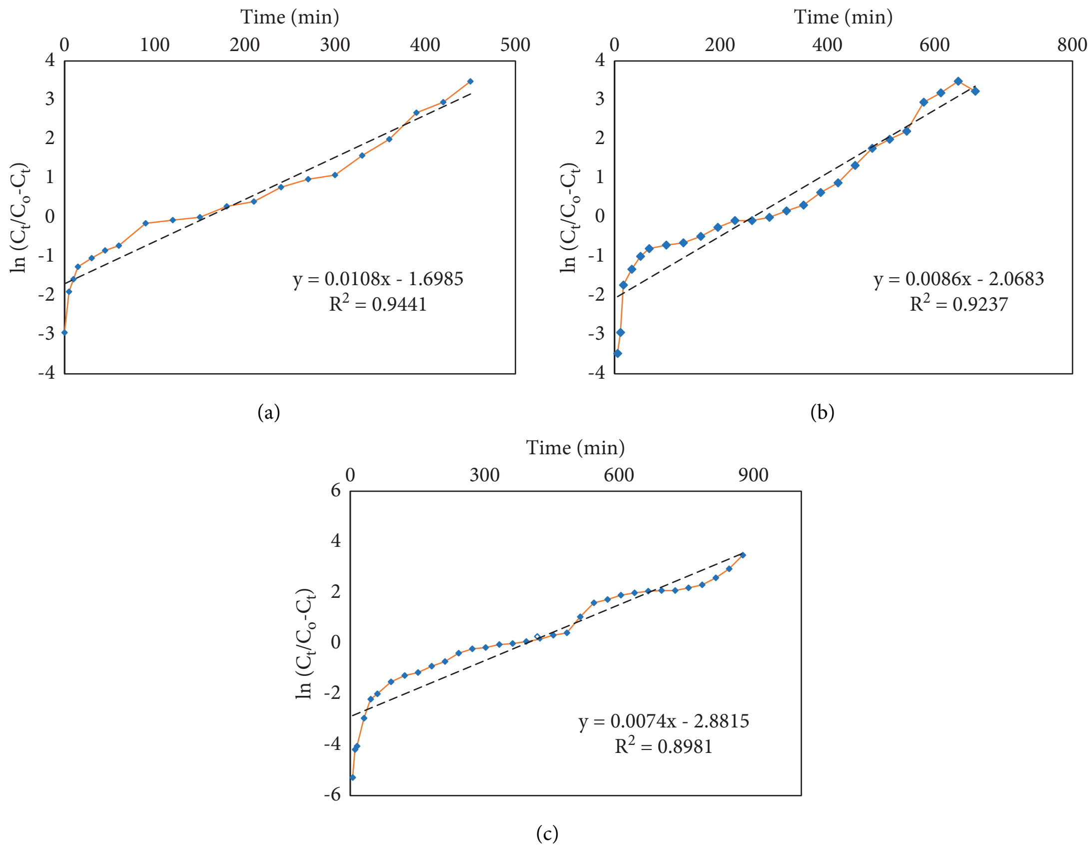

Figure 8: Yoon–Nelson plot for cadmium removal at different bed depths. (a) Bed depth of 3 cm. (b) Bed depth of 6 cm. (c) Bed depth of 9 cm.

Table 7: Yoon–Nelson parameters for cadmium removal.

Flow rate (mL/min)	Z (*cm*)	$\mathbf{K}_{\mathbf{YN}}$ (L/min)	t	R^2
	3	0.0108	157.27	0.944
2	6	0.0086	311.98	0.924
	9	0.0074	389.39	0.898

from the slope and intercept of the trend line resulting from the plot of ln $(C_0/C_t - 1)$ against time as shown in Figure 9.

The parameters of the Thomas model for copper removal data are listed in Table 8. It was found that, at a constant flow rate of 2 mL/min, with an increase in the depth, Thomas constant rate $\mathbf{k}_{\mathbf{TH}}$ increased, and adsorption capacity decreased.

It can be observed that the constant rate was increased from 0.00032 to 0.00064 and 0.0007 with the increases in depths from 3 to 6 and 9 cm, respectively. In contrast, adsorption capacity decreased from 4.06 to 1.21 and 0.96 mg/g with increases in depths from 3 to 6 and 9 cm, respectively. Furthermore, the coefficient of correlation (R^2) was at its highest at a depth of 9 cm with a value of 0.97, and it was 0.94 for the depth of 6 cm. However, at a depth of 3 cm, it was 0.89, which indicated somewhat poor fitting as shown in Figure 9. The points were not in a straight line for the bed depth of 3 cm. Nevertheless, straight lines can be observed for depths of 6 cm and 9 cm.

4.3.6. Thomas Model for Cadmium Removal Experiments. The adsorption behavior of cadmium in column studies was also tested using the Thomas model. The values of constant rate (k_{TH}) and adsorption capacity q_0 were calculated from the slope and intercept of the trend line resulting from the plot of ln $(C_0/C_t - 1)$ against time as shown in Figure 10. The inclinations were negative in these relationships as they were in Figure 9.

The parameters of the Thomas model for cadmium removal data are shown in Table 9. It was found that, at a constant flow rate of 2 mL/min and by increasing in the depths, the Thomas constant rate was increased, but adsorption capacity has been decreased. This could be attributed to the increase in mass transfer resistance due to the increase in depth [5].

Cadmium was removed using oil palm shell-based activated carbon. The adsorption capacity achieved using the Thomas model ranged from 1.4 to 7.4 mg/g with an initial concentration of 200 mg/L and a depth ranging from 3 to

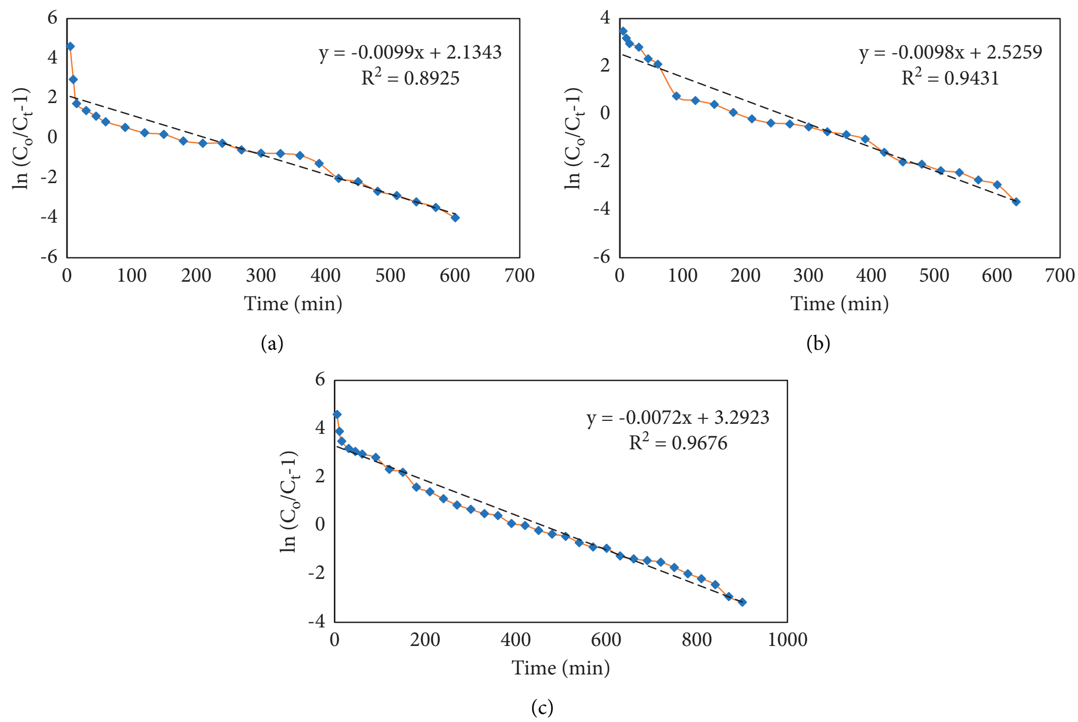

FIGURE 9: Thomas model plot for copper removal at different bed depths. (a) Bed depth of 3 cm. (b) Bed depth of 6 cm. (c) Bed depth of 9 cm.

TABLE 8: Thomas model parameters for copper removal.

Flow rate (mL/min)	Z (cm)	C_0 (mg/L)	k_{TH} (mL/min.mg)	q_0 (mg/g)	R^2
	3	100	0.00032	4.06	0.892
2	6	100	0.00064	1.21	0.943
	9	100	0.0007	0.96	0.967

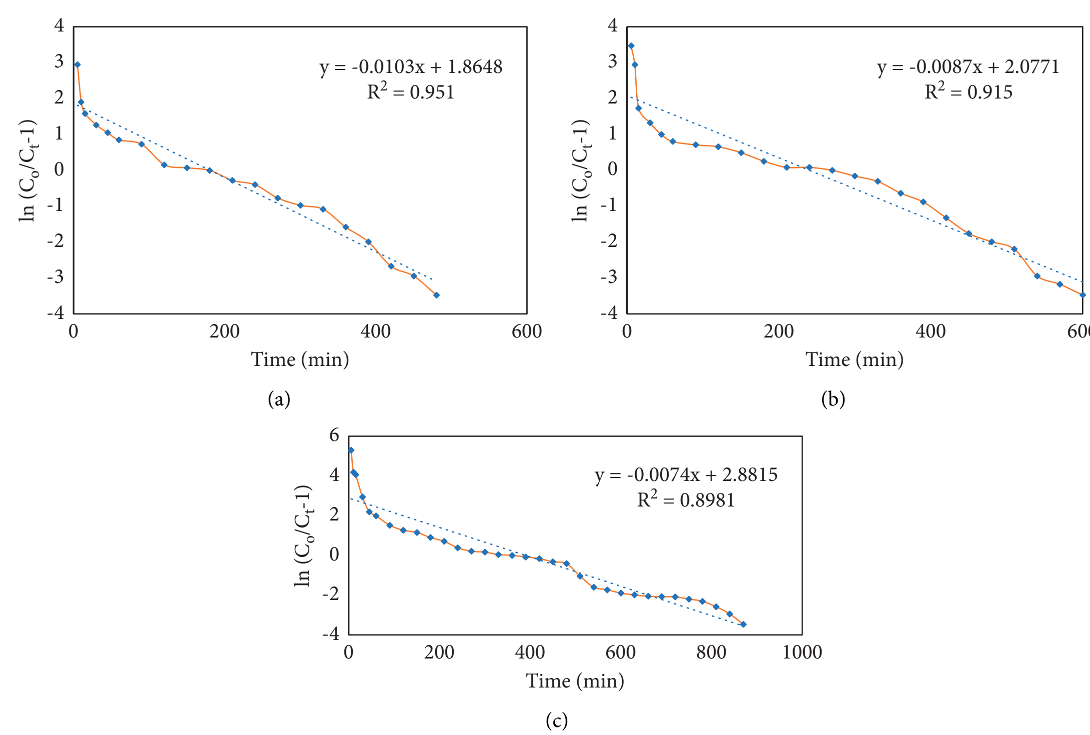

FIGURE 10: Thomas model plot for cadmium removal at different bed depths. (a) Bed depth of 3 cm. (b) Bed depth of 6 cm. (c) Bed depth of 9 cm.

Table 9: Thomas model parameters for cadmium removal.

Flow rate (mL/min)	Z (cm)	C_0 (mg/L)	k_{TH} (mL/min.mg)	q_0 (mg/g)	R^2
	3	100	0.00033578	3.41	0.95
2	6	100	0.00056724	1.12	0.92
	9	100	0.00072372	0.59	0.90

5.5 cm. This can be assigned to the high surface area that formed using oil palm shells compared to sewage sludge [24]. As shown in Figure 10, the correlations coefficients were 0.95, 0.92, and 0.90 for the bed depths 3 cm, 6 cm, and 9 cm, respectively. Therefore, the correlation coefficients proved that the Thomas model was the best to describe the breakthrough curve for cadmium compared to the Yoon–Nelson model. However, the Yoon–Nelson was the best to describe the copper removal breakthrough curve [25].

5. Conclusions

Adsorption experiments at a constant continuous flow of 2 ml/min were carried out to investigate the removal of copper and cadmium from synthetic solutions onto sewage sludge-based activated carbon. Copper and cadmium adsorption were performed in a fixed-bed column under a fixed preoptimized initial metal concentration of 100 ppm and pH of 5. The columns were packed with activated carbon at three different bed depths, 3, 6, and 9 cm, to monitor the behavior of the breakthrough curves. In copper removal, the highest breakthrough point was achieved at 60 min for bed depth of 9 cm, whereas in cadmium removal, the highest breakthrough point was achieved at 30 min for bed depth of 9 cm. Three kinetics models were applied to investigate the breakthrough curves, including Adam–Bohart, Yoon–Nelson, and Thomas. However, the Adams–Bohart model described only the initial part of breakthrough curves. Among them, the Yoon–Nelson model was found to be the best model to describe copper removal data, whereas the Thomas model was the best to describe cadmium removal data. This study showed that sewage sludge could be utilized as a starting material for producing activated carbon which can be applied to remove different types of contaminants.

Data Availability

The data used in this study are available from the corresponding author upon request only for research purposes.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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