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Equilibrium Isotherm Studies for the Multicomponent Adsorption of Lead, Zinc, and Cadmium onto Indonesian Peat

R. Balasubramanian, S. V. Perumal, and K. Vijayaraghavan

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This study evaluates the potential of Indonesian peat to sequester Pb, Cd, and Zn in single-, double-, and triple-solute systems. The adsorption isotherms of Pb, Cd, and Zn onto peat in single-solute and multisolute systems were simulated using the Langmuir two-site model satisfactorily. The model and experimental data of binary and ternary systems demonstrated that the presence of the secondary metal ions in the system resulted in a decrease in the sorption capacity of the primary metal, mainly because of the competitive effects of metals for adsorption sites. The metal adsorption follows the order of sequence Pb > Cd > Zn for both single-solute and multisolute systems. A three-dimensional representation of the total metal uptake in binary systems showed a good agreement with the corresponding experimental data. In addition to ion exchange, a surface adsorption—complexation mechanism must be involved in the sorption mechanism of metal ions. Fourier transform IR results confirm that the carboxyl functional groups participated in metal binding. Desorption experiments revealed that greater than 90% of Pb, Cd, and Zn can be eluted from the peat. In addition, results suggested that the desorption efficiency decreased with an increase in the adsorbed metal concentration.

1. Introduction

The increase of industrial activities has intensified environmental pollution problems with the accumulation of many pollutants, especially heavy metals. Heavy metals are generally considered as a threat toward human health and ecosystems because of their potential high toxicity. Pb, Zn, and Cd belong to the group of serious hazardous heavy metals. Treatment processes for metal-contaminated wastewater include adsorption, and over the past 2 decades, research on heavy-metal adsorption has focused on the use of low-cost and effective sorbents.

Peat is defined as young coal, organogenic sedimentary rock in the first stage of coalification and ranks as one of the lowest grades of solid carbonaceous fuels. The material composed primarily of vegetable tissue in various stages of decomposition usually has a dark-brown to black color, a distinctive odor of decaying vegetation, and a spongy consistency without exhibiting distinct plasticity. According to the incomplete list of peat resources, ~77% of peat deposits occur in Canada and the U.S.A. and 7.5% in Scandinavia. In the southern hemisphere, the richest deposits are in Indonesia (>6%) and in other subtropical regions of Central and South America and Africa. Peat is a natural material containing lignin, cellulose, and humic acid as its major constituents. These constituents are potentially very useful from an adsorption standpoint because they contain polar functional groups such as alcohols, aldehydes, carboxylic acids, ketones, and phenolic hydroxides, which can all be involved in heavy-metal adsorption. Peat is known to have excellent ion-exchange properties similar to natural zeolites. For exploration of its potential application, the sorption capacity and binding strength of peat with respect to various metal ions under different conditions, as well as the binding-release mechanisms, should be thoroughly investigated and reported in the literature. To date, this knowledge is still limited, and a complete understanding of the adsorption mechanism is yet to be fully elucidated. A comparison of the available adsorption data is also difficult because of the great variety of peat types and the lack of information on their performance characteristics.

Thus, this study was aimed at examining the adsorption capacity of Indonesian peat toward three metals (Pb, Zn, and Cd) in single-metal and multimetal systems. Also, the mechanism involved in the removal of these metal ions onto the peat was studied in detail. Results obtained from this study are presented and discussed.

2. Experimental Methods

2.1. Materials. The peat sample used in this study was collected from Sungai Sembilan peat deposit, a subprovince 200 km away from the city of Dumai in Sumatra, Indonesia. The subsurface layer of the peat was collected from the site. It was then dried under sunlight for 3 days and further dried in the oven at 60 °C for 2 days. The sample was then ground and sieved through a 150 μm sieve, followed by usage in experimental studies. All chemicals obtained from Merck (Darmstadt, Germany) including Pb(NO3)2, ZnCl2, and 3CdSO4·8H2O were of analytical grade.

<table>
<thead>
<tr>
<th>Table 1. Physical Properties of Peat</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH&lt;sub&gt;pzc&lt;/sub&gt;</td>
</tr>
<tr>
<td>organic matter (%)</td>
</tr>
<tr>
<td>C (%)</td>
</tr>
<tr>
<td>H (%)</td>
</tr>
<tr>
<td>N (%)</td>
</tr>
<tr>
<td>BET surface area (m&lt;sup&gt;2&lt;/sup&gt;/g)</td>
</tr>
<tr>
<td>pore volume (cm&lt;sup&gt;3&lt;/sup&gt;/g)</td>
</tr>
</tbody>
</table>

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† Division of Environmental Science and Engineering.
‡ Singapore—Delft Water Alliance.
Concentration

MileStone MLS 1200 Mega microwave digestor, 8 filtered present in the raw peat was determined using the closed-vessel overall physical characterization of the adsorbent is outlined in Perkin-Elmer PE 2400 series II CHNS/O microanalyzer. The tively. Elemental composition analysis was performed using a by BET and Barret–Joyner–Hallenda (BJH) methods, respec-

Emmett using the nitrogen gas adsorption technique using a Brunauer surface area and total pore size distribution were determined

Figure 2. Adsorption kinetics of Pb, Zn, and Cd onto peat (pH 6; temperature = 23 ± 2 °C; initial metal concentration = 20 mg/L).

through 0.2 µm poly(tetrafluoroethylene) syringe filters, and analyzed by inductively coupled plasma-mass spectrometry (ICP-MS; Perkin-Elmer Elan 6100). The concentrations (µg/ml) of heavy metals were as follows: Fe, 570.4; Cu, 12.51; Pb, 2.58; Zn, 698.2; Ni, 15.69; Ar, 39.72. The determination of the pHpzc of the sample was carried out as follows: 50 mL of a 0.01 M NaCl solution was placed in a closed Erlenmeyer flask. The pH was adjusted to a value between 2 and 12 by adding 0.1 M HCl or NaOH. Then, 0.15 g of each peat sample was added, and the final pH was measured after 48 h under agitation at 25 °C. The pHpzc is the point where the curve pHfinal vs pHinitial crosses the line pHinitial = pHfinal.

2.2.2. IR Analysis. The predominant functional groups of the peat adsorbent were determined using a Shimadzu FTIR-8400 Fourier transform IR spectrophotometer. The samples were prepared in the form of pellets using KBr.

2.2.3. Ion-Exchange Mechanism. The existence of an ion-exchange mechanism was investigated in this study by measuring the release of Ca²⁺, Mg²⁺, and K⁺ ions from the peat adsorbent during the adsorption of Pb, Zn, and Cd. For these experiments, 0.5 g of adsorbent was added to 100 mL of a metal solution (100 mg/L) maintained at pH 6. The peat suspension was then stirred until the equilibrium time was reached and was analyzed using ICP optical emission spectroscopy.

2.3. Adsorption Isotherm and Kinetics. Single, binary, and ternary adsorption of Pb(II), Zn(II), and Cd(II) ions onto Indonesian peat was performed in a batch mode at 23 ± 2 °C. Basically, 0.1 g of the adsorbent was added to 100 mL of solute concentration, at the desired pH, in 250 mL Erlenmeyer flasks and was agitated at 150 rpm in a rotary shaker until the equilibrium time was reached. The pH of the solution was adjusted using 0.1 M HNO₃ or NaOH. At the end of the experiment, the content of the flask was separated by filtration, using Whatman No. 1 filter paper. The concentration of the metal ions in the filtrate was determined using ICP Auger emission spectroscopy (Perkin-Elmer Optima 3000). The influence of the pH (3–7) and the mass concentration of adsorbent (0.5–1.0 g/L) on the uptake capacity was studied for optimiza-

Table 2. Single-Solute Model Parameters with Error Analysis for Pb, Cd, and Zn onto Peat

<table>
<thead>
<tr>
<th>parameter</th>
<th>Pb</th>
<th>Cd</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_m$ (mg/g)</td>
<td>79.68 ± 0.45</td>
<td>37.39 ± 0.1</td>
<td>23.00 ± 0.97</td>
</tr>
<tr>
<td>$h$ (L/mg)</td>
<td>0.17 ± 0.01</td>
<td>0.47 ± 0.01</td>
<td>0.13 ± 0.03</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.947</td>
<td>0.961</td>
<td>0.972</td>
</tr>
<tr>
<td>SE</td>
<td>7.80</td>
<td>2.31</td>
<td>2.28</td>
</tr>
</tbody>
</table>

Langmuir Two-Site Model

| $q_m$ (mg/g) | 10.42 ± 0.43 | 13.99 ± 0.15 | 6.91 ± 0.61 |
| $h$ (L/mg) | 8.45 ± 1.35 | 3.11 ± 0.01 | 3.36 ± 1.29 |
| $a_1$ (mg/g) | 93.61 ± 3.70 | 43.59 ± 1.47 | 25.16 ± 2.84 |
| $a_2$ (L/mg) | 0.08 ± 0.01 | 0.024 | 0.07 ± 0.04 |
| $q_m$ (mg/g) | 103.95 | 57.58 | 32.07 |
| $R^2$ | 0.998 | 0.999 | 0.991 |
| SE | 1.15 | 0.62 | 1.06 |

Freundlich Model

| $K_F$ (L/g) | 13.01 ± 0.87 | 3.65 ± 0.01 | 4.72 ± 0.23 |
| $1/n$ | 0.46 ± 0.02 | 0.47 ± 0.01 | 0.34 ± 0.01 |
| $R^2$ | 0.997 | 0.977 | 0.972 |
| SE | 2.04 | 1.50 | 1.34 |

2.2. Methods. 2.2.1. Characterization of the Adsorbent. Surface characteristics of the adsorbent such as the specific surface area and total pore size distribution were determined using the nitrogen gas adsorption technique using a Brunauer—Emmett—Teller (BET) NOVA-3000 version 6.07 micropore analyzer. The surface area and total pore volume were calculated by BET and Barret–Joyner–Hallenda (BJH) methods, respectively. Elemental composition analysis was performed using a Perkin-Elmer PE 2400 series II CHNS/O microanalyzer. The overall physical characterization of the adsorbent is outlined in Table 1. The average concentration of the heavy-metal ions present in the raw peat was determined using the closed-vessel MileStone MLS 1200 Mega microwave digestor, 8 filtered

Figure 1. Effect of the peat dosage on the adsorption of Pb, Zn, and Cd (pH 6; temperature = 23 ± 2 °C; initial metal concentration = 20 mg/L).
ducted in duplicate, and the average values were reported. The evaluation of the specific metal uptake \( q_e \) (mg/g of dry weight adsorbent) was obtained by using mass balances of the metal and adsorbent in the system:

\[
q_e = \frac{V(C_0 - C_e)}{M}
\]

where \( C_0 \) and \( C_e \) are the initial and equilibrium metal concentrations in the solution (mg/L), respectively, \( V \) is the solution volume (L), and \( M \) is the mass of the adsorbent (g).

2.4. Adsorption Models. The distribution of the metal ion between the liquid phase and sorbent is a measure of the position of equilibrium in the adsorption process and can generally be expressed by a series of isotherms. In this work, the Langmuir isotherm, two-site Langmuir isotherm, and Freundlich isotherm were used to describe the equilibrium isotherm data and can be represented as follows:

Langmuir model:\(^{10}\)

\[
q_e = \frac{bq_m C_e}{1 + b C_e}
\]

Langmuir two-site model:\(^{11}\)

\[
q'_m = \frac{b_1 q_{m,1} C_e + b_2 q_{m,2} C_e}{1 + b_1 C_e + 1 + b_2 C_e}
\]

Freundlich model:\(^{12}\)

\[
q_e = K_F C_e^{1/n}
\]

where \( q_m \) is the maximum adsorption capacity (mg/g), \( q_{m,1} \) and \( q_{m,2} \) are the maximum populations of adsorption sites for two different sites (mg/g), respectively, \( b, b_1, \) and \( b_2 \) are the adsorption equilibrium constants (L/mg), \( K_F \) is the equilibrium constant indicative of the adsorption capacity (L/g), and \( 1/n \) is the adsorption constant whose reciprocal is indicative of the adsorption intensity. For the fitting of the Langmuir two-site model, the total adsorption maximum capacity \( (q'_m) \) should be

\[
q'_m = q_{m,1} + q_{m,2}
\]

The goodness of fitting of the above-mentioned models was verified by using the following equation:

\[
SE = \left[ \sum (q - q^*)^2 / (n - 2) \right]^{1/2}
\]

where \( SE \) represents the standard error, \( q \) the measured adsorption capacity, \( q^* \) the predicted adsorption capacity, and \( n \) the number of experimental points.

2.5. Desorption. To evaluate the desorption efficiency, the metal-loaded peat obtained from equilibrium sorption experiments was dried at 60 °C for 24 h. The dried peat was then contacted with 100 mL of 0.1 M HNO\(_3\) for 24 h to allow the metals to be released into the aqueous solution. The filtrate was then analyzed for desorbed metals, and the desorption efficiency was calculated as follows:

\[
\text{efficiency (\%)} = \frac{\text{released metal (mg/L)}}{\text{initial sorbed metal (mg/L)}} \times 100
\]

3. Results and Discussion

The surface area and pore volume of the peat sample are shown in Table 1, which are almost comparable with the findings reported in the other parts of the world for peat.\(^{13}\)

3.1. Batch Adsorption Equilibrium. Batch equilibrium adsorption experiments were performed at different pH values in the range of 3–7 and variable doses of peat in the range of 0.5–5 g/L. The initial metal concentration was fixed at 10 mg/L. The removal of Pb, Zn, and Cd by the adsorbent is highly dependent on the pH, with maximum adsorption at the highest pH values. Optimum adsorption occurs at pH 6 without any precipitation of ions from the solution. The solution pH usually plays a major role in adsorption and seems to affect the solution chemistry of the metals and the surface charge of the adsorbent. The pH\(_{PZC}\) is an important characteristic of any adsorbent because it indicates the surface charge of the adsorbent in the solution. Any oxide surface creates a charge (positive or negative) on its surface, which is proportional to the pH of the solution surrounding the oxide particles. A convenient index of the propensity of a surface to become either positively or negatively charged as a function of the pH is the pH value
required to give zero net surface charge (pH\text{PZC}). From the pH drift data, the pH\text{PZC} of peat was determined as 6.56. At pH < pH\text{PZC}, the peat surface will have a net positive charge, while at pH > pH\text{PZC}, the surface will have a net negative charge.\textsuperscript{14} The pH also influences the chemical speciation of metals in the solution. For instance, Pb\text{II} exists as Pb\text{Zn} and PbOH\text{+} at pH ≤ 6, beyond which Pb(OH)\text{3} tends to dominate.\textsuperscript{15} In the case of Cd\text{II}, it exists as Cd\text{Zn} up to pH ~8.0, after which CdOH\text{+} and Cd(OH)\text{2} start to form.\textsuperscript{16} On the other hand, Zn\text{II} is present mainly as Zn\text{Zn} at pH < 7, and at pH 8 ~9, it exists mainly as Zn\text{Zn} and Zn(OH)\text{2} and in lesser quantities as Zn(OH)\text{3}.\textsuperscript{17} Therefore, at pH 6, the predominant species of Pb, Cd, and Zn were Pb\text{Zn}, Cd\text{Zn}, and Zn\text{Zn}, respectively, and were adsorbed onto the peat surface.

The influence of the peat dosage on Pb, Zn, and Cd adsorption was examined by varying dosages from 0.5 to 5 g/L. Figure 1 presents a typical set of results obtained by varying adsorbent dosages during Pb, Zn, and Cd adsorption. From the analysis of the experimental data obtained for three metal ions, it was observed that the removal efficiency increases with an increase in the adsorbent dosage. An increase in the adsorbent concentration generally increases the adsorbed metal ions because of an increase in the surface area of the adsorbent, which, in turn, increases the number of binding sites.\textsuperscript{18,19} On the other hand, the metal uptake decreases with an increase in the adsorbent dosage. This anomaly may be due to complex interactions of several factors. The important factor is that at high sorbent dosages the available metal ions are insufficient to cover all of the exchangeable sites on the adsorbent, usually resulting in a low metal uptake. In the present study, the lowest adsorbent dosage (0.5 g/L) resulted in the highest metal uptake capacity and the lowest removal efficiency. The metal uptake capacity and removal efficiency are equally important in sorption experiments because both usually take part in decisions about the sorption performance of a given adsorbent. Taking this into consideration, the adsorbent dosage of 1 g/L was selected for further studies because it showed both relatively high metal uptake and removal efficiency for all three metal ions.

Kinetics experiments showed that the adsorption of Pb, Zn, and Cd onto peat increased with the lapse of time (Figure 2). The adsorption rate was rapid for the first 30 min of contact, after which the rate slowed down. The complete adsorption equilibrium was attained within 210 min, and this equilibrium time is found to be the same for all of the sorbates studied.

### 3.2. Adsorption Isotherms of Pb, Zn, and Cd onto Peat in Single-Solute Systems

Langmuir one-site and Freundlich and Langmuir two-site models were used to fit the adsorption isotherm of Pb, Zn, and Cd onto peat in single-solute systems. The isotherm parameters and SE are summarized in Table 2. The Langmuir two-site model was found to describe the isotherms well, followed by Freundlich and Langmuir one-site models. The Langmuir two-site model was developed based on the Langmuir one-site model to solve the heterogeneity problem of adsorption sites. It has been successfully applied to represent the equilibrium adsorption data of Cd onto bone char\textsuperscript{20} and Pb onto activated carbon.\textsuperscript{21} The equilibrium constant \( b_1 \) value was much higher than that of \( b_2 \), indicating that the surface of peat was heterogeneous. The high-energy sites with higher equilibrium constants \( (b_1) \) had a significantly higher affinity than that for low-energy sites with lower equilibrium constants \( (b_2) \). The high-energy sites on which metals were tightly held had a low adsorption maximum \( (q_{m,1}) \). The low-energy sites on which metals were loosely held had a high adsorption maximum \( (q_{m,2}) \), accounting for 88.7%, 75.3%, and 78.7% of the total Pb, Cd, and Zn adsorption, respectively. The metal adsorption follows the order of sequence Pb > Cd > Zn. This order may be related to the differences in the electronegativity and ionic radius of the atoms. The electronegativity decreases in the following order: Pb (2.33) > Cd (1.69) > Zn (1.65). Similarly, the ionic radius of Pb was found to be relatively high (133 pm), compared to those of Cd (109 pm) and Zn (88 pm). Thus, it can be confirmed that both the electronegativity and ionic radius determine the order of preference of metal binding onto peat.

#### 3.3. Adsorption Isotherms of Pb, Zn, and Cd onto Peat in Multisolute Systems

The competitive adsorption isotherms in binary and ternary mixtures of Pb, Zn, and Cd onto peat are shown in Figure 3. Because the Langmuir two-site model gives a better fit for the single-solute systems, the same model was used to simulate the competitive adsorption isotherms for the multisolute systems and the results are summarized in Table 3. From the results obtained, it was observed that Pb was favorably adsorbed onto peat over Cd and Zn and Cd over Zn in the multisolute systems. Also, when compared with their adsorption in single-solute systems, the individual adsorption capacities \( (q_{m}) \) of all of the three metals showed obvious decreases both in binary and in ternary systems; the decrease was greater in the ternary systems as compared to the binary systems. These results indicated the competitiveness between the metals for the adsorption sites. Moreover, \( q_{m,2} \) decreased to a much larger degree than \( q_{m,1} \), indicating that the competitive effect of Pb, Cd, and Zn mainly took place on the low-energy sites. Because metals on the low-energy sites were loosely held, they could be easily replaced by other metal ions.

#### 3.4. Model Development for Binary Component Systems

The total equilibrium uptake capacities of binary systems were fitted to the extended Langmuir model. The model was developed based on the concept of the original Langmuir model, which can be expressed as\textsuperscript{22}

\[
q[M + N] = \frac{b_M C_M[M] + b_N C_N[N]}{1 + b_M C_M[M] + b_N C_N[N]}
\]
The binary component system, and $M$ and $N$, respectively, where $q$, $m$, $e$, $K^+$, $R_{nb}$, $q_m$, $e_M$, and $e_N$ are the sorption capacities of the two metal components $M$ and $N$, respectively. The parameters of the model were estimated using the MS EXCEL 2003 program, whereas the three-dimensional adsorption isotherm surfaces were generated using MATLAB, version 7. Figure 4 presents the three-dimensional isotherm plots for the total metal uptakes of the Pb–Cd, Pb–Zn, and Zn–Cd systems. Here the continuous surface of the plot represents the model prediction and the experimental results are shown by discrete points. From Figure 4, it is evident that the experimental points fit adequately to the predicted isotherm surface. Also, Figure 3 and Table 3 reveal that (i) the total sorption capacity for double and triple-solute systems was higher when compared to the adsorption capacity in single-solute systems, attributed to the greater adsorption in the combined system than that on sites specific for each ion and (ii) the individual metal adsorption in binary and ternary systems shows a decrease in trend mainly due to metal interaction and competition for adsorption sites.

### 3.5. Ion-Exchange Mechanism

The phenomenon of ion exchange during the sorption of $Pb^{2+}$, $Zn^{2+}$ and $Cd^{2+}$ ions onto peat was studied by calculation of the amount of $Ca^{2+}$, $Mg^{2+}$, and $K^+$ released from the adsorbent (Table 4). Because the adsorbent was not washed, the release of dissolved cations ($Ca^{2+}$, $Mg^{2+}$, and $K^+$) by simple dissolution without ion exchange was also measured. The net release of cations (mequiv/g) due to Pb, Zn, and Cd sorption has been calculated by subtraction of the amount of dissolved cations released (control) to the amount of cations measured in the supernatant after Pb, Zn, and Cd sorption processes. The effect of protons in the exchange mechanism has been neglected because almost no significant variation of the pH during the sorption process was observed. As seen in Table 4, there is a significant release of $Ca^{2+}$, $Mg^{2+}$, and $K^+$ from the peat adsorbent due to the uptake of $Pb^{2+}$, $Zn^{2+}$, and $Cd^{2+}$ ions. It appears that there was more $Ca^{2+}$ released than the other cations, which is consistent with the fact that Ca is the major cation present in peat. For the ion-exchange phenomenon, the relative quantities of the heavy-metal ions taken up by the sorbent and the alkaline-earth metals released into the aqueous solution should be approximately equal. Therefore, the coefficients $R_{nb}$ were calculated as the ratio of sum of the cation released during adsorption to the metal bound on the peat sorbent. From Table 4, it was observed that, for every 1 mol of Pb, Cd, and Zn adsorbed, 0.76, 0.62, and 0.58 mol of exchangeable cations were released. From the results, it was confirmed that, in addition to ion exchange, a surface adsorption–complexation mechanism may be involved in the sorption of metals. Earlier studies have found evidence that peat takes up metal ions through complexation, surface absorption, and chemisorption.

### 3.6. FTIR

The FTIR spectrum of the peat adsorbent displays a number of absorption peaks, indicating the complex nature of the adsorbent. The following peaks were observed in the

---

**Table 4. Release of Exchangeable Ions ($Ca^{2+}$, $Mg^{2+}$, and $K^+$) Due to Sorption of $Pb^{2+}$, $Zn^{2+}$, and $Cd^{2+}$ onto Peat**

<table>
<thead>
<tr>
<th>system</th>
<th>total metal bound (mM)</th>
<th>amount of cation released (mM)</th>
<th>$R_{nb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb$^{2+}$</td>
<td>Zn$^{2+}$</td>
<td>Cd$^{2+}$</td>
<td>Ca$^{2+}$</td>
</tr>
<tr>
<td>control</td>
<td>0.0882</td>
<td>0.1735</td>
<td>0.1286</td>
</tr>
<tr>
<td>Pb$^{2+}$</td>
<td>0.0262</td>
<td>0.057</td>
<td>0.0785</td>
</tr>
<tr>
<td>Zn$^{2+}$</td>
<td>0.0353</td>
<td>0.0690</td>
<td>0.0209</td>
</tr>
<tr>
<td>Cd$^{2+}$</td>
<td>0.0123</td>
<td>0.00109</td>
<td>0.0029</td>
</tr>
</tbody>
</table>

---

**Figure 4.** Three-dimensional binary sorption isotherm surface for the total adsorption capacity of (a) Pb–Cd, (b) Pb–Zn, and (c) Zn–Cd systems (continuous surface, model prediction; discrete points, experimental results).
spectrum (Figure 5): (1) the OH stretch of aliphatic alcohols in carbohydrates (3500–3200 cm\(^{-1}\)), adsorbed water (3400 cm\(^{-1}\)), phenols from lignin (3300 cm\(^{-1}\)), and possibly some contribution from carboxylic acids (3100–2300 cm\(^{-1}\)), (2) the CH stretch of aliphatic carbons (small peaks at 2850 and 2950 cm\(^{-1}\)), (3) the band centered in 1720 cm\(^{-1}\) assigned to the C\(_{\text{d}}\)O stretch from carboxylic groups, (4) the C\(_{\text{d}}\)C stretch, probably from the aromatic ring carbon in lignin (large peak at 1610 cm\(^{-1}\) and a smaller peak at 1500 cm\(^{-1}\)), (5) the band centered in 1720 cm\(^{-1}\) assigned to the C\(_{\text{d}}\)=O stretch from carboxylic groups, (4) the C\(_{\text{d}}\)=O stretch, probably from the aromatic ring carbon in lignin (large peak at 1610 cm\(^{-1}\) and a smaller peak at 1500 cm\(^{-1}\)), (5) the broad absorption band between 1450 and 950 cm\(^{-1}\) composed of individual peaks from the CH bending of aliphatic carbons (methylene 1450–1475 cm\(^{-1}\) and methyl 1365–1390 cm\(^{-1}\)) and the CO stretch in esters (1130–1260 cm\(^{-1}\)), phenols (1125–1190 cm\(^{-1}\)), ethers (1110–1155 cm\(^{-1}\)), and aliphatic alcohols (1030–1108 cm\(^{-1}\)), and (6) two small peaks at 815 and 750 cm\(^{-1}\) representing out-of-plane CH bending in aromatic compounds.\(^{27}\) In order to investigate the functional groups responsible for adsorption, FTIR spectra of peat samples with and without metals loaded are compared in Figure 5. The broad absorption peak around 3365 cm\(^{-1}\) are indicative of both −OH and −NH groups present in the adsorbent. The metal-adsorbed peat exhibited a stretching band shift at 1723.5 and 1631 cm\(^{-1}\), corresponding to the complexation of metal ions toward C\(_{\text{d}}\)=O and C\(_{\text{d}}\)=O bonds. In general, carbon−oxygen surface functional groups were considered to be responsible for the adsorption of heavy-metal ions.\(^{28}\) Also, a small increase in the intensity of peak and a band shift at 1430.5 cm\(^{-1}\) are attributed to the C−H bending. The formation of a new peak at 2365.4 cm\(^{-1}\) shows the possibility of some contribution from carboxylic acid to the adsorption. Thus, it seems that these functional groups are likely to participate in metal binding.

3.7. Desorption Studies. To investigate the feasibility of reusing the adsorbent and metal ions, desorption experiments were conducted. The desorption was attempted by elution of the metal-loaded peat with 0.1 M HNO\(_3\) at different metal concentrations of Pb, Cd, and Zn. Figure 6 explains the desorption results of Pb-, Cd-, and Zn-loaded peat, with maximum desorption observed as 96.6%, 92.9%, and 90.1%, respectively, at an initial metal concentration of 10 mg/L. Also, Figure 6 clearly explains that the desorption efficiency decreased with an increase in the adsorbed metal concentration. This implies that when more metal ions were loaded onto peat, the volume of elutant was not sufficient to desorb all of the metal ions.

4. Conclusion
This work confirms the potential use of the Indonesian (Sumatra) peat as a metal adsorbent. The adsorption isotherms of Pb, Cd, and Zn in single-solute and multisolute systems were simulated using the Langmuir two-site model satisfactorily. The model and experimental data of binary and ternary systems demonstrated that the presence of secondary metal ions in the system resulted in a decreased sorption capacity of the primary metal, mainly due to the competitive effect of metal ions for adsorption sites. In the multisolute systems, the uptake at the low-energy sites (\(q_{\text{m,2}}\)) decreased to a larger degree when compared to that at the high-energy sites (\(q_{\text{m,1}}\)), which confirms that the competitive effects of Pb, Cd, and Zn mainly occurred at low-energy sites. The metal adsorption follows the order of
sequence Pb > Cd > Zn, for both single-solute and multisolute systems. A three-dimensional representation of the total metal uptake in binary systems showed a good agreement with the corresponding experimental data. Furthermore, the mechanism study confirmed that, in addition to ion exchange, a surface adsorption–complexation mechanism may also be involved in the sorption of metals. The FTIR analysis demonstrated that the carboxyl functional groups were mainly responsible for the metal binding. Approximately greater than 90% of Pb, Cd, and Zn can be eluted from the peat; however, the desorption efficiency decreased with an increase in the loaded metal concentration. Overall, this study provides insight into the uptake mechanism and adsorption behavior of peat for both single-component and multicomponent systems.

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