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Acid leaching of heavy metals from contaminated soil collected from Jeddah, Saudi Arabia: kinetic and thermodynamics studies

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Abstract

Urban soils polluted with heavy metals are of increasing concern because it is greatly affecting human health and the ecological systems. Hence, it is mandatory to understand the reasons behind this pollution and remediate the contaminated solid. The removal of heavy metals from contaminated soil samples collected from the vicinity of the sewage lake in Jeddah, Saudi Arabia, was explored. The leaching process was studied kinetically and thermodynamically for better understanding of the remediation process. The results showed that the soil samples were slightly basic in nature, and tend to be more neutral away from the main contaminated sewage lake area. The total metal content in the soil samples were measured using the aqua regia extractions by ICP-OES and the results showed that many of
the heavy metals present have significant concentrations above the tolerable limits. In general, the metal concentrations at different sites indicated that the heavy metal pollution is mainly due to the sewage discharge to the lake. The results showed excellent correlation between the concentrations of Co, As, and Hg with the distance from the main contaminated area. The leaching of Co, As, and Hg using 1.0 M hydrochloric acid from the soil was studied kinetically at different temperatures and the experimental results were fitted using different kinetics models. The experimental data were best described with two-constant rate and Elovich equation kinetic models. Also, the thermodynamic study showed that the leaching process was, spontaneous, endothermic and accompanied with increase in the entropy. In general, the polluted soil could be remediated successfully from the heavy metals using the acid leaching procedure in a short period of time.

Keywords: Acid leaching; Contaminated soil; Heavy metals; Kinetics; Thermodynamics

Introduction

Since the industrial revolution, anthropogenic activities introduced various hazardous heavy metals into soil. Heavy metal pollution of soils is an increasingly urgent problem all over the world, resulting from the intensive use of wastewater for irrigation, sewage sludge, pesticide and emissions from vehicle exhausts, mining, and smelting (Shi et al. 2009). Generally, heavy metals are persistent, and undegradable unlike other organic pollutants (Islam et al. 2012). Normally, soil works as a natural adsorbent which immobilizes heavy metals and decreases their bioavailability through different mechanisms (precipitation, adsorption process and redox reactions), but when the concentrations of heavy metals exceed the soil capacity, the heavy metals become mobilized, resulting in serious
Contamination of agricultural products or ground water. Contamination of the soil by heavy metals has a great impact on the soil parameters, and it may negatively affect the soil characteristics and limit their productive and environmental functions. For example, heavy metals decreases the microbial activity of the soil microorganisms. These microorganisms usually contribute significantly to the degradation and mineralization of organic matter and consequently to the recycling of nutrients in the soil (Castaldi et al. 2004). Also, the immobilization of the heavy metals within different organic and inorganic colloids present in the soil may decrease their availability as nutrients for other living organisms including plants (Nannipieri et al. 1997). Furthermore, the presence of heavy metals in the soil may lead to a great change in the physiological and biochemical processes in plants, which cause growth reduction, and accordingly reduces crop yield (Chibuike and Obiora, 2014). Hence, remediation of polluted soils from heavy metal contamination is crucial (Rosestolato et al. 2015; Szendrak et al. 2011). Soil washing using chemical reagents is considered as one of the few permanent treatment to remove heavy metals from polluted soils (Dermont et al. 2008). Chemical reagents such as acids/bases, and chelating agents are usually employed to remove the heavy metals from the soils into an aqueous solution. Hydrochloric acid, EDTA, and subcritical water are the most used reagents used for soil washing and removal of metals from contaminated soil due to their high metal removal efficiency (Fedje et al. 2013; Wasay et al. 2001; Isoyama and Wada 2007; Rao et al. 2007; Udovic and Lestan 2007; Buglar and Lestan 2013). Many of the research studies mentioned the higher efficiency of soil washing using HCl compared with other leaching agents including EDTA, H2SO4 and HNO3 (Moutsatsou et al. 2006; Moon et al. 2012). Generally, soil washing with acids such as HCl relies on ion exchange and dissolution of soil components/discrete metal compounds to extract metals, whereas chelating agents such as EDTA solubilize metals through complexation. One of the important factors which affects the soil’s washing efficiency is the extraction time with the chemical reagent as the rate of metal extraction is a factor of
time. However, despite the fact that many studies focus on the soil washing using different chemical reagents, the number of researches focused on the leaching process kinetically and thermodynamically are still scarce in literature. Kinetic studies are crucial to understand the factors and means of transport for metals from the soil to the aqueous phase. Thermodynamic calculation of the washing process is required to understand the mechanism of dissolution and mobilization and their spontaneity by calculating the different thermodynamic parameters.

There has been a considerable increase in the population of Jeddah, Saudi Arabia, during the last few decades. Most of the collected treated sewage in Jeddah, usually treated in several sewage treatment plants, are usually discharged into the Red Sea and/or a sewage lake. This sewage lake was established in 1992, and stretched over an area of 2.6 km$^2$. It became the main sewage downstream, which makes the lake a direct source of pollution in the city, especially to residential areas around the lake. The hypotheses of this research is that the sewage discharge is the main source of contamination of the soils around the sewage lake, and this contamination reached its maximum in the vicinity of the lake and decreased as we go further from the lake. Also, the acid leaching could be an effective procedure for the environmental remediation of the polluted soil from heavy metals.

The objectives of this research was to investigate the heavy metals contamination and remediation of three soil samples collected from different areas in the vicinity of the sewage lake in Jeddah, Saudi Arabia, in addition to studying the correlation between the heavy metal contamination and the distance from the main contamination site. This research also focused on the remediation of the contaminated soils using the acid leaching procedure using 1.0 M hydrochloric acid and explore the effect of leaching time, and temperature kinetically and thermodynamically in order to achieve a better understanding of the metal leaching and mobilization process from the contaminated soil samples.
Material and Methods

Chemicals

All chemicals used in this study were obtained from Sigma-Aldrich (analytical grade), and all solutions were prepared using deionized water.

Soil samples collection and preparation

As it is presented in Fig. 1, soil samples were collected with a shovel forced into the soil; 10 cm depth approximately, from three different areas around the sewage lake; soil samples from area (A) (representing the area around lake drainage which is usually contaminated by the sewage water), soil samples from the National Park area (B) (located southeast of the Lake (2.7 km from area A) and is irrigated by the recycled water from the lake), and finally, soil samples from area (C) (representing the residential neighborhood adjacent to the lake (13.0 km from area A) in the northwest and its level is below the lake level). The collected soil samples were air-dried at room temperature (20–30 °C) for seven days, then were passed through a No. 14 stainless steel sieve to obtain particle size of 1.40 mm, where rocks and other large material unable to pass through the sieve were taken away, and then the soil samples were thoroughly mixed to ensure uniformity. The soil samples were then dried at 80 °C until a constant weight was achieved, and finally were directly cooled down in desiccators to room temperature before being stored in self-sealing plastic bags for subsequent experiments.

2.3. Soil characterization

Soil pH was determined in a soil:distilled water ratios of 1:2.5 suspensions by a combined glass-reference electrode and Mettler Delta 3510 pH meter. Soil conductivity was determined in a 1:2.5 soil: water suspensions by accumet conductivity meter. The
Suspensions were prepared by weighing 10 g sample of each soil into 120 ml screw cap glass bottles, 25 ml water was added to each bottle and the pH and conductivity were measured.

2.4. Total metal determination

The total metal contents in the soil samples were determined using the aqua regia extractions. Samples were digested at room temperature with 37% HCl / 70% HNO_3 (3:1) mixture (10.0 ml per 0.5 g of sample) for 12 h. After this, the suspension was digested at 30 °C, for 3 h under reflux conditions. The suspension was then filtered and diluted to 100 ml with 0.50 M HNO_3 for analysis. The total metal concentrations were determined using inductively coupled plasma-optical emission spectrometry (ICP-OES Optima 4100 DV), Perkin Elmer, USA. Calibration curves were constructed for the target heavy metals using ICP-OES, the measurements were verified using initial calibration verification (ICV) solution contain the target heavy metals. The ICV values were within 95 - 105% of the expected value, and the limits of detection were calculated; based on 3 x standard deviation of the blank, and were 2.9, 27.0, and 30.0 mg/kg for Co, As, and Hg; respectively. The leachate samples were then analyzed using the calibration of internal standard addition, based on four measurements and the reported value was the average ± their standard deviation.

2.5. Acid leaching kinetic experiment

5.0 g of soil sample were added to 0.250 L of the leaching reagent; 1.0 M HCl, and continuously stirred at 500 rpm and at different temperatures; 298±1 K, 308±1 K, and 323±1 K, separately. At defined points in time, a part of the soil leachate solution was withdrawn using a glass pipette, and filtered immediately through a filter paper. The filtrate was kept at 5 °C in the dark for metal analysis. The percentage metal leached from the soil
and the amount of metal leached per unit mass of soil at any time; \( q_t \), were calculated using Equation (1) and (2), respectively.

\[
\% \text{Metal leached} = \frac{C_V}{C_s m_s} \times 100
\]  

\[
q_t = \frac{C_i V_i}{m_s}
\]

Where \( C_i \) and \( C_s \) are the concentrations of metal in supernatant (in mg/L) and soil (mg/kg), respectively; \( V_i \) is the volume of supernatant (in L) and \( m_s \) is the dry mass of the soil (in kg). The leaching experimental data was analyzed using different kinetic models that frequently used for the description of soil leaching.

3. Results and Discussion

3.1. Soil Characterization

Soil mineral characterization was performed using XRD, and the results showed that soil collected from site A composed of quartz (SiO\(_2\)), albite (NaAlSi\(_3\)O\(_8\)), halite (NaCl), sylvite (KCl), and synthetic iron (Fe), soil collected from site B composed of quartz (SiO\(_2\)), albite (NaAlSi\(_3\)O\(_8\)), synthetic magnesium calcite, dolomite (MgCO\(_3\))\(_2\), and synthetic hematite (Fe\(_2\)O\(_3\)), whereas soil collected from site C composed of quartz (SiO\(_2\)), albite (NaAlSi\(_3\)O\(_8\)), halite (NaCl), and sylvite (KCl). Generally, most contaminants in soil exist as cationic species of metals. These metals cations can complex with inorganic soil constituents, e.g., carbonates, sulfates, hydroxides, sulfides, to form either precipitates or positively charged complexes. Both complexation and precipitation reactions are pH dependant. Therefore, although these metals can form complexes with a net negative charge, under most environmentally relevant scenarios (pH = 4 to 8.5), these metals either precipitate or exist as cations (US-EPA 2003). The pH values were 8.74, 8.56, and 7.80 for
soil samples collected from sites A, B, and C, respectively. This indicates the slight basic nature of the soil sample in general and the tendency to be more neutral away from the main contaminated sewage lake site A.

The total metal contents in the soil samples were measured using the aqua regia extractions by ICP-OES and the results are tabulated in Table 1. It is clear from the table that only As, Co, Cr, Ni, Pb, V, Hg and Zn presents with significant concentrations in the soil collected from the three sites A, B and C. The total metal concentrations were significantly above the tolerable limits recommended by World Health Organization (WHO) and European Union (EU) (Lee et al. 2009). In general, the concentrations of the metals were in the order of Site A > Site B >> Site C; indicating that the metal pollution is mainly due to the sewage discharge to the lake at site A. Studying the correlation between the different sites and the metal concentrations revealed the existence of strong correlation between Co, As, and Hg and the soil samples collected from Site A, B, and C, as it is presented in Fig. 2. The correlation coefficients ($R^2$); which indicated the true correlation between X and Y within the general population, were 0.9922, 0.9287, and 0.9964, for the Co, As, and Hg, respectively. This indicates the strong relation between the metal concentration and the distance from the main discharge area; site A. The concentration of the total metal decreased away from the main contamination site. Accordingly, this study focus on environmental remediation of the soil collected from sites A, B, and C, from their contamination with Co, As, and Hg using the chemical leaching treatment.

3.2. Kinetics study

The influence of time on the leaching of Co, As, and Hg from Site C soil was studied using 1.0 M HCl at different temperature and the results were presented in Fig. 3. It is clear from the figure that leaching percentage of the target metal enhanced significantly with the leaching time till equilibrium was attained. Leaching of Co from the soil increased with
time and start to equilibrate after 5.0 hrs with leaching percentage equals 71.90 % (151.0 mg Co/kg soil), and this percentage reached 77.8 % (163.3 mg Co/kg soil) within 24 hrs at 298 K. Also, leaching of As from the soil increased with time and start to equilibrate with leaching percentage equals 55.70 % (38.7 mg As/kg soil) after 12.0 hrs, and this percentage reached 59.2 % (41.1 mg As/kg soil) within 24 hrs. The same trend was observed for Hg, leaching percentage increased with time and start to equilibrate after 5.0 hrs with leaching percentage equals 82.1 % (9.52 mg Hg/kg soil), and this percentage reached 83.9 % (9.73 mg Hg/kg soil) within 24 hrs. This could be attributed to the accessibility of the HCl solution to the metal cations from their complexes with organic matter, or their salts within the soil with time. Also, it was clearly observable that raising the treatment temperature, associated with remarkable increase in the % metal leached from the soil. Raising the treatment temperature from 298 K, to 308 K, and 323 K increased the leaching percentage from 77.8 %, to 82.8 %, and 87.1 % for Co, from 59.2 %, to 71.7 %, and 83.7 % for As, from 83.9 %, to 87.5 %, and 93.0 % for Hg, respectively. This is mainly due to the enhancement of the target metal salts solubility as a result of raising the treatment temperature and hence they are more accessible to the HCl solution, which increased the leaching percentage.

The leaching behavior of C7o, As, and Hg from Site C soil using HCl acid was studied kinetically to understands the rate processes by which the acid leaching of target metals occurs from soil. The evaluation of the leaching rate usually generates valuable information about the interactions between the metal ions, the leaching agent, and the soil. There are many theoretical models that could be serve this purpose, and the best fit of experimental data to any of these models can be interpreted as providing appropriate kinetics for the leaching process. The leaching kinetics data of Co, As, and Hg from Site C soil by acid washing at different temperature; Fig. 3, were analyzed using the most common kinetic models used for the description of metal desorption from soil; zero-order (Dang et
Kinetic models are shown in Table 2. Applying these models to the current leaching experiments data, it was found that only the two-constant rate and Elovich kinetic models converge well with acceptable regression coefficients, as it is presented in Table 3, and Fig. 4 and Fig. 5, respectively. This indicates the suitability of the two-constant rate and Elovich kinetic models for the description of the leaching of Co, As, and Hg from contaminated soil C by acid washing. As it is presented in Table 3, there was a good correlation between the values obtained from the rate constants for the two-constant rate equation and the values obtained from simple Elovich equation. The same observations were found when copper was desorbed from selected calcareous soils collected from Iran by di-ethylenetriamin-penta-acetic acid (Reyhantabar and Karimian 2008; Fasaei et al. 2006), and for the cadmium desorption from selected sub-tropical soils (Rashti et al. 2014). These results indicated the dependency of the acid leaching soil remediation procedure on the nature of the soil as well as the type of the heavy metals present within the soil.

It is noteworthy to mention the presence of an excellent correlation between the calculated initial metal desorption rate constants and coefficients obtained from both of two-constant rate equation model and Elovich equation model with the temperature for Co, As and Hg leached from soil using HCl as it is shown in Fig. 6, and Fig. 7. It was observed that raising the temperature of the leaching process accompanied by a significant increase in the calculated initial metal desorption rate constants obtained from both models with excellent regression coefficients values. This is another trend which confirm the suitability of the two-constant rate equation model and Elovich equation model for the description of the leaching process. As it is presented in Fig. 7, there was a little variation of the effect of the
Temperature with calculated initial metal desorption rate coefficients obtained from the two kinetic model, especially for leaching of Hg, which showed very poor correlation coefficient with the application of the Elovich model. This may indicate that the two-constant rate equation model is the most appropriate model compared with the Elovich equation kinetic model.

### 3.3.3 Thermodynamic studies

The acid leaching of Co, As, and Hg from contaminated soil C was studied thermodynamically to explore the feasibility and spontaneity of the leaching process through the calculation of thermodynamic parameters: Gibbs free energy change ($\Delta G$), enthalpy change ($\Delta H$), and entropy change ($\Delta S$). The thermodynamic parameters were calculated from the variation of the thermodynamic distribution coefficient $D$ with a change in temperature and according to equation (3):

$$D = \frac{q_i}{q_s}$$  \hspace{1cm} (3)

Where $q_i$ and $q_s$ are the amount of metal in supernatant and the soil at equilibrium (mg metal/kg soil), respectively. The $\Delta H$ and $\Delta S$ may be calculated according to the following equation (Abdel Salam 2013):

$$\ln D = \frac{\Delta S}{R} - \frac{\Delta H}{RT}$$  \hspace{1cm} (4)

The $\Delta H$ and $\Delta S$ values were calculated from the slope and the intercept of the straight line of the $\ln D$ vs $1/T$ plot presented in Fig. 8; respectively. The enthalpy change value; $\Delta H$, were found to be positive; +20.9 kJ mole$^{-1}$, +40.4 kJ mole$^{-1}$, and +30.3 kJ mole$^{-1}$, for Co, As, and Hg; respectively, confirming the endothermic nature of the acid leaching of these metals from the contaminated soil as it is presented in Table 4. The positive values of
Entropy change; $\Delta S$, $\pm 80.75$ J mole$^{-1}$ K$^{-1}$, $+138.9$ kJ mole$^{-1}$ K$^{-1}$, and $+115.1$ kJ mole$^{-1}$ K$^{-1}$, for Co, As, and Hg; respectively, suggested an increase in randomness due to the leaching of the metal from the contaminated soil. The $\Delta G$ value was calculated according to the following equation at different temperature:

$$\Delta G = \Delta H - T \Delta S$$  \hspace{1cm} (5)

The $\Delta G$ calculated value at 298 K was equal to $-3.14$ kJ mole$^{-1}$, $-0.947$ kJ mole$^{-1}$, and $-3.99$ kJ mole$^{-1}$, for Co, As, and Hg; respectively, as would be expected for a product-favored and spontaneous reaction, indicating the high affinity of the metal ions towards the acidic leaching solution and the spontaneity of the leaching process. Also, the negative value also confirms the exothermic nature of the leaching of the heavy metal by the 1.0 M HCl, which explains the enhancement of the leaching process by raising the solution temperature. The magnitude of $\Delta H$ suggests a weak type of bonding between heavy metals and the soil, such as physical binding, rather than chemical binding (Nollet et al. 2003). These results verified that the Co, As, and Hg complexes with the soil were not stable, and most of these heavy metal ions were mobilized and washed upon chemically treating the soil with 1.0 M HCl solution. It is noteworthy to mention that soil washing and acid leaching is one of the common engineering practice that had been adopted (USEPA, 1991; Stegmann et al. 2001, Wise et al. 2000) for the remediation of different soils contaminated with heavy metals.

4 Conclusions

Different soil samples were collected from the vicinity of the sewage lake to study the heavy metal contamination and remediation. The pH values were in the range of 8.74-7.80. For soil samples, these values decreased further down from the main contaminated site. The metal contents in the soil samples were measured and the results showed that As, Co, Cr, Ni, Pb, V, Hg and Zn were present with significant concentrations above the tolerable
limit. Also, excellent correlation between the concentrations of Co, As, and Hg with the
distance from the main contaminated area was obtained which confirms that the
contamination was mainly due to the discharge of the untreated sewage to the lake. The
leaching of Co, As, and Hg using 1.0 M hydrochloric acid from one of the contaminated
soil was studied kinetically and thermodynamically at different temperatures, and the
experimental data were best described with the two-constant rate and Elovich equation
kinetic models. Also, the thermodynamic study showed that the leaching of Co, As, and Hg
from the soil were spontaneous at all temperature, endothermic, and accompanied with
increase in the entropies. Finally, it could concluded that the contamination of the soil was
mainly due to the discharge of the untreated sewage to the sewage lake and this
contamination became minimum further away from the main contamination site. The
contaminated soil could be remediated by using the acid leaching process effectively and
successfully within short period of time and at ambient conditions.

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Table 1. Average concentrations of heavy metals in area A, B, and C using aqua regia digestion in mg/kg.

<table>
<thead>
<tr>
<th>Element</th>
<th>Area (A) Soil</th>
<th>Area (B) Soil</th>
<th>Area (C) Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>As</td>
<td>122.6 ± 0.2</td>
<td>100 ± 0.5</td>
<td>69.4 ± 0.4</td>
</tr>
<tr>
<td>Co</td>
<td>310 ± 0.8</td>
<td>263.4 ± 1.4</td>
<td>210 ± 0.9</td>
</tr>
<tr>
<td>Cr</td>
<td>872 ± 2.5</td>
<td>1128 ± 5.4</td>
<td>680 ± 3.4</td>
</tr>
<tr>
<td>Ni</td>
<td>434.6 ± 3.1</td>
<td>870 ± 2.5</td>
<td>394.8 ± 1.8</td>
</tr>
<tr>
<td>Pb</td>
<td>7.2 ± 0.2</td>
<td>ND</td>
<td>1.8 ± 0.4</td>
</tr>
<tr>
<td>V</td>
<td>152.6 ± 2.5</td>
<td>75.4 ± 3.1</td>
<td>124.8 ± 1.4</td>
</tr>
<tr>
<td>Hg</td>
<td>208 ± 2.6</td>
<td>120 ± 2.1</td>
<td>11.6 ± 1.0</td>
</tr>
<tr>
<td>Zn</td>
<td>4821 ± 10.2</td>
<td>1108.6 ± 9.5</td>
<td>2339.8 ± 8.7</td>
</tr>
</tbody>
</table>
Table 2. Different kinetic models used to study the leaching of Co, As, and Hg from contaminated soil C using HCl.

<table>
<thead>
<tr>
<th>Kinetic Model</th>
<th>Equation</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero order</td>
<td>$q_t = q_0 - k_0 \cdot t$</td>
<td>$k_0$, zero-order rate constant [ (\text{mg metal kg}^{-1} \text{ hr}^{-1}) ]</td>
</tr>
<tr>
<td>First order</td>
<td>$\ln q_t = \ln q_0 - k_1 \cdot t$</td>
<td>$k_1$, first-order rate constant [ (\text{hr}) ]</td>
</tr>
<tr>
<td>Second order</td>
<td>$1/q_t = 1/q_0 - k_2 \cdot t$</td>
<td>$k_2$, second-order rate constant [ (\text{mg metal kg}^{-1}) ]</td>
</tr>
<tr>
<td>Third order</td>
<td>$(1/q_t) = (1/q_0) - k_3 \cdot t$</td>
<td>$k_3$, third-order rate constant [ (\text{mg metal kg}^{-1})^2 ]</td>
</tr>
<tr>
<td>Parabolic</td>
<td>$q_t = q_0 + k_p \cdot t$</td>
<td>$k_p$, diffusion rate constant [ (\text{mg metal kg}^{-1} \cdot \text{hr}^{-0.5}) ]</td>
</tr>
<tr>
<td>Two-constant</td>
<td>$q_t = a \cdot t^b$</td>
<td>$a$, initial metal desorption rate constant [ (\text{mg metal kg}^{-1} \text{hr}^{-1}) ] and $b$, desorption rate coefficient</td>
</tr>
<tr>
<td>Elovich equation</td>
<td>$q_t = (1/\beta_s) \cdot \ln (\alpha_s \cdot \beta_s) + (1/\beta_s) \cdot \ln t$</td>
<td>$\alpha_s$ and $\beta_s$, the initial adsorption rate [ (\text{mg metal kg}^{-1} \cdot \text{hr}^{-1}) ] and the desorption coefficient [ (\text{mg metal kg}^{-1} \cdot \text{hr}^{-1}) ], respectively.</td>
</tr>
</tbody>
</table>
Table 3. Different kinetic models parameters for the leaching of Co, As, and Hg from soil collected from Site C at different temperatures.

<table>
<thead>
<tr>
<th></th>
<th>Co</th>
<th></th>
<th>Hg</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Two-constant rate equation model</strong></td>
<td></td>
<td><strong>Two-constant rate equation model</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td><strong>a [ mg Co kg(^{-1})hr(^{-1})]</strong></td>
<td><strong>b</strong></td>
<td><strong>R(^2)</strong></td>
<td><strong>α [ mg As kg(^{-1})hr(^{-1})]</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>298 K</td>
<td>63.15</td>
<td>0.374</td>
<td>0.970</td>
<td>5.74</td>
</tr>
<tr>
<td>308 K</td>
<td>74.06</td>
<td>0.367</td>
<td>0.957</td>
<td>6.52</td>
</tr>
<tr>
<td>323 K</td>
<td>95.73</td>
<td>0.270</td>
<td>0.966</td>
<td>7.67</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td><strong>Elovich equation model</strong></td>
<td></td>
<td><strong>Elovich equation model</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td><strong>α [ mg Co kg(^{-1})hr(^{-1})]</strong></td>
<td><strong>β [ (mg Co kg(^{-1})·)(^{-1})]</strong></td>
<td><strong>R(^2)</strong></td>
<td><strong>α [ mg As kg(^{-1})hr(^{-1})]</strong></td>
</tr>
<tr>
<td>298 K</td>
<td>543.5</td>
<td>0.040</td>
<td>0.886</td>
<td>83.92</td>
</tr>
<tr>
<td>308 K</td>
<td>698.7</td>
<td>0.036</td>
<td>0.917</td>
<td>174.3</td>
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<td>361.1</td>
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</table>


Table 4: Values of the different thermodynamic parameters for the acid leaching of Co, As, and Hg from soil collected from Site C.

<table>
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<th>Temperature (K)</th>
<th>D</th>
<th>$\Delta G^\circ$ (KJ/mol)</th>
<th>$\Delta H^\circ$ (KJ/mol)</th>
<th>$\Delta S^\circ$ (J/K mol)</th>
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<td></td>
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<td>6.75</td>
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<tr>
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Fig. 1. Locations of the soil sample A, B, and C, around the sewage lake; Jeddah, Saudi Arabia.
Fig. 2. Correlation between the metal concentrations and the soil location collected from the sewage lake, Jeddah.
Fig. 3. Effect of the temperature and time on the leaching of Co, As, and Hg from contaminated soil by 1.0 M HCl.
Fig. 5. The two-constant equation kinetic model plots for the leaching of Co, As, and Hg from soil using 1.0 M HCl.
Fig. 4. The Elovich equation kinetic model plots for the leaching of Co, As, and Hg from soil using 1.0 M HCl.
Fig. 6. Correlation between the initial metal desorption rate constants obtained from the two-constant rate equation and Elovich equation kinetic models with the temperature for Co, As and Hg leached from soil using 1.0 M HCl.
Fig. 7. Correlation between the initial metal desorption rate coefficients obtained from the two-constant rate equation and Elovich equation kinetic models with the temperature for Co, As and Hg leached from soil using 1.0 M HCl.
Fig. 8. Plot of $\ln D$ vs. $1/T$ for the calculations of thermodynamic parameters for the leaching of Co, As, and Hg from soil by 1.0 M HCl.
Graphical Abstract

Locations of the soil sample A, B, and C, around the sewage lake; Jeddah, Saudi Arabia.