Removal of heavy metals from waste phosphogypsum materials using polyethylene glycol and polyvinyl alcohol polymers

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KEYWORDS
Phosphogypsum; Mobility of heavy metal; Polyethylene glycol; Polyvinyl alcohol; Ecological risk assessment

Abstract
Enormous stockpiles of phosphogypsum (PG) generated during the wet process production of phosphoric acid are stored at many sites around the world and pose problems for their safe storage, disposal, or utilization. The aim of this study was to investigate the performance of two polymers polyethylene glycol (PEG) and polyvinyl alcohol (PVA) in removing heavy metal from waste PG materials with a batch reaction approach. Batch experiments showed that the adsorption capacities of PEG and PVA polymers increased quietly as a result of molecular weight with increase in active surfaces of adsorbents. It is important to note that the adsorption capacities of the PEG and PVA polymers presented in this paper vary, depending on the characteristics of the individual adsorbent, the extent of molecular weight, and the concentration of adsorbate. The maximum percentage removal with PEG of Cd, Cr, Cu, Pb, Zn, and Mo followed the order: Cu (96%) > Cr (94%) = Mo (94%) > Zn (74%) > Cd (70%) > Pb (11%), while the removal of Cd, Cr, Cu, Mo, Pb, and Zn with PVA adsorbents followed the order: Cu (95%) > Mo (93%) > Cr (91%) > Cd (84%) > Zn (78%) > Pb > (10%). Obviously, PEG and PVA polymers are suitable for industrial hazardous solid waste containing Cd, Cr, Cu, Mo, Pb, and Zn contaminations. The calculated singular indices including ecological risk factors ($E_i$) showed that Cd should be considered a moderate potential ecological risk, while Cr, Cu, Pb, and Zn indicated a low ecological risk. The calculated integrated...
1. Introduction

Phosphogypsum (PG) is a waste by-product of the wet process of phosphoric acid production, which contains variable amounts of some impurities such as naturally occurring radionuclides, fluoride, and heavy metals depending on the source (Rutherford et al., 1996; Al-Hwaiti et al., 2013). About 5 tonnes of PG are generated for every tonne of phosphoric acid (H₃PO₄) manufactured. The operative chemical reaction is generalized as

\[
\text{Ca}_5(\text{PO}_4)_2\text{F} + 5\text{H}_2\text{SO}_4 + 10\text{H}_2\text{O} \\
\rightarrow 3\text{H}_3\text{PO}_4 + 5\text{CaSO}_4 \cdot 2\text{H}_2\text{O} + \text{HF}
\]  

(1)

At present, worldwide production of PG is over 100–280 Mt/a (Parreira et al., 2003). Only 14% of the worldwide production is reprocessed, 28% is dumped into water bodies, and 58% is being stockpiled and may cause huge environmental problems (Carmichael, 1988).

Studies have been conducted on the beneficial ways of utilizing PG in order to reduce the disposal problem and the environmental implications. These include uses of PG: (1) agricultural fertilizer or for soil stabilization amendments (Al-Oudat et al., 1998; El-Mrabet et al., 2003), (2) cement industry as a setting regulator in place of natural gypsum (van der Merwe and Strydom, 2004; Kacimi et al., 2006), as raw material in the raw mix of cement (Singh, 1987; Ali, 2004), and in other binder materials (Singh et al., 1996; Taher, 2007). Tayibi et al. (2009), reported a preliminary study of a PG stabilization process using a sulfur polymer matrix in order to improve mechanical properties of PG concretes. Results show a new PG concrete product with good mechanical properties and low radionuclide contents, and it can be considered a very suitable and efficient option for PG disposal.

Polymer–metal ion interactions are a subject of great interest as they have potential analytical and technological applications in fields such as environmental science, industrial effluent treatment, and the metallurgy industry (Mamta et al., 2012). By increasing downstream industry, heavy metal ions undergo several technical processes and finally fate of effluent, solid waste, sewage, dumps and dust, into the water, the earth and the air and thus into the food chain as finely dispersed and/or in solutions.

In this sense, numerous research efforts are being done to develop methods to remove heavy metal ions, particularly in waste streams of hydro-metallurgy and related industries, and to subsequently reuse them. These techniques include filtration, chemical precipitation, neutralization, reverse osmosis and electrolys, chelating ion exchange and adsorption (Zamzow and Murphy, 1992; Rivas et al., 2001; Dabrowski et al., 2004; Hema et al., 2011; Nafeif and Güven, 2012).

Among these techniques, utilizing chelating polymers was of great importance in environmental applications (Yahia et al., 2013); for example, biosorption of heavy metal using polyvinyl alcohol (PVA) for immobilization has long been reported and includes immobilized enzymes (Imai et al., 1986; BAI and Abraham, 2003). Eisazadeh (2007), reported the removal of heavy metals from water and wastewaters using conductive electroactive polymers such as polypyrrole and polyaniline, and the removal of arsenic in wastewater using poly ethylene glycol (PEG) and its composites in the presence of FeCl₃ as an oxidant has been employed (Eisazadeh, 2008).

Reverse osmosis has been also applied in the removal of chromium from wastewater (Selvaraj et al., 1997). The removal of nonpolar organic material from water and wastewater using activated carbon has been adapted by Ying et al., (1990), whereas the removal of heavy metals from water and wastewaters using bentonite has been a topic of Christidis et al. (1997). Nevertheless, these methods used for the removal of heavy metals, may be efficient but expensive (Hema et al., 2003).

As mentioned above, a number of workers have used different adsorbent systems, developed from various industrial waste materials, for the removal of heavy metals. There still exists a need to develop a low cost and efficient adsorbent for the removal of heavy metals from solid waste. However, the commercial use of PG in Jordan is currently limited to the production of cement, as agriculture and soil amendment (Al-Hwaiti et al., 2010). In the present work, an attempt has been made to utilize an inexpensive adsorbent system for the removal of heavy metals from PG using PEG and PVA. The preliminary study of a PG stabilization process using a sulfur polymer matrix in order to improve mechanical properties of PG concretes. Results show a new PG concrete product with good mechanical properties and low radionuclide contents, and it can be considered a very suitable and efficient option for PG disposal.

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\[
\begin{align*}
\text{H} & \quad \text{O} \\
\text{O} & \quad \text{H}
\end{align*}
\]

and polyvinyl alcohol (PVA) which has the following structure:

\[
\begin{align*}
\text{OH} & \\
\text{OH}
\end{align*}
\]
The purpose of using these polymers is that (1) they have unpaired electrons while the heavy metals have valence shells and by the 18-electron rule the unpaired electrons will bond with these shells and remove it from water. Further, these polymers are cheap and available and (2) to determine influence of PEG molecular weight and PVA molecular weight in removing heavy metal from waste PG materials and their influence on heavy metals risk assessment to assess safe use of purification PG in agriculture and soil amendment.

2. Materials and methods

2.1. Materials

Phosphogypsum samples were taken from the stacks in Ehideya Mines area, Jordan (Fig. 1). The representative samples were selected, ground, dried overnight at 45 °C, and then carried out for leaching experiments. 2 g of PG was used in each leaching test.

2.2. Leaching experiments

Leaching experiments were conducted with polyethylene glycol (PEG) and polyvinyl alcohol (PVA) to determine concentrations of heavy metals that are released from PG to the aqueous phase. Four kinds of polymers with different weight average molecular weights were applied as follows: PEG-1, MW = 10,000; polyethylene glycol (PEG-2, MW = 35,000), polyvinyl alcohol 80% hydrolyzed (PVA-1, MW = 9500), and polyvinyl alcohol 87–89% hydrolyzed (PVA-2, MW = 18,000). These polymers were obtained from Merck, Germany, and used without purification. Distilled water was used as dispersing medium.

PEG and PVA were used as polymers. The reaction was carried out in an aqueous media at room temperature for 4 h. Total 2.2 g of PEG and PVA was used for leaching test. Masses of 0.5 g, 0.7 g and 1 g were weighed and volumes of 100 ml of distilled water were added to each experiment to produce surfactant solutions. The surfactant solution was then added followed by 2 g of PG for each test, assuring that the solid always remained in suspension. Important parameters, such as, room temperature of 30 °C, leaching duration of 24 h, and liquid/solid (L/S) ratio influencing the leaching process, were investigated in order to obtain metal concentrations as high as possible or select optimal parameters for the leaching process. Finally, the mixing products of PG and surfactant solutions were then separated by centrifugation at 3000 rpm for 5 min. The extract was decanted and filtered through 0.45 μm filter paper. The treated PG mass was dried overnight at 65 °C, and then analyzed by AAS analysis. Each test was conducted simultaneously in triplicate and results were averaged for data analysis.

2.3. Chemical analysis

Digestions were performed on 15 samples in triplicate. 1 g of each PG sample was put in Teflon beakers, to which 5 ml of aqua regia (3 ml of conc. HCl and 2 ml conc. HNO3) was added before allowing the reaction to subside. This was followed by the addition of 2 ml conc. HNO3. Samples were then taken to dryness on a hotplate at 110 °C. A further 1 ml of conc. HNO3 was then added and the sample was again taken to dryness. Dried samples were then removed from the hotplate and cooled, 19 ml of 1% HNO3 was added, and the solution was heated in an oven at 100 °C for 30 min. The concentrations of Cd, Cr, Cu, Ni, Pb, V, and Zn were measured using an atomic absorption spectroscopy (AAS, Model Perkin Elmer A800 “Graphite and Flame”, Varian, USA) at Bin Hayyan-Aqaba International Laboratories Management, Aqaba Special Economic Zone Authority (ASEZA), Jordan. Quality assurance and control were assessed using the duplicates and blanks method, prepared in the laboratory following the procedures as described in Method ISO 11466 (ISO 11466, 1995).

2.4. Calculating heavy metals removal

The percentage of metals removed and leached from the PG during the batch reaction experiments. The % removal of the elements was calculated based on the following equation:

\[
\% \text{Removal} (\% R) = \frac{C_i - C_f}{C_i} \times 100
\]

\[
\% \text{Leachable} (\% L) = \frac{C_f}{C_i} \times 100
\]

where \( C_i \) is the initial concentration in mg/kg, and \( C_f \) is the final concentration in mg/kg.

2.5. Risk assessment

Potential ecological risk index is a powerful tool for processing, analyzing, and conveying raw environmental information to decision-makers, managers, technicians, and the public (Hakanson, 1980). The heavy metal i.e. Cd, selected in this investigation is because of its interest from environmental and biological points of view (Mamta et al., 2012). Nowadays, Cadmium is regarded as the most serious contaminant of water, soil, sediment, and plants. Caeiro et al. (2005), used ecological risk indices to assess heavy metal pollutions in the ecosystem. In this study, potential ecological risk index was assessed.

In this study, the assessment of ecological risk (RI) of Cd, Cr, Cu, Pb, and Zn in PG was carried out by using the potential ecological risk index (RI) proposed by Hakanson (1980):

\[
RI = \sum_{i=1}^{n} E_{ir} = \sum_{i=1}^{n} T_i r_i x C_i = \sum_{i=1}^{n} T_i x \left( \frac{C_i}{C_o} \right)
\]

\( R_i \) is the sum of the single ecological risk factors (\( E_i \)) of five pollutants, Cd, Cr, Cu, Pb, and Zn. In this study, the single potential ecological risk factor (\( E_i \)) of Cd, Cr, Cu, Pb, and Zn was calculated. \( T_i \) is the metal toxic response factor according to Hakanson (1980); the values for Cd, Cr, Cu, Pb, and Zn were 30, 2, 5, 5, and 1 (μg/g), respectively. \( C_i \) is the single pollution index which is equal to the ratio of the metal toxic concentration in samples (\( C_i \)) to the background value (\( C_o \)) of Cd, Cr, Cu, Pb, and Zn i.e. 1, 90, 50, 70, and 175 (μg/g) respectively in the pre-industrial reference (Hakanson, 1980; Xu et al., 2008). The potential ecological risk (RI) degree of a given region was divided into 4 grades: RI < 150, low ecological risk;
Figure 1  Sampling collection and location map of the study area.

<table>
<thead>
<tr>
<th>Element</th>
<th>Dosage 0.5 (g)</th>
<th>Dosage 0.7 (g)</th>
<th>Dosage 1 (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T</td>
<td>CX</td>
<td>%L</td>
</tr>
<tr>
<td>Cd</td>
<td>2.81</td>
<td>1.59</td>
<td>56.58</td>
</tr>
<tr>
<td>Cr</td>
<td>52</td>
<td>42.75</td>
<td>82.21</td>
</tr>
<tr>
<td>Cu</td>
<td>10.9</td>
<td>10.2</td>
<td>93.58</td>
</tr>
<tr>
<td>Pb</td>
<td>0.5</td>
<td>0.039</td>
<td>7.80</td>
</tr>
<tr>
<td>Zn</td>
<td>46</td>
<td>27.8</td>
<td>60.43</td>
</tr>
<tr>
<td>Mo</td>
<td>17</td>
<td>13.79</td>
<td>81.12</td>
</tr>
</tbody>
</table>

Abbreviation: $T$ = total, $CX$ = extraction, $L$ = leached ($%L = (C_{x,Cd}/T_{Cd}) \times 100\%$, $M$ = mobility ($%M = (T_{Cd} - C_{x,Cd}/T_{Cd}) \times 100\%$).
Table 2  Degree of element mobility based on PEG and PVA leaching method for the phosphogypsum samples.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Reagent</th>
<th>( (r) ) values</th>
<th>Degree of mobility</th>
<th>Overall assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd</td>
<td>PEG</td>
<td>0.59( ^c )</td>
<td>Intermediate</td>
<td>Intermediate</td>
</tr>
<tr>
<td></td>
<td>PVA</td>
<td>0.63( ^c )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>PEG</td>
<td>0.90( ^d )</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>PVA</td>
<td>0.84( ^d )</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Cu</td>
<td>PEG</td>
<td>0.98( ^d )</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>PVA</td>
<td>0.84( ^d )</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Pb</td>
<td>PEG</td>
<td>0.32( ^b )</td>
<td>low</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>PVA</td>
<td>0.64( ^c )</td>
<td>Intermediate</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>PEG</td>
<td>0.97( ^d )</td>
<td>High</td>
<td>Intermediate</td>
</tr>
<tr>
<td></td>
<td>PVA</td>
<td>0.53( ^c )</td>
<td>Intermediate</td>
<td>High</td>
</tr>
<tr>
<td>Mo</td>
<td>PEG</td>
<td>0.74( ^c )</td>
<td>Intermediate</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>PVA</td>
<td>0.93( ^d )</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

\( ^a \) Very low mobility \( (r = 0–0.25) \).
\( ^b \) Low mobility \( (r = 0.26–0.50) \).
\( ^c \) Intermediate mobility \( (r = 0.51–0.75) \).
\( ^d \) High mobility \( (r = 0.76–1.00) \).

Figure 2  Relationship between the total Cd, Cr, and Cu content and their metal extract using PEG and PVA polymer.
150 \leq RI < 300, moderate ecological risk; 300 \leq RI < 600, considerable ecological risk; and RI \geq 600, very high ecological risk. The following terminologies are used to describe the risk factor: $E'_{ri} < 40$, low potential ecological risk; $40 \leq E'_{ri} < 80$, moderate potential ecological risk; $80 \leq E'_{ri} < 160$, high potential ecological risk; $160 \leq E'_{ri} < 320$, very high potential ecological risk; and $E'_{ri} \geq 320$, extremely high potential ecological risk.

3. Results and discussion

3.1. Effect of heavy metals

The heavy metals (mg kg$^{-1}$) removal capacities and selectivity properties of PEG-1, PEG-2, PVA-1 and PVA-2 polymers in PG are shown in Table 1.

3.1.1. Cadmium

The maximum percentage removal of cadmium was found to be 65%, 69%, 75% and 82% from original Cd present in PEG-1, PEG-2, PVA-1, and PVA-2, respectively, indicating that the removal of Cd increased with increased polymer MW and dosage. That is to say, PEG mobility and PVA mobility would be improved with PEG and PVA molecular weight increasing. So an increment in PEG and PVA molecular weight had two contrary effects on PEG mobility and PVA mobility. This is because higher MW and dosage of adsorbent increase the surface area, thereby increasing the greater availability of exchangeable sites for the metal ions to get adsorbed. It can be concluded that the cadmium ions are then electrostatically attracted to the high electron density regions of the functional groups and form coordination bonds to the polymer.
Due to its strong di positive charge, it often forms coordinating bonds between multiple functional groups within PEG and PVA polymers. Accordingly, the amounts of Cd in the PEG-1, PEG-2, PVA-1, and PVA-2 may be remobilized from treated PG to the ecosystem which are 35%, 31%, 25%, and 18%, respectively. However, the removal of cadmium with different polymers followed the order: PEG-1 \( > \) PEG-2 \( > \) PVA-1 \( = \) PEG-2. The low negatively significant correlation between the total Pb content and the amount of Pb leached by PEG is \( r = 0.32 \) and good positively significant correlation between the total Pb content and the amount of Pb leached by PEG is \( r = 0.64 \), shown in Fig. 2. It is evident that Pb has high mobility, indicating Pb \((<96)\) is going to be leached from treated PG into environment (Table 2).

### 3.1.4. Lead

The maximum percentage removal of Pb was found to be 10%, 11%, 9% and 10% from original Pb present in PG of PEG-1, PEG-2, PVA-1, and PVA-2, respectively (Table 1), indicating the high percentage of lead in the four adsorbents indicated that Pb present in different mineral surfaces varied considerably. It was high probably due to weak specific (covalent) interaction of Pb with organic matter and other surfaces (Zimdahl and Skogerboe, 1997). Accordingly, the amounts of Pb may be remobilized from treated PG to the ecosystem which are 96%, 96%, 94%, and 95%, respectively. However, the removal of Pb with different polymers followed the order: PVA-1 \( > \) PVA-2 \( > \) PEG-1 \( = \) PEG-2. The low negatively significant correlation between the total Pb content and the amount of Pb leached by PEG is \( r = 0.32 \) and good positively significant correlation between the total Pb content and the amount of Pb leached by PEG is \( r = 0.64 \), shown in Fig. 3. It is evident that Pb \((<96)\) has low to intermediate mobility, indicating Pb \((<64)\) is going to be leached from treated PG into environment (Table 2).

### 3.1.5. Zinc

The maximum percentage removal of Zn was found to be 68%, 74%, 67% and 79% from original Zn present in PG of PEG-1, PEG-2, PVA-1, and PVA-2, respectively (Table 1), indicating that most of the Zn accommodating in different mineral phases in PG, may be because it was associated with Fe-oxides in the PG lattice structures (Nathan et al., 1997). A sizably greater presence of Zn was also seen in the organic phase. Zinc as a substitute for Ca, entering the gypsum crystal phase. Zinc as a substitute for Ca, entering the gypsum crystal

### Table 3 The potential ecological risk factors and risk indices of metals based on different polymers dosages in phosphogypsum.

<table>
<thead>
<tr>
<th>Reagent</th>
<th>Dosage</th>
<th>( E_r )</th>
<th>Cd</th>
<th>Cr</th>
<th>Cu</th>
<th>Pb</th>
<th>Zn</th>
<th>RI</th>
<th>Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG</td>
<td>–</td>
<td>84.3 (^a)</td>
<td>1.16</td>
<td>1.09</td>
<td>0.04</td>
<td>0.26</td>
<td>86.85</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>PEG-1</td>
<td>0.5</td>
<td>47.7</td>
<td>0.95</td>
<td>1.02</td>
<td>0.003</td>
<td>0.160</td>
<td>49.83</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>51.0</td>
<td>0.97</td>
<td>1.03</td>
<td>0.003</td>
<td>0.175</td>
<td>53.18</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>54.6</td>
<td>1.00</td>
<td>1.05</td>
<td>0.004</td>
<td>0.180</td>
<td>56.83</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>PEG-2</td>
<td>0.5</td>
<td>55.5</td>
<td>1.08</td>
<td>1.03</td>
<td>0.003</td>
<td>0.160</td>
<td>57.78</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>56.7</td>
<td>1.05</td>
<td>1.04</td>
<td>0.003</td>
<td>0.184</td>
<td>58.98</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>58.5</td>
<td>1.08</td>
<td>1.05</td>
<td>0.004</td>
<td>0.200</td>
<td>60.83</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>PVA-1</td>
<td>0.5</td>
<td>59.4</td>
<td>0.92</td>
<td>0.98</td>
<td>0.003</td>
<td>0.140</td>
<td>61.45</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>60.0</td>
<td>0.99</td>
<td>1.02</td>
<td>0.003</td>
<td>0.163</td>
<td>62.18</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>63.0</td>
<td>1.02</td>
<td>1.03</td>
<td>0.003</td>
<td>0.180</td>
<td>65.22</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>PVA-2</td>
<td>0.5</td>
<td>60.9</td>
<td>1.00</td>
<td>1.02</td>
<td>0.003</td>
<td>0.150</td>
<td>63.07</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>68.7</td>
<td>1.03</td>
<td>1.03</td>
<td>0.003</td>
<td>0.164</td>
<td>70.92</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>69.3</td>
<td>1.05</td>
<td>1.04</td>
<td>0.004</td>
<td>0.210</td>
<td>71.60</td>
<td>Low</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\) Moderate risk.  
\(^{b}\) considerable risk; \(^{c}\) high risk; \(^{d}\) very high risk.

\(RI\) Degree: Low (RI < 60), Moderate (60 \( \leq \) RI < 80), High (80 \( \leq \) RI < 90), Very High (RI \( \geq \) 90).
PG to the ecosystem which are 32%, 26%, 33%, and 21%, respectively. The removal of Zn with different adsorbents followed the order: PVA-1 > PEG-1 > PEG-2 > PVA-2. The high positively significant correlation between the total Zn content and the amount of Zn leached by PEG and PVA is \( r = 0.98 \) and \( r = 0.53 \), respectively, shown in Fig. 3. It is evident that Zn has high mobility, indicating Zn (<33) is going to be leached from treated PG into environment (Table 2).

3.1.6. Molybdenum

The maximum percentage removal of Mo was found to be 86%, 94%, 89% and 93% from original Mo present in PEG-1, PEG-2, PVA-1, and PVA-2, respectively (Table 1), indicating that the removal of Mo increased with increased polymer MW and dosage. Accordingly, the amounts of Mo may be remobilized from treated PG to the ecosystem are 14%, 6%, 11%, and 7%, respectively. However, the removal of Mo with different polymers followed the order: PVA-1 > PEG-1 > PVA-2 > PEG-2. The high positively significant correlation between the total Mo content and the amount of Mo leached by PEG and PVA is \( r = 0.74 \) and \( r = 0.94 \), respectively, shown in Fig. 3. It is evident that Mo has high mobility, indicating Mo (<14) is going to be leached from treated PG into environment (Table 2).

3.2. Ecological risk assessment

Table 3 summarizes the potential ecological risk factors \( (E_i) \) and risk indices (RI) for Cd, Cr, Cu, Pb, and Zn values in untreated PG samples and treated PG samples. It was found that \( E_i \) values in the untreated Cd were 84, indicating considerable potential ecological risk, while Cd values in the treated PG were below 80, indicating moderate potential ecological risk (Fig. 4). The values \( (E_i) \) of Cr, Cu, Pb, and Zn in untreated PG samples and treated PG samples were below 40, which indicate that all investigated heavy metals except Cd posed no potential hazard to the ecosystem (Fig. 4). The rank of risk contribution rate \( (E_i/RI) \) among the heavy metals in a descending order is Cd > Zn > Cu > Cr > Pb. Thus, Cd made the largest contribution to the total risk index while Pb made the smallest contribution. Since Cd is more highlighted than other elements in terms of the ecological risk factor in the PG, it should be paid special attention to. The order of the potential risk indices (RI) for the four polymers is PVA-2 > PVA-1 > PEG-2 > PEG-1. The risk level of PVA-2, PVA-1, PEG-2 and PEG-1 was low degree. The calculated integrated potential ecological risk indices (RI = \( \sum E_i \)) considered that Cd, Cr, Cu, Pb, and Zn indicated pollution in all studied samples is less.

4. Conclusion

The results of the present work suggested that the addition of PEG and PVA with different molecular weights could change the PG structure and properties to remove heavy metals. During batch experiments, because of the addition of PEG and PVA with increasing molecular weight and with increasing dosage, a decrease in mobility increases the heavy metals removal. The results of heavy metal removal from PG leachate with polymer methods consisting of PEG and PVA were approved. The batch experiments’ result obtained showed that the removal of Cd, Cr, Cu, Pb, Zn and Mo in these samples ranged from 57% to 70%, 80% to 94%, 90% to 96%, 7% to 11%, 55% to 74%, and 81% to 94%, respectively for PEG, and from 70% to 84%, 80% to 91%, 89% to 95%,
7% to 10%, 55% to 78%, and 82% to 93%, respectively for PVA. The potential ecological risk factors ($E_i$) showed that Cd should be considered a moderate potential ecological risk, whereas Cr, Cu, Pb, and Zn indicated a low ecological risk. The potential ecological risk indices (RI) considered that Cd, Cr, Cu, Pb, and Zn indicated pollution in all studied samples is less. These results indicated that Cd, Cr, Cu, Pb, and Zn content removal using PEG and PVA polymers would be of great importance in environmental applications, and they can be considered a very suitable safe use of PG in agriculture and soil amendment.

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References


