Removal of Pb(II) from aqueous solutions using waste textiles/poly(acrylic acid) composite synthesized by radical polymerization technique

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ABSTRACT

Waste textiles (WTs) are the inevitable outcome of human activity and should be separated and recycled in view of sustainable development. In this work, WT was modified through grafting with acrylic acid (AA) via radical polymerization process using ceric ammonium nitrate (CAN) as an initiator and microwave and/or UV irradiation as energy supply. The acrylic acid-grafted waste textiles (WT-g-AA) thus obtained was then used as an adsorbent to remove Pb(II) from Pb(II)-containing wastewater. The effects of pH, initial concentrations of Pb(II) and adsorbent dose were investigated, and around 95% Pb(II) can be removed from the aqueous solution containing 10 mg/L at pH 6.0–8.0. The experimental adsorption isotherm data was fitted to the Langmuir model with maximum adsorption capacity of 35.7 mg Pb/g WT-g-AA. The Pb-absorbed WT-g-AA was stripped using dilute nitric acid solution and the adsorption capacity of Pb-free material decreased from 95.4% (cycle 1) to 91.1% (cycle 3). It was considered that the WT-g-AA adsorption for Pb(II) may be realized through the ion-exchange mechanism between -COOH and Pb(II). The promising results manifested that WT-g-AA powder was an efficient, eco-friendly and reusable adsorbent for the removal of Pb(II) from wastewater.

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Keywords: Adsorption Pb(II) Waste textiles Graft copolymerization

Introduction

Various water polluted by heavy metals from industrial activities (Celik and Demirbas, 2005; Pastirckova, 2004) has been considered as a serious problem for their harmful effects on living organisms and environment, especially their bio-accumulation tendency and persistency in nature (Garg et al., 2007; Wang and Li, 2015; Zhang et al., 2016). And the increasing accumulation of heavy metals especially bioaccumulation through the food chain, has caused serious threat to human health (Ghorai et al., 2012; Kieu et al., 2011). Therefore, it is of great interest and very necessary to remove heavy metals from wastewater (Hua et al., 2012; Nguyen et al., 2013). Nowadays, several techniques have been developed for removing heavy metals from natural water and industrial wastewaters, such as chemical precipitation, ion-exchange, filtration, membrane separation, photocatalytic degradation and adsorption methods (Constantin et al., 2013; Fu and Wang, 2011; Hashim et al., 2011; Sekhavat Pour and Ghaemy, 2015; Shibi and Anirudhan, 2002). Amongst them, adsorption is now the most commonly used option for removing heavy metals from wastewater due to its high efficiency.
1. Materials and methods

1.1. Materials

Waste textiles were obtained from one waste collector nearby Tongji University, in Shanghai, China. The raw materials were cut into pieces (1 cm × 1 cm), ground into powder by planetary ball mill machine (QM-1SP4) with 400 r/min for 6 hr. Acrylic acid monomer, nitric acid, sodium hydroxide, lead nitrate (Pb(NO_3)_2) and cerium(IV) ammonium nitrate (CAN) were used as commercially available. Cerium (IV) ammonium nitrate was used as an initiator for grafting acrylic acid monomer onto WT.

1.2. Graft copolymerization

Before the initiation of graft polymerization, 5 g of WT powder was immersed with 100 mL 64 wt% sulfuric acid at 30°C for 0.5 hr, followed by a stir in 55°C thermostat water bath for 2 hr. The pretreated material was washed with deionized water and alcohol and then dried at 40°C.

The experiments were performed on an UWave-1000 UV ultrasonic microwave extracting apparatus (Sineo, Shanghai, China). A 250 mL triangular flask equipped with a mechanical stirrer was used as the reactor, in which 50 mL of 2 wt% WT/water suspension was prepared and pH was adjusted to 2 with...
diluted nitric acid. Nitrogen was bubbled through the mixture; after 15 min of stirring, cerium(IV) ammonium nitrate was added as the initiator. Acrylic acid monomer was then added gradually over a period of 30 min. The triangular flask was heated by the microwave irradiation (150 W) for 3 min and then was cooled in an ice bath for 3 min to stop the reaction; after that, the above process was repeated for four times. The UV irradiation (365 nm) was performed throughout the experiments.

After the centrifugation of the reaction mixtures, the solid substance was washed with water to remove the traces of initiator and acrylic acid. The free homopolymers and copolymers were removed through washing with deionized water. WT-g-AA was dried at 60°C in a vacuum oven until achieving constant weight and ground with mortar to fine particles. The particle size distribution of the resultant powder was then analyzed by a Mastersizer 2000 Granularity meter (Malvern, UK), and the results are shown in Fig. 1. The average particle size of the final products was determined to be 39.9 μm.

1.3. Characterization

Fourier transform infrared spectroscopy (FT-IR) (Nicolet 5700 FT-IR Spectrometer) was used to qualify the chemical bonds between the functional groups of raw material and graft copolymer. The samples were subjected to wave numbers within the range of 500–4000 cm\(^{-1}\) at a resolution of 4 cm\(^{-1}\). Scanning electron microscopy (SEM) (FEI Nova Nano SEM 450) was used to study the surface morphology of WT-g-AA. X-ray diffraction (XRD) measurements were carried out using an X-ray diffractometer (XRD, D8 Advance). The patterns with the CuKa radiation (1.5418 Å) at 40 kV and 40 mA were recorded in the 2 theta region from 10° to 80°. The X-ray photoelectron spectroscopy (XPS) characterizations were done with a Kratos AXIS 165 electron spectrometer with monochromatic AlKa radiation at 100 W and high resolution measurements in carbon C 1s and oxygen O 1s regions were used.

![Particle size distribution of the acrylic acid-grafted waste textiles (WT-g-AA) powder.](image)

**Fig. 1** – Particle size distribution of the acrylic acid-grafted waste textiles (WT-g-AA) powder.

1.4. Heavy metal adsorption experiments

1.4.1. Batch adsorption experiments

Batch adsorption experiments were conducted to study the adsorption capacity of WT-g-AA powder to Pb(II). For determining the optimum dosage of the adsorbent, the experiments were carried out using powder in the range of 0.5–3 g/L in the solution of Pb(II) (10 mg/L), and the mixture was stirred at 150 r/min and 25°C for a predetermined time. The effect of pH was studied in the range of 2–8, and the initial pH of solution was adjusted to the said value using either 0.2 mol/L HNO\(_3\) or 0.2 mol/L NaOH. The operational parameters were determined in triplicate.

Adsorption isotherms were studied with a constant dosage of powder (1 g/L) and different initial concentrations of Pb(II) in the range of 10–200 mg/L. The concentration of Pb(II) was determined with Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES, Optima 2100 DV, PerkinElmer). The removal efficiency (R, %) and the adsorption capacity (\(Q_e\), mg/g) of the particles was calculated via the following equations.

\[
R = \frac{C_0 - C_e}{C_0} \times 100\% 
\]

\[
Q_e = \frac{(C_0 - C_e)V}{m} 
\]

where \(C_0\) (mg/L) and \(C_e\) (mg/L) are the concentrations of Pb(II) in the initial solution and the aqueous phase after adsorption, respectively; \(V\) (L) is the volume of the aqueous phase; and \(m\) (g) is the dosage of adsorbent.

1.4.2. Adsorption isotherm experiment

The adsorption equilibrium experiment of WT-g-AA was carried out at 30°C and pH 7. The initial concentration of Pb(II) was ranged from 10 to 200 mg/L. The adsorption isotherm experimental data were fitted by Langmuir and Freundlich models. The Langmuir isotherm model, it has been assumed that the monolayer coverage of sorption occurs in the process and the adsorption sites are identical and energetically equivalent (Ge et al., 2016). The Langmuir equation can be expressed as follows:

\[
\frac{C_e}{Q_e} = \frac{1}{Q_mK_L} + \frac{1}{Q_m} 
\]

where, \(Q_e\) (mg/g) is the amount of heavy metal ions adsorbed at equilibrium; \(C_e\) (mg/L) is the residual concentration of tested heavy metal ions in solution at equilibrium; \(Q_m\) (mg/g) is the maximum adsorption capacity when an adsorbent is fully covered; and \(K_L\) (L/mg) is a constant related to the affinity of the binding sites.

The Freundlich model is an empirical equation that can be used to describe the multilayer adsorption equilibrium on a heterogeneous surface (Agarwal et al., 2004). It is mathematically described by Eq. (4).

\[
\ln Q_e = \ln K_f + \frac{1}{n} \ln C_e 
\]

where, \(K_f\) ((mg/g)(L/mg)\(^{1/n}\)) and \(n\) are the Freundlich constants related to adsorption capacity and adsorption intensity,
respectively. $K_F$ and $n$ can be determined from the linear plot of $\ln Q_e$ versus $\ln C_e$.

1.4.3. Kinetics adsorption experiment
The kinetics adsorption experiments were also measured at 30°C and pH 7. The initial Pb(II) concentration of solution is 10 mg/L. The adsorption kinetics of Pb(II) on WT-g-AA was investigated with the help of two kinetic models, namely pseudo-first order (Eq. (5)) and pseudo-second order models (Eq. (6)).

$$\ln (Q_e - Q_t) = \ln Q_e - k_1 t$$  \hspace{1cm} (5)

$$\frac{t}{Q_t} = \frac{1}{k_2 Q_e^2} + \frac{t}{Q_e}$$  \hspace{1cm} (6)

where, $k_1$ (min$^{-1}$) and $k_2$ (g/(mg·min)) are successively the pseudo first-order and pseudo second-order rate constants; $Q_t$ (mg/g) is the amount adsorbed at time $t$ (min), and $Q_e$ (mg/g) denotes the amount adsorbed at equilibrium.

1.4.4. Desorption and reusability experiments
Desorption of Pb(II) adsorbed WT-g-AA powder was carried out in 100 mL of 0.01 mol/L HNO$_3$ solution and the initial Pb(II) concentration of solution was 10 mg/L. After removal of powder from the desorption medium by centrifugation, the particles were washed with distilled water and dried at 60°C in a vacuum oven and used for the subsequent runs. The adsorption–desorption cycles were repeated three times using the same adsorbents.

2. Results and discussion

2.1. Adsorbent characterization
The chemical structures of the WT, and WT-g-AA were established using FT-IR and the results are shown in Fig. 2a. The broad absorption peak was located at 3400–3600 cm$^{-1}$ and a sharp peak at 2888.7 cm$^{-1}$, indicating the presence of $\text{OH}$ group and $\text{C–H}$ stretching, respectively. Also, the peak at 1721.3 cm$^{-1}$ was due to $\text{C=O}$ stretching and the absorption bands at 1436.2 and 1267.3 cm$^{-1}$ were attributed to $\text{C–C}$ and $\text{C–O}$ stretching, respectively.

The WT-g-AA exhibited a broad signal at 3552.2 and 3430.1 cm$^{-1}$ representing the overlap of $\text{O–H}$ and $\text{N–H}$ stretching vibrations. And the $\text{N–H}$ group was required to form a chelate with heavy metals. Compared with the spectra of WT, the graft copolymer exhibited the strong absorption bonds at 1617.8 cm$^{-1}$ due to $\text{C=C}$ stretching. These results reflected that the surface of WT was grafted successfully with AA copolymer. Furthermore, the absorption bands at 1721.3 cm$^{-1}$ was due to $\text{C=O}$ stretching and there would exist ion-exchange between $\text{C=O}$ and heavy metals the $\text{COO}^-$ group at 1721.3 cm$^{-1}$.

Fig. 2b exhibits the XRD pattern of raw material and the graft copolymers. The main XRD patterns of waste textiles were recorded at $2\theta$ = 19.74, 29.39 and 44.52°. A strong $2\theta$ XRD pattern was found at 19.74, indicating that WT had a crystalline domain of cellulose substrate ($2\theta = 19.74^\circ$). In the

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**Fig. 2** – (a) Fourier transform infrared spectroscopy, (b) X-ray diffraction, and (c), (d) scanning electron microscopy photographs of (A) waste textile (WT), (B) WT-g-AA.
crystalline regions, cellulose molecules (major component of WT) were arranged in ordered lattices in which hydroxyl groups were bonded by strong secondary forces. Compared with the diffraction patterns of original waste textiles, the diffraction patterns of the grafted WT showed a decrease of intensity and a broadening of peak at around \(2\theta = 29.39^\circ\). Meanwhile, two peaks appeared at \(2\theta = 20.29^\circ\) and \(2\theta = 21.78^\circ\) in the graft copolymer, as compared with WT. The phenomenon may be the destruction of raw material and the randomness of the amorphous phase caused by the grafting with AA under the combination of microwave and UV irradiation. Moreover, the grafting with AA also caused a perturbation of long-ranged spacing between the chains compared with raw materials.

SEM was used to examine the surface characteristics of WT and graft copolymer (Fig. 2c and d). The even and smooth surface was observed in the micrograph of original WT, and the roughness in surface morphology after grafting with AA was clearly manifested by the SEM micrograph. This behavior indicated that grafting operation affected the surface of original WT. The unevenness of surface resulted from deposition of polymer, which formed during graft copolymerization with AA. No porosity was observed from the image of WT-g-AA suggested the good interaction between the AA and WT. In addition, the roughness of the surface should be considered as a factor providing an increase in the surface area, which will facilitate the diffusion of heavy metals on the surface of WT-g-AA.

### 2.2. Adsorption of heavy metal ions

**2.2.1. Effect of pH**

The initial pH of the solution plays a key role in the adsorption process, because H\(^+\) are strong competing adsorbates and the solution pH influences the aqueous metal ion speciation, the adsorbent surface charge, and the degree of adsorbent ionization during the desorption process (Zhu et al., 2014). Fig. 3a shows the influence of pH on adsorption of Pb(II). It was found that the adsorption was highly dependent on pH. When pH < 6, the removal rate of metal increased sharply with the increasing of pH value, because the acidic solution inhibited the adsorption process of metal. In acidic solution, the active groups of WT-g-AA, such as carboxyl and hydroxyl groups, are protonated. The competition between H\(^+\) and metal ions for exchange sites in the system led to little adsorption of Pb(II).

However, with increasing pH, deprotonation of the protonated groups took place and the WT-g-AA surface charge became negative, which led to higher adsorption of cationic species. At the optimum pH of 7, the removal efficiencies (\(R, \%\)) of WT and WT-g-AA for Pb(II) were 70.38% and 94.22%, respectively. Solution pH was controlled at 7.0 for further investigations.

**2.2.2. Effect of adsorbent dosage**

The effect of WT-g-AA powder dosage (0.5–3 g/L) on Pb(II) removal was studied and the results are shown in Fig. 4b. The removal efficiency for Pb(II) was improved with the increase of adsorbent dosage and reached the maximum of 95.3% at 3 g/L.
WT-g-AA powder. However, saturation occurred at 1 g/L, at which a further increase in dosage caused negligible effect upon ion adsorption. Hence, 1 g/L was determined as the optimum dosage. The improvement of adsorption with increasing sorbent mass can be ascribed to the larger surface area and the more available adsorption sites.

2.2.3. Effect of initial Pb(II) concentration and contact time

Fig. 3c shows the effect of reaction time (0–120 min) on the adsorption capacity of WT-g-AA powder; the initial concentration of Pb(II) was 10 mg/L. Fig. 3d shows the data of Pb(II) adsorption by WT-g-AA for different initial concentrations plotted as a function of time. As presented in Fig. 3c, the WT-g-AA showed a good adsorption property for Pb(II); the adsorption capacity was enhanced with increasing reaction time and after 30 min it gradually approached an equilibrium condition at a low speed. The maximum removal efficiency of Pb(II) was about 95.3%. The sharp increase in removal efficiency during the initial stage might be due to the sufficient available exchange sites, strong chelation, and the effective mass transfer. Under the studied experimental conditions, the adsorption equilibrium was achieved within about 120 min. According to the results in Fig. 3d, the removal efficiency of Pb(II) decreased from 95.7% to 17.5% when the initial Pb(II) concentration was increased from 10 to 200 mg/L. It obviously shows that the removal of Pb(II) is concentration-dependent, and low Pb(II) content (20 mg/L) seems quite necessary in order to obtain higher removal efficiency.

2.2.4. Adsorption isotherm

The adsorption isotherm studies are of fundamental importance in determining the adsorption capacity of the powder to diagnose the nature of adsorption and evaluate the commercial potential of the adsorbent.

The effect of initial Pb(II) concentration on the adsorption of Pb(II) by WT-g-AA was assessed at the range of 10–200 mg/L and the corresponding results are presented in Fig. 3d. From the figure, the adsorption capacity increased gradually as the initial Pb(II) concentration increased up to 100 mg/L; thereafter the equilibrium adsorption capacities were obtained, as showed in Fig. 4a. The obtained isotherm parameters, \( Q_m \), \( K_L \), \( K_F \), \( n \) and the correlation coefficients (\( R^2 \)) are listed in Table 1. The \( R^2 \) of the linear form of isotherm equations for tested heavy metal was much closer to unity for the Langmuir model than for the Freundlich model. And the maximum adsorption capacity of Pb(II) on WT-g-AA was 35.7 mg/g. It can be concluded that WT-g-AA powder had good potential for the removal of Pb(II) from aqueous solutions. The applicability of Langmuir isotherm suggested that the surface of Pb(II) loaded on WT-g-AA was homogeneous with the adsorption mechanisms of monolayer uptake, and the \( R_L \) values of 0.0251–0.340 (0 < \( R_L < 1 \)) indicated that the adsorption processes were favorable.

2.2.5. Adsorption kinetics

The ability of WT-g-AA interacted with Pb(II) was desirable and beneficial with respect to practical application. To study the adsorption kinetics of Pb(II) on WT-g-AA, 10 mg/L of initial concentrations were used. The uptake of Pb(II) was found to

| Table 1 – Isotherm parameters for Pb(II) sorption onto WT-g-AA. |
|-------------------|-------------------|-------------------|
| \( Q_{m,exp} \) (mg/g) | Langmuir model | Freundlich model |
| \( Q_{m,cal} \) (mg/g) | \( R^2 \) | \( R_L \) | \( K_F \) | \( n \) | \( R^2 \) |
| 35.5 | 35.7 | 0.194 | 0.992 | 0.0251–0.340 | 12.80 | 4.85 | 0.958 |

| Table 2 – Kinetic models parameters for Pb(II) sorption onto WT-g-AA. |
|-------------------|-------------------|-------------------|
| \( Q_{e,exp} \) (mg/g) | Pseudo-first order | Pseudo-second order |
| \( Q_e \) (mg/g) | \( k_1 \) | \( R^2 \) | \( k_2 \) | \( R^2 \) |
| 9.41 | 9.37 | 0.239 | 0.998 | 9.81 | 0.049 | 0.985 |
be rapid at the initial period (0–10 min), then became slow and stagnate with the increase of contact time (10–120 min).

The two kinetics models are shown in Fig. 4b. The results of kinetic constants and correlation coefficients ($R^2$) are listed in Table 2. Higher correlation coefficient ($R^2 = 0.998$) was achieved for pseudo first-order model, which showed that the adsorption of Pb(II) onto WT-g-AA preferably fitted pseudo-first-order model.

2.2.6. Desorption and regeneration studies
Desorption studies help to elucidate the mechanism of adsorption and recycling of the adsorbent and it is one of the most important properties for environmental and economic reasons. In this study, the amount of heavy metal of solution in 1 hr was measured. Desorption of adsorbed Pb(II) was carried out using nitric acid solution and the reusability was evaluated three times. For four adsorption/desorption cycles, the Pb(II) adsorption capacity of the WT-g-AA material was 95.4% (cycle 1), 92.2% (cycle 2), 91.1% (cycle 3) and 86.1% (cycle 4). After the treatment of WT-g-AA, the quality of the treated aqueous solution in regard to Pb(II) is up to the standard of “Integrated wastewater discharge Standard (GB8978-1996)” of China. The reduction in Pb(II) uptake in four cycles of adsorption/desorption indicated that the binding sites of the adsorbent were little destroyed and the WT-g-AA powder was suitable for Pb(II) removal from wastewater for industrial applications.

2.3. Adsorption mechanism
To further analyze the adsorption mechanisms of Pb(II) on WT-g-AA, Pb(II)-loaded WT-g-AA were prepared at pH 7.0. In this experiment, the XPS was further used to characterize the surface states of WT-g-AA before and after adsorption of Pb(II) of WT-g-AA.

Fig. 5 – (a) Low resolution X-ray photoelectron spectroscopy and X-ray photoelectron high-resolution (b) C1s of WT and WT-g-AA, (c) O1s before and (d) after adsorption of Pb(II) of WT-g-AA.

Table 3 – Binding energies, quantitation and assignment of X-ray photoelectron spectroscopy (XPS) spectral bands of WT and WT-g-AA.

<table>
<thead>
<tr>
<th>Element</th>
<th>WT</th>
<th>WT-g-AA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak (eV)</td>
<td>Atomic (%)</td>
<td>Assignment</td>
</tr>
<tr>
<td>C1s</td>
<td>285.48 ± 0.12</td>
<td>76.8 ± 0.21</td>
</tr>
<tr>
<td>C1s</td>
<td>287.30 ± 0.32</td>
<td>6.5 ± 0.34</td>
</tr>
<tr>
<td>C1s</td>
<td>289.40 ± 0.24</td>
<td>16.7 ± 0.25</td>
</tr>
<tr>
<td>Total C</td>
<td>286.12 ± 0.16</td>
<td>73.93 ± 0.12</td>
</tr>
</tbody>
</table>
High resolution carbon C1s spectra yielded information on the relative abundance of carbon atoms in different molecular environments (Fig. 5a). The symmetric three-component fit as used, was based on carbons with 0, 1, or 3 bonds to oxygen. The component for carbon without oxygen neighbors was at the lowest binding energy, at 285.48 eV, and carboxylic carbons, having three bonds to oxygen, showed up at the highest binding energy, at 289.40 eV.

The appearance of such functional groups (Fig. 5b) is common to most polymers, but there are always differences between specific polymers. In the original WT, the main components in C1s spectra were C-C and C-O bonds (Fig. 5b and Table 3). In grafted samples, the modifications showed up as changes in distribution of the carbon component.

According to the XPS carbon data, there was an obvious decrease of the C-C shake-up from 76.8% to 51.7%, when the AA was grafted onto WT. And the signal of C-O was intensifying practically in the XPS spectrum (from 6.5% to 37.9%). This indicated that a dense layer of grafted polymer had attenuated the signal for cellulose of the fibril backbone.

The XPS wide scan spectra of Pb(II) and WT-g-AA-Pb(II) are shown in Fig. 6a. It can be seen that the major peaks such as C 1s, O 1s and N 1s were present. After adsorption, a new peak assigning to Pb appeared, indicating that Pb(II) was successfully adsorbed onto the surface of WT-g-AA. This result was consistent with the EDS analysis (Fig. 6).

On the other hand, the XPS spectra of O 1s on WT-g-AA before and after adsorption of Pb(II) are shown in Fig. 5c and d, respectively and the binding energies of O 1s and their variations on the surface are listed in Table 3. The two peaks at 531.64 and 532.93 eV appeared due to the minor O-containing groups (C−O−C, C=O, COOH, C−OH and −COO−). No new peaks was observed after the adsorption of Pb(II) demonstrating that the mechanism between O and metal ion was not chelating interaction. However, the area ratio for the peak located at 531.1 eV, which was assigned to hydroxyl bond to the metal oxide (M-OH), increased from 6.5% to 14.7% after reaction with Pb(II). This is possibly due to the ion-exchange between −COOH and Pb(II), as a result of which the −COOH groups translated into −COO−, resulting in the changes of the peak dimension ratio. Based on the above analysis, the main mechanism of Pb(II) adsorbed onto WT-g-AA could be the ion-exchange between −COOH and Pb(II). The proposed ion-pathway was illustrated in Fig. 7.

2.4. The environmental benefit analysis

In order to evaluate the environmental benefit of WT-g-AA, the graft copolymerization of WT was compared with other conventional techniques in Table 4. Grafting of WT is a good way to improve its properties such as increasing ion-exchange, chelation and enhancing adsorption properties. Furthermore, grafted WT composites may be the potential materials for heavy metals adsorption and a new way to reuse and recycle waste textiles.

### Table 4 – The comparison of different techniques for treating WT.

<table>
<thead>
<tr>
<th>Treatment techniques</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill</td>
<td>Convenience, low-cost</td>
<td>Generation of organic pollutants (measured as COD and BOD) and NH₃-N emissions</td>
</tr>
<tr>
<td>Incineration</td>
<td>Having a considerable calorific value</td>
<td>Emissions of NOₓ, CO₂ as well as dioxin pollutants</td>
</tr>
<tr>
<td>Carbonization</td>
<td>Obtaining activated carbon</td>
<td>Co-production of pyrolysis gas and tar</td>
</tr>
<tr>
<td>Graft copolymerization</td>
<td>Potential materials for adsorption</td>
<td>Catalysts and additives need for initiation, dependant on temperature</td>
</tr>
</tbody>
</table>

### 3. Conclusions

This study demonstrated the potential and viability of WT-g-AA particles for removing Pb(II) from contaminated water. The characterization of WT-g-AA powder indicated that carboxyl groups were successfully introduced into the crosslinked hydrogel powder. The adsorption experiments confirmed that the adsorption capacity of WT-g-AA powder to Pb(II) depended upon the pH and initial Pb(II) concentration of the solution. WT-g-AA exhibited the highest effectiveness for the removal of Pb(II) over the pH 6.0–8.0. About 95.4% Pb(II) removal was achieved from aqueous solutions containing 10 mg/L of Pb(II). The Langmuir isotherm model was able to interpret the equilibrium adsorption data with maximum adsorption capacity of 35.7 mg/g, and the R² values of 0.0251–0.340 (0 < R² < 1) indicated that the adsorption processes were favorable. Sorption kinetic tests showed that the adsorption of Pb(II) onto WT-g-AA preferably fitted pseudo first-order model. The reuse of WT-g-AA as a potential material for removal of heavy metals from wastewater maintained almost constant even after four cycles. Moreover, the employed adsorbent can be regenerated and reused upon treatment with nitric acid.

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