Kinetic and Equilibrium Studies of Cesium-137 Adsorption on Olive Waste from Aqueous Solutions.

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ABSTRACT

The agricultural by-product olive pomace either in its raw material or carbonized form was used for the removal of $^{137}$Cs from aqueous solutions. Experimental studies were conducted to evaluate and optimize some affecting factor such as contact time, adsorbent dosage, pH value and initial $^{137}$Cs concentration ions. The sorption process was described by pseudo first-order, pseudo second-order and Intra-particle diffusion models. Data have been interpreted in terms of Langmuir, Freundlich and Dubinin-Radushkevich (D-R) isotherms. The obtained data showed that 120 minutes are sufficient time to attain equilibrium and maximum % removal of $^{137}$Cs was found 80% and 99% for raw olive pomace and its carbonized form, respectively. The maximum sorption capacity of raw and carbonized adsorbent for cesium removal was 0.360 and 0.565 mol/g respectively.

Key word: Adsorption/ Olive pomace/ Cesium-137/ Kinetic/ Carbonization

INTRODUCTION

The use and subsequent disposal of radioactive waste is of major concern for any unclear facility. The presence of radionuclides and other even at low concentration, in various industrial wastes is of major concern, as they pose serious chemical and radiological toxicity threats to living organisms\(^{(1,2)}\). Isotope of cesium is among the most hazardous radioactive contaminants of the environment\(^{(3)}\). Due to their relativity long half-lives, high solubility and possibility of migration to biosphere, they are potentially very hazardous. Therefore, it’s required to remove these isotopes before discharge of waste to the environment\(^{(4)}\). A number of methods are available for the removal of radioactive isotope from aqueous solutions. These are ion exchange, solvent extraction, reverse osmosis, precipitation and adsorption. Adsorption process has been actually is the most frequently applied method in the industries, and consequently the most extensively studied\(^{(5)}\).

Agricultural by–products are promising sorbents due to their minimum cost and high sorption ability\(^{(6)}\). Biosorbents are prepared from naturally abundant waste biomass. Several authors\(^{(7,8)}\) have reviewed bioseparation processes for removing metal ions from wastewater using agricultural by products, such as rice husk; saw dust of various plants, bark of the trees\(^{(9)}\), apple residues\(^{(10)}\), coconut shells\(^{(11)}\), carrot residue\(^{(12)}\), rice straw\(^{(13)}\), orange residue\(^{(14)}\), apricot stone\(^{(15)}\) and olive pomace which used in the removal of chromium ion from wastewater with capacity of 23.3 mg/g\(^{(16)}\).

Olive pomace, agro-industrial wastes, consists of aligno-cellulosic matrix with polyphenolic compounds, uronic acids and oily residues\(^{(17)}\). Numerous sites potentially active in metal removal, such as carboxylic, hydroxyl, methoxy and phenolic groups are present. Olive pomace contains the olive fruit skin, pulp and seed fragments as a result of olive oil production\(^{(18-21)}\). In this work, waste olive cake, a major surplus waste produced was utilized as the raw material and for the production of biosorbents by physical treatment and there adsorption capacity for cesium ion was evaluated. The
influence of several operating parameters, such as contact time, pH, initial concentration and adsorbent dose was studied.

**EXPERIMENTAL**

**Reagents and materials:**

All reagents used were of analytical grade. Solutions were prepared from CsCl salt in double distilled water and were diluted further to obtain the lower concentration solutions.

**Preparation of adsorbent (Olive waste):**

The olive pomace (OP) waste was collected from Eslheia factory (Egypt) in 2011 as ground solid particles. Olive pomace was washed with double distilled water four times at least, dried in an oven at 80 °C for 24 hours, ground and sieved to particle size (24-28) mesh. The material after sieving is divided into two parts the first part was used as it is for adsorption of Cesium ions, it was labeled by (OP). The second part was placed in a purpose-made stainless steel tube and positioned at the center of muffle furnace for on hour at 500 °C and labeled by modified olive pomace (MHOP).

**Apparatus:**

Cesium ions in the solution were determined by measuring the $^{137}\text{Cs}$ activity using single channel analyzer supplied with a well-type NaI (TI) detector of the type Scaller-Ratemeter SR5. In all cases, the activity was determined as a mean value after subtracting the background. Three replicates were prepared in each case. pH Orion Research digital ion analyzer 501, Reciprocal shaker, Electronic balance type BL-320H and furnace of type Stuart Scientific.

**Adsorption studies:**

Unless otherwise is specified, the equilibrium experiments were carried out by agitating certain weight of olive pomace or its modified form, with 10 ml of $10^{-4}$ M cesium solution, traced with the radioactive isotope. The samples were shaken for 2 hrs in sealed polyethylene vials in a thermostated water bath shaker. After equilibration, the samples were separated from solution by centrifugation.

The % uptake and the amount of $^{137}\text{Cs}$ ion sorbed were calculated using the relations:

\[
\% \text{ uptake} = \left(\frac{C_o - C_e}{C_o}\right) \times 100 \tag{1}
\]

\[
q_t = \frac{(C_o-C_e)V}{M} \tag{2}
\]

Where $C_o$ and $C_e$ are the initial and equilibrium concentration (mg/L) of ion in solution, V is the volume (L) and M is the weight (g) of the adsorbent.

**Characterization of adsorbents:**

The specific surface areas of the studied samples (OP) and (MHOP) were determined using Nova SA instrument 3200 by applying the BET method using a gas mixture of 30 % N$_2$/Ar. A Fourier transform infrared (FTIR) spectrometer from Perkin Elmer 1600 was used to analyze the matrices in the wave number range 600–4000 cm$^{-1}$. Thermogravimetric analysis (TGA) was carried out by using TA 50 Shimadzu, Japan. Temperature was cycled at a constant rate of 20°C/min from ambient temperature to 500 °C under nitrogen atmosphere.
RESULTS AND DISCUSSION

Characterization of the used adsorbents:

The specific surface area of the raw and modified olive Pomace was 1.9 and 30.5 m$^2$/g respectively. Infrared spectroscopy was used to obtain information about the chemical structure and functional groups of the two samples under investigation. The FTIR spectrum of the olive pomace cakes is shown in Fig. 1(a, b). This spectrum is quite similar to that of other lignocellulosic materials such as pistachio-nut shell and rockrose$^{(22)}$. The band located at 3348 and 3411.6 cm$^{-1}$ in raw and modified olive cake corresponds to stretching of OH group. The band located at 2924.9 and 2913 cm$^{-1}$ corresponds to the C–H vibrations in methyl and methylene groups. The band at 1743.8 cm$^{-1}$ in raw but disappear in modified one is ascribed to carbonyl C=O groups. The olefinic (C=C) vibrations cause the emergence of the band at about 1651 cm$^{-1}$, while the skeletal C=C vibrations in aromatic rings cause another two bands at 1517 and 1539 cm$^{-1}$. The vibrations at 1461 and 1379.6 cm$^{-1}$ are assigned to the bands –CH$_3$ and –CH$_2$–. The band at 1318 cm$^{-1}$ can be attributed to ν(C–O) vibrations in carboxylate groups. The band at 1241 cm$^{-1}$ may be attributed to esters (e.g. R–CO–O–R’), ethers (e.g. R–O–R’) or phenol groups. The relatively intense band at 1055 cm$^{-1}$ can be assigned to alcohol groups (R–OH).

![Fig. (1): FTIR spectra of (a) OP and (b) MHOP sample.](image-url)
Fig. 2 shows the TGA curves of raw and modified olive waste which was carried out at a heating rate of 20°C /min. with a temperature range of 25°C to 500 °C. The weight loss at the beginning of the process was due to evaporation of free moisture content. As the temperature increased further, the water in the lignocellulosic material also evaporated. A major weight loss occurs in the temperature range of 200 to 400°C and 410 to 450°C for OP and MHOP samples respectively that is attributed to the release of volatile matter[23].

![TGA diagram of OP and MHOP](image-url)

**Fig. (2):** TGA diagram of OP and MHOP

**Effect of pH:**
Since pH is one of the main variables affecting the adsorption process a preliminary study was carried out to determine the optimum pH value for the uptake of 10^{-4} M Cs solution, at room temperature (25°C) for 2 hrs of equilibration on 0.2 g OP or MHOP samples. From Fig.3 it was found that the maximum adsorption capacity of $^{137}$Cs obtained at pH of 5.4 and 3.6 for raw and modified olive pomace respectively. At low pH (<2.0) the adsorption capacity is very low, because large quantity of hydrogen ions competes with $^{137}$Cs ions at sorption sites. As the pH increases, more negatively charged surface becomes available thus facilitating greater metal uptake[24].

![Effect of pH on the removal of $^{137}$Cs onto MHOP and OP](image-url)

**Fig. (3):** Effect of pH on the removal of $^{137}$Cs onto MHOP and OP.

**Effect of sorbent mass:**
The effect of adsorbent amount on the sorption of $^{137}$Cs ion was tested utilizing the batch procedures. The results were shown in Fig. 4. It can be seen that, the percentage removal increases with the increase in adsorbent dosage (0.01–0.5 g), for the OP and MHOP samples. This trend is
expected because as the adsorbent dose increases the number of adsorbent particles increases and thus more $^{137}$Cs ion is attached to their surfaces when the sorbent dose was $0.2$ g, the sorption efficiency were above $80\%$ for OP and $99\%$ for MHOP, $0.2$ g of sorbent was chosen for further experiments.

![Graph showing the effect of different mass on the removal of $^{137}$Cs onto OP and MHOP.](image)

**Fig. (4): Effect of different mass on the removal of $^{137}$Cs onto OP and MHOP.**

**Kinetic studies:**

The relationship between contact time and percent removal (%) of $^{137}$Cs ion by the two samples OP and MHOP, are presented in Fig. (5). From this figure, it is clear that, the rate of adsorption increases with the increase in shaking time, and equilibrium is reached after $1$ h in two samples, with easily accessible surface layers of the particles saturating first and fast. Adsorption of $^{137}$Cs ion onto OP and MHOP include two apparent steps, a fast initial step followed by a slower phase that reflects the penetration of sorbate into the particles. Correspondingly, the adsorption increased sharply in the first 30 min, with more than $80\%$ and $99\%$ for OP and MHOP respectively, and then continued increasing but with slower rate. As seen from Fig. 5 the equilibrium was reached in less than $60$ min. A further increase in contact time had a negligible effect on the amount of $^{137}$Cs ion adsorption. According to these results, the shaking time was fixed at $2$ hrs for the rest of the batch experiments to make sure that the equilibrium was reached.

A distinct two-step behavior has often been reported for $^{137}$Cs ion biosorption, While Liu and Huang attributed the two-step sorption characteristic to the heterogeneity of the surface binding sites on sorbents asserted that the fast initial sorption was the result of the fast transfer of metal ions to the surface of biomaterial, followed by a relatively slow uptake caused by the slow diffusion of $^{137}$Cs ion into the intra-particle spaces of two sorbents. To describe the changes in the sorption of ion with time, three simple kinetic models, pseudo first order, pseudo second order and intra-particle rate, were tested in order to establish the mechanism of $^{137}$Cs ion adsorption onto OP and MHOP samples.

![Graph showing the effect of contact time on the amount sorbed of $^{137}$Cs onto MHOP and OP](image)

**Fig. (5): Effect of contact time on the amount sorbed of $^{137}$Cs onto MHOP and OP.**
Pseudo-first-order kinetic model:

Kinetics of $^{137}$Cs ion adsorption was treated using pseudo-first order rate of Lagergren:\n
$$\log (q_e - q_t) = \log q_e - \left(\frac{K_1}{2.303}\right)t$$ \hspace{1cm} (3)

Where $q_t$ and $q_e$ are the amounts of $^{137}$Cs ion on two samples under test (mg/g) at time $t$ and at equilibrium, respectively, the $K_1$ is the rate constant of uptake (min$^{-1}$). The obtained plots of log $(q_e - q_t)$ against time $t$, Fig. (6) are linear and indicate the applicability of the Lagergren equation for the two samples. The calculated values of $K_1$ which obtained from the slopes of these linear plots and the linear correlation coefficients ($R^2$) of each plot are presented in Table (1).

![Fig. (6): Lagergren plot for adsorption of $^{137}$Cs onto OP and MHOP.](image)

Pseudo-second-order model:

The kinetics was also described with pseudo-second-order process:\n
$$\frac{t}{q_t} = \frac{1}{k_2q_e^2} + \frac{1}{q_e}t$$ \hspace{1cm} (4)

Where, ‘$q_e$’ and ‘$q_t$’ are the amount of $^{137}$Cs ion adsorbed (mg g$^{-1}$) at equilibrium and at time $t$, respectively, and $k_2$ is the rate constant of pseudo-second-order kinetics. The plots between $t/q_t$ versus $t$ were drawn and are shown in Fig. 7. The values of $K_2$, $q_e$ and $R^2$ are listed in Table1. Further, the correlation coefficient ($R^2$) was 0.999 suggesting that the present adsorption system can be described more favorably by pseudo-second-order process. The calculated $q_e$ values which agree perfectly with the experimental $q_e$ values.

![Fig. (7): Second-order plot for adsorption of $^{137}$Cs ion onto OP and MHOP.](image)
The intraparticle diffusion model is\(^{(29)}\):

\[
q_t = k_d t^{1/2} + C
\]  

(5)

Where, \(k_d\) is the intraparticle diffusion rate constant and \(C\) is the intercept related to the boundary layer. The amount of \(^{137}\)Cs adsorbed \((q_t)\) at time \((t)\), was plotted against the square root of time, \((t^{1/2})\) according to Eq. (5) and the resulting plot is shown in Fig. (8) The intra-particle diffusion kinetic model provides information about the nature of the adsorption process. A plot of \(q_t\) vs. \(t^{1/2}\) for \(^{137}\)Cs ion adsorption on OP and MHOP afforded two linear sections. A deviation of the straight line from the origin indicates that the intra-particle diffusion is not the only rate controlling step and boundary layer diffusion controls the adsorption process\(^{(30)}\). If the regression of \(q_t\) vs. \(t^{1/2}\) is linear and passes through the origin, intra-particle diffusion is the sole rate-controlling step\(^{(31)}\). The first straight portion was attributed to the fast mass transfer of sorbate molecules from the bulk solution to the sorbent surface and the second linear portion attributed to the slower intraparticle diffusion into the biosorbent. Similar results were found by Hameed\(^{(32)}\).

![Intraparticle plot for adsorption of \(^{137}\)Cs onto OP and MHOP.](image)

The results suggest that intra-particle diffusion is not the sole rate controlling step because the plot does not pass through the origin. This is in agreement with the results obtained by using intra-particle diffusion model at the same time, indicating that the mechanism of \(^{137}\)Cs adsorption by OP and MHOP is complex and, external mass transport as well as intra-particle diffusion contributes to the rate determining step.

**Table (1): Kinetic models for \(^{137}\)Cs ions sorbed by OP and MHOP.**

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>First-order rate (K_f (mg/g\cdot min^{-1}))</th>
<th>(R^2)</th>
<th>(q_e) Exp. ((mg/g))</th>
<th>(q_e) Cal ((mg/g))</th>
<th>Second-order rate (K_2 (mg/g/min^{-1}))</th>
<th>(R^2)</th>
<th>intra-particle diffusion rate (K_d (mg/g \cdot min^{-0.5}))</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP</td>
<td>0.045</td>
<td>0.80</td>
<td>0.55</td>
<td>0.57</td>
<td>0.45</td>
<td>0.99</td>
<td>0.11</td>
<td>0.94</td>
</tr>
<tr>
<td>MHOP</td>
<td>0.055</td>
<td>0.84</td>
<td>0.68</td>
<td>0.69</td>
<td>0.78</td>
<td>0.99</td>
<td>0.16</td>
<td>0.94</td>
</tr>
</tbody>
</table>
Effect of initial concentration

Sorption equilibrium is usually described by an isotherm equation whose parameters express the surface properties and affinity of the sorbent, at a fixed temperature and pH. An adsorption isotherm describes the relationship between the amount of adsorbate on the adsorbent and the concentration of dissolved adsorbate in the liquid at equilibrium\(^\text{(33)}\). The effect of \(^{137}\)Cs concentration on its sorption onto two samples OP and MHOP were studied under the optimized conditions of shaking time, pH and the amount of adsorbent. The Cs concentration has been tested, in the concentration range of \(10^{-4}\) to \(10^{-2}\) M. The adsorption was almost constant up to \(10^{-4}\) M of \(^{137}\)Cs ions beyond this concentration the adsorption decreased gradually with the increase of \(^{137}\)Cs concentration(Fig. 9). This can be explained in terms of the relatively smaller number of active sites at a higher concentration of \(^{137}\)Cs\(^\text{(18)}\).

![Fig. (9): Effect of initial concentration on the adsorption of \(^{137}\)Cs onto OP and MHOP.](image)

Langmuir isotherm model\(^\text{(34)}\):

Langmuir isotherm model was chosen to estimate the maximum adsorption capacity suggests that the uptake occurs on homogeneous surface by monolayer sorption without interaction between adsorbed ions. The linear form of the Langmuir equation is represented by the following equation:

\[
\frac{C_e}{q_e} = \frac{1}{K_L Q_o} + \frac{C_e}{Q_o}
\]

(6)

Where, \(q_e\) is the amount of \(^{137}\)Cs ion adsorbed at the equilibrium (mol/g), \(C_e\) is the equilibrium solution concentration (mol/l), \(K_L\) is Langmuir constant and \(Q_o\) is the maximum \(^{137}\)Cs ions uptake per unit mass of adsorbent (mol/g) related to adsorption capacity. Therefore, a plot of \(C_e /q_e\) versus \(C_e\) gives a straight line of slop \(1/Q_o\) and intercept \(1/(Q_o K_L)\) as shown in Fig.(10). These values are listed in Table 3. In order to justify the validity of olive pomace as an adsorbent for \(^{137}\)Cs ions adsorption. Its adsorption potential must compare with other adsorbents as listed in Table 2.

![Fig. (10): Langmuir isotherm plot for adsorption of \(^{137}\)Cs onto OP and MHOP.](image)
A further analysis of the Langmuir equation can be made on a dimensionless equilibrium parameter, $R_L$, also known as the separation factor, given by \(^{(34)}\):

$$R_L = \frac{1}{1 + K_L C_o} \quad (7)$$

Where $K_L$ is the Langmuir constant and $C_o$ is the initial Cs ion concentration (mg/L). The isotherm is favorable when $0 < R_L < 1$. The average of the $R_L$ values for each of the different initial concentrations used is between 0 and 1 indicating favorable adsorption of $^{137}$Cs ion onto both samples under test.

**Table (2): Comparison of maximum adsorption capacity of MHOP with different adsorbent for $^{137}$Cs ion.**

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>Capacity (mg/g)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peach stone shell</td>
<td>4.5</td>
<td>34</td>
</tr>
<tr>
<td>Hexacyanoferrate loaded activated carbon</td>
<td>13.38</td>
<td>35</td>
</tr>
<tr>
<td>Nanozirconium vanadate ionexchanger</td>
<td>9.9</td>
<td>36</td>
</tr>
<tr>
<td>Modified moss</td>
<td>17</td>
<td>37</td>
</tr>
<tr>
<td>Guava leaves</td>
<td>8.02</td>
<td>38</td>
</tr>
<tr>
<td>OP</td>
<td>49.3</td>
<td>This work</td>
</tr>
</tbody>
</table>

**Freundlich isotherm model:**

The Freundlich isotherm is an empirical model that is based on adsorption on heterogonous surface and given by the following equation \(^{(38)}\):

$$\log q_e = \log K + \left(\frac{1}{n}\right) \log C_e \quad (8)$$

Where $q_e$ is the amount of $^{137}$Cs ion adsorbed at the equilibrium (mol/g), $C_e$ is the equilibrium concentration of the $^{137}$Cs ion solution (mol/l), $K$ and $n$ are Freundlich constants, which represent adsorption capacity and adsorption intensity, respectively. A plot of $\log q_e$ versus $\log C_e$ were shown in Fig. 11 and the constants were determined from the slope and intercept and reported in Table (3). Examination of Table 3 showed that the values of $n$ were found to be 1.3 and 1.5 for OP and MHOP respectively greater than unity which is reflect that the sorption are simultaneously precipitation in a direction to sorption and indicated a favorable adsorption processes \(^{(39)}\).
Dubinin-radushkevich (R-R) isotherm model:

Another equation used in the analysis of experimental data was proposed by D-R model\(^{(40)}\):

\[
\ln q_e = \ln q_m - K \varepsilon^2
\]  

(9)

Where, \(q_e\) is the amount of \(^{137}\text{Cs}\) ion adsorbed at the equilibrium (mol/g), \(q_m\) is the maximum sorption capacity, \(K\) is activity coefficient related to mean sorption energy and \(\varepsilon\) is the Polanyi potential, which is equal to:

\[
\varepsilon = RT \ln(1+1/C_e)
\]  

(10)

Where R is the gas constant in (kJ/mole.K), T is the absolute temperature in Kelvin and \(C_e\) is the equilibrium concentration of cesium in solution (mol/l). A Plot of \(\ln q_e\) vs. \(\varepsilon^2\) results in a straight line as shown in Fig. 12, indicating the validity of the D–R equation. From the intercept and the slope of the plot the values of \(q_m\) and \(K\) were listed in Table 3.

The mean free energy, \(E\), of adsorption can be estimated from the relationship\(^{(41)}:\)

\[
E = (-2K)^{-1/2}
\]  

(11)

The values of the mean free energy, \(E\), of sorption in two samples is in the range of 8-16 kJ/mol, which are within the energy ranges of ion exchange reaction.
Table 3: Langmuir, Freundlich and D-R parameters for sorption of $^{137}$Cs on OP and MHOP

<table>
<thead>
<tr>
<th>Adsorbent</th>
<th>Langmuir</th>
<th>Freundlich</th>
<th>D-R</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Q_o$ (mol/g)</td>
<td>$K_L$ (mol/l)$^{-1}$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>OP</td>
<td>0.360</td>
<td>0.005</td>
<td>0.98</td>
</tr>
<tr>
<td>MHOP</td>
<td>0.565</td>
<td>0.030</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Effect of temperature:

Figure (13) shows the equilibrium removal of $^{137}$Cs as a function of temperature on the OP sample. It can be seen that the $q_e$ decrease as the temperature increase and this behavior confirms that the adsorption process is exothermic process. In this work the results are in a good agreement with those obtained for the removal of iron using olive cake (42). This decreasing in adsorption as temperature increase may be due to the relative increase in the escaping tendency of the cesium ion from the solid phase to the bulk phase; or due to the weakness of the adsorptive forces between the active sites of the adsorbents and the adsorbate species and also between the adjacent molecules of adsorbed phase.

![Fig. (13): Effect of temperate on the amount sorbed of $^{137}$Cs on OP.](image)

Desorption

Desorption studies can help to elucidate the mechanism of adsorption. HCl solutions of different concentration were chosen as eluents in this study. According to the results 3 M HCl was more effective for desorption of $^{137}$Cs on MHOP 96.3% than 80.7 % for raw olive waste Fig. 14. The ion-exchange mechanism was dominated by the results of 3 M HCl desorption.

![Fig. (14): Desorption of OP and MHOP by HCl.](image)
CONCLOSNN

In this study, olive pomace and its converted into carbonaceous form by heating at 500°C was investigated for the removal of $^{137}$Cs from aqueous solution. The kinetics of $^{137}$Cs ions was experimentally studied and the obtained data were analyzed using pseudo first-order and pseudo second-order kinetic models. Results suggest that the sorption of $^{137}$Cs ion onto each samples followed the pseudo second-order rate model. Equilibrium study have been determined and tested for different isotherm and the sorption data were successfully modeled using Langmuir, Freundlich, and Dubinin-Radushkiveich (D-R) approaches. Based on the D-R model expression, the maximum sorption capacity and the mean free energy of the studied have been determined. The values of the mean free energy, $E$, of sorption in two samples is in the range of 8-16 kJ/mol, which are within the energy ranges of ion exchange reaction. The best condition was 0.2g of adsorbent dose, 120 min. for contact time and at natural pH. Higher concentration of HCl may lead to complete desorption (100%) of $^{137}$Cs from loaded adsorbent used which allow regeneration of adsorbent and reuse of $^{137}$Cs ion solution. These results demonstrate the great potential of plant residues, as low-cost radioactive isotope adsorbents. Cesium ion removal technique using such adsorbents would be an effective method for the economic treatment of wastewater.

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