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2 Uranium removal from aqueous solutions by wood powder 3 and wheat straw

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7 Received: 4 May 2009
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9 **Abstract** The influence of initial uranium concentration,
10 solution pH, contact time and adsorbent mass was investi-
11 gated for removal of uranium from aqueous solutions by
12 pine wood powder and wheat straw using a batch technique.
13 The maximum removal efficiency of uranium achieved at
14 pH 8 and 7 for pine wood powder and wheat straw,
15 respectively. *Langmuir* and *Freundlich* adsorption iso-
16 therms and three kinetic models of adsorption including;
17 *Elovich*, *Lagergren* pseudo-first and *Lagergren* pseudo-
18 second order were used to describe the adsorption mecha-
19 nisms. The uranium sorption onto wood and wheat straw
20 powders followed a *Freundlich* isotherm. The kinetic stud-
21 ies showed that the data fitted very well to the pseudo-second
22 order model in the studied concentration range of uranium
23 for both adsorbents. Uranium desorption from loaded
24 adsorbents also studied using batch techniques as a function
25 of desorptive reagent, desorption time and desorptive
26 reagent concentration. The results of the experiment indi-
27 cated that the optimum desorption efficiency of uranium for
28 wood powder and wheat straw occurred in 5 min shaking
29 time, using 1.5 M HNO₃ and 2 M Na₂CO₃ solutions,
30 respectively.
31

Keywords Uranium · Wood powder · Wheat straw ·
Adsorption isotherms · Adsorption kinetics

Introduction

Uranium is a naturally occurring lithophilic metal with
atomic number 92 and its concentration in the earth's crust
is about 1.7 mg/kg [1]. The natural uranium is found in
various chemical forms including abiotic and biotic envi-
ronmental forms, e.g. in soils, rocks, seas, oceans and
microorganisms [1, 2]. Anthropogenic activities change the
natural abundance of uranium in both aquatic and terres-
trial ecosystems. It is likely accumulated as a contaminant
in the environment as a results of nuclear testing [3],
emissions from the nuclear industry, improper waste stor-
age practices [4, 5], inappropriate conditioning and dis-
posal of tailings waste, fuel combustion, use of phosphate
fertilizers, use of depleted uranium metal in ammunitions
and soluble products of rock weathering [1, 6–11]. Ura-
nium (IV) and (VI) are typically observed in the environ-
ment. Under strongly reducing conditions, it occurs in the
tetravalent (IV) oxidation state.

The sorption studies of uranium are important for
nuclear and hazardous wastes management. Different
organic and inorganic adsorbents have been widely used
for removal of U(VI) from aqueous solutions. Hydroxy-
apatite [12, 13], composite ion exchangers [14], bacteria
[15, 16], akagenite and zeolites [17, 18] were examined for
removal of uranium from aqueous solutions by many sci-
entists. Uranium has a great diversity in aqueous media.
Therefore, it would be advisable to use polyfunctional
adsorbents for uranium removal from aqueous solution.
Wood powder is a solid waste product obtained from
mechanical wood processing and essentially composed of

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65 cellulose, hemicelluloses, lignin and extractive materials.
66 Cellulose is the major chemical component of fiber wall
67 and contributing 40–45% of the wood's dry weight.

68 Natural and low cost ion exchangers like wood powder
69 have been used for removal of uranium and other heavy
70 metals from contaminated wastewater [19–25]. The sta-
71 bility of pine wood under water is from 50 to 100 years
72 [26]. Straw makes up about half of the yield of cereal
73 crops such as barley, oats and wheat. Wheat straw is one
74 of the main agricultural by-products that almost entirely
75 made of cellulose, hemicellulose, peptic and storage
76 polysaccharides, glucans, fructans, mannans and silica
77 [27, 28]. These materials have high chemical, biological,
78 radiation resistance and a low ash content (<5%) [21].
79 Wood powder and wheat straw do not noticeably swell in
80 water and do not decompose upon prolonged contact with
81 water.

82 Both of wood and wheat straw powders have a good
83 ability for binding metal cations due to hydroxyl, carbox-
84 ylic and phenolic groups present in their structure.

85 The objective of this research was to investigate the
86 sorption capacity of wood powder and wheat straw to
87 remove uranium from aqueous solution and optimize the
88 experimental conditions, such as initial uranium concen-
89 tration, solution pH, the mass of adsorbent and contact
90 time.

91 Experimental

92 Adsorbents

93 The sawdust of pine (*Pinus sylvestris*) wood (PW) obtained
94 from a lumber mill of *Vakil Abad*, Mashhad, Iran and wheat
95 (*Triticum aestivum*) straw (WS) obtained from a local silo
96 were used as adsorbents. Both adsorbents were milled and
97 passed through 20 mesh sieve. Wood and wheat straw pow-
98 ders were washed with distilled water, then filtered and dried
99 over night at 50 °C. The BET (*Brunauer-Emmett-Teller*)
100 surface area of PW and WS were determined by low tem-
101 perature nitrogen absorption using a Micrometrics ASAP
102 2000 Surface Area Analyser and were found to be 1.41 and
103 1.23 m² g⁻¹, respectively.

104 Reagents

105 Arsenazo (III), PAR (1,2-pyridyalzo resorcinol), UO₂
106 (NO₃)₂·6H₂O and the buffer solutions (pH 4, 7 and 9)
107 were obtained from Merck company. Uranium solutions
108 were prepared by dissolving appropriate amount of
109 UO₂(NO₃)₂·6H₂O in distilled water. Sample solutions were
110 filtered through a Whatman filter paper (No. 40).

Adsorption and desorption experiments

112 Batch techniques to study the adsorption of U(VI) onto PW
113 and WS were conducted in polypropylene bottle. About
114 0.3 g of each adsorbent was added to 10 mL of solutions
115 containing different concentration of U(VI) and stirred in a
116 thermostated shaker batch, GFL-1083 model. All experi-
117 ments were performed in duplicate at 28 °C and since the
118 variation of the experimental data was within the mea-
119 surement error (±5%) the mean values have been used for
120 data evaluation. The pH of each sample solution was
121 adjusted using HNO₃ or Na₂CO₃. The concentrations
122 of U(VI) in solution were determined spectrophotometri-
123 cally employing Shimadzu UV-VIS-1601 spectrophotom-
124 eter using arsenazo (III) as complexing reagent [29]. The
125 amount of adsorbed U(VI) was estimated from the differ-
126 ence of U(VI) concentrations in the solution before and
127 after the adsorption. The percent of adsorbed U(VI) onto
128 PW and WS was determined according to the following
129 equation:

$$\text{Adsorption (\%)} = (C_{\text{int}} - C_{\text{fin}}/C_{\text{int}}) \times 100$$

131 where C_{int} and C_{fin} are the concentrations of U(VI) on
132 initial and after equilibration, respectively. In the second
133 part of experiments, different reagents were examined for
134 recovery of adsorbed U(VI) from loaded PW and WS at
135 28 °C.

136 Desorption experiments were carried out as a function of
137 the shaking time, concentration of the desorptive reagents
138 and desorption stages. The U(VI) content in the solution
139 after the desorption process was determined with a
140 shimadzu UV-VIS 1601 UV spectrophotometer using PAR
141 (1,2-pyridyalzo resorcinol) as complexing agent at 510 nm
142 against reagent blank [30]. Uranium desorption was com-
143 puted as follows:

$$\text{Desorption (\%)} = (\text{amount of desorbed U} / \text{amount of adsorbed U}) \times 100$$

145 Results and discussion

146 Adsorption experiments

147 *Effect of initial uranium concentration*

148 The effect of initial U(VI) concentration was studied in the
149 concentration range between 50 and 2000 mg L⁻¹ at 28 °C
150 for 1 h shaking time. The pH of solution adjusted to the
151 natural pH (7 ± 0.1) using a concentrated solution of
152 Na₂CO₃ as the original U(VI) solution was strongly acidic.
153 The results showed in Fig. 1 that the U(VI) adsorption onto
154 PW and WS were strongly affected by the initial U(VI)
155 concentration.
156

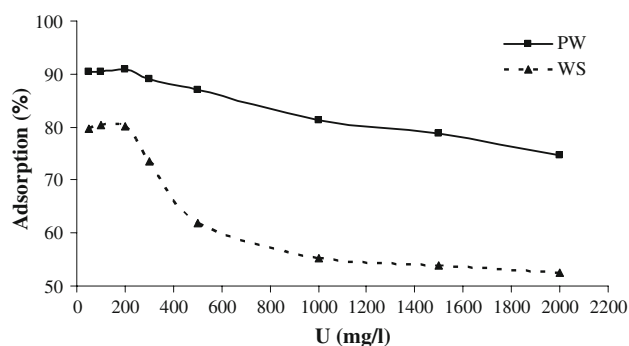


Fig. 1 The effect of initial uranium concentrations on U(VI) adsorption by PW and WS (mass of PW and WS = 0.3 g, $V = 10$ mL, pH = 7, shaking time: 1 h, temperature: 28 °C)

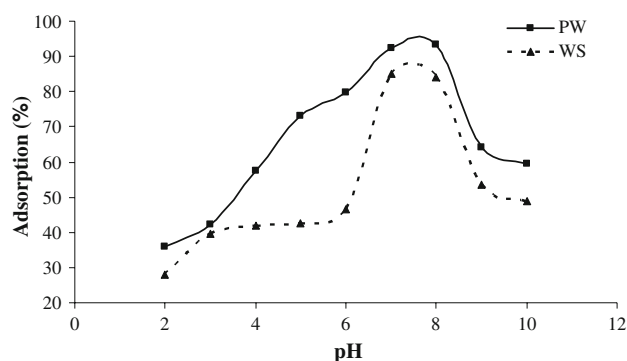


Fig. 2 The effect of solution pH on U(VI) adsorption by PW and WS (for PW [U(VI)] = 200 mg L⁻¹, $V = 10$ mL, mass = 0.3 g, shaking time: 1 h, temperature: 28 °C; for WS [U(VI)] = 100 mg L⁻¹, shaking time: 1 h, $V = 10$ mL, mass = 0.3 g, temperature: 28 °C)

Both adsorbents presented relatively higher U(VI) adsorption at 50–200 mg L⁻¹. It is evident from Fig. 1 that the amounts of adsorbate on PW and WS with lower initial concentration of adsorbate were higher than the amount when smaller initial concentrations were used. In all initial U(VI) concentrations, PW removed more U(VI) from solution compared to WS. According to these results, U(VI) concentrations for PW and WS were choiced 200 and 100 mg L⁻¹, respectively, for further studies.

Effect of pH

One of the most important parameters in the adsorption of U(VI) by PW and WS is the initial pH of the adsorption medium. The effect of pH on U(VI) adsorption by PW ([U(VI)] concentration = 200 mg L⁻¹, mass = 0.3 g, $V = 10$ mL) and WS ([U(VI)] concentration = 100 mg L⁻¹, mass = 0.3 g, $V = 10$ mL) was studied in the pH range of 2–10 at 28 °C for 1 h shaking time. Figure 2 shows the effect of pH on U(VI) adsorption by PW and WS. Uranium adsorption by both adsorbents was strongly affected by pH. As seen in Fig. 2, with increasing pH, the adsorption of U(VI) on PW tends to sharply increased until pH 8 and then decreased. For WS, The U(VI) uptake reached a maximum at pH 7.

The pH of solution could affect the solubility and speciation of metal ions in solution. The influence of solution pH on adsorption process can also be interpreted with the help of the structure and surface charge of the adsorbent.

The formation of various uranium complexes is important on the adsorption of uranium. U(VI) basically exists as free uranyl ion, its hydrolysis complexes, and multinuclear hydroxide and carbonate complexes as a function of pH and U(VI) concentration under our experimental conditions. Free uranyl ion is the dominant species in the acidic pH range up to 6, UO₂OH⁺ in the range of pH 5, UO₂(CO₃)₃⁴⁻ in the range of pH higher than 7 [14].

With increasing the pH of U(VI) solutions, the fraction of the anionic complex species of U(VI) tends to increase [21]. This is accompanied by an increase in the degree of U(VI) sorption by PW and WS, which suggests a poly-functional sorption mechanism for these sorbents. The difference in pH dependence on the degree of uranium sorption for PW and WS may be attributed to the difference in the content of their constituent functional groups.

These results are in conformity with U(VI) and Cr(III) sorption onto sawdust [21, 24]. The sorption at near neutral pH should be due to the cellulose where site-binding sorption might occur. It might be also due to the surface complexation phenomenon, facilitated by dissociation of acidic functional groups (–COOH, –SH, etc.) present on the sawdust [24, 25]. The U(VI) adsorption increased up to 93% at pH 8 for PW and 85% at pH 7 for WS. At acidic pH, the main species of U(VI) are positively charged and the positive charges density on the adsorbent surfaces also increased. Therefore, the U(VI) adsorption is not considerable [14]. On the basis of these results, pH 8 and 7 was chosen as an optimum pH for PW and WS, respectively.

Effect of shaking time

The effect of shaking time on U(VI) adsorption by PW ([U(VI)] concentration = 200 mg L⁻¹, pH = 8, mass = 0.3 g, $V = 10$ mL) and WS ([U(VI)] concentration = 100 mg L⁻¹, pH = 7, mass = 0.3 g, $V = 10$ mL) at different contact time varying between 5 and 120 min at 28 °C was studied. The results are presented in Fig. 3. The sorption increased with the increase in shaking time up to 60 min, beyond which it attained almost a constant value. Adsorption of U(VI) reached to 92 and 84% for PW and WS, respectively. Therefore, 60 min shaking time was considered to be sufficient for the sorption of U(VI) ions onto sawdust and was used for all experiments.

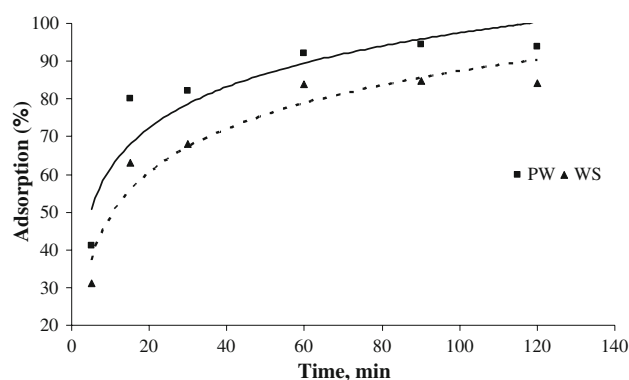


Fig. 3 The effect of shaking time on U(VI) adsorption by PW and WS (for PW [U(VI)] = 200 mg L⁻¹, V = 10 mL, mass = 0.3 g, pH = 8, shaking time: 1 h, temperature: 28 °C; for WS [U(VI)] = 100 mg L⁻¹, shaking time: 1 h, V = 10 mL, mass = 0.3 g, pH = 7, temperature: 28 °C)

Effect of adsorbent mass

The effect of adsorbent mass on the U(VI) adsorption process by PW ([U(VI)] = 200 mg L⁻¹, pH = 8, shaking time = 60 min) and WS ([U(VI)] = 100 mg L⁻¹, pH = 7, shaking time = 60 min) at 28 °C was investigated. The results are depicted in Fig. 4. We found that for different adsorbents, the mass increment differently affects the sorption. For example, three fold increases (0.1–0.3 g) of the mass of PW increases the degree of sorption from 75 to 94%. However, further increase of the mass does not afford exhaustive recovery of U(VI) while for WS, the degree of U(VI) sorption increased up to 0.5 mg. These results are in conformity with U(VI) and Cr(III) sorption onto saw dust [21, 24]. Therefore, 0.2 and 0.5 g of adsorbents were chosen as an optimum amount for further use.

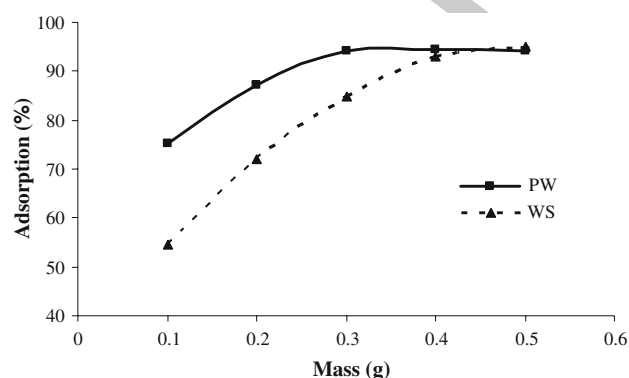


Fig. 4 The effect of mass of adsorbent on U(VI) adsorption by PW and WS (for PW [U(VI)] = 200 mg L⁻¹, V = 10 mL, pH = 8, shaking time: 1 h, temperature: 28 °C; for WS [U(VI)] = 100 mg L⁻¹, shaking time: 1 h, V = 10 mL, pH = 7, temperature: 28 °C)

Adsorption isotherms

Langmuir and *Freundlich* models were used for evaluation of experimental results [14, 17, 18, 22, 24]. The *Langmuir* isotherm assumes that the sorption is monolayer and the strength of the intermolecular attractive forces is believed to fall off rapidly with distance [24].

The *Langmuir* equation is given by [14, 17]:

$$\frac{C_e}{q_e} = \frac{1}{b \cdot Q_0} + \frac{C_e}{Q_0}$$

where q_e is the amount of U(VI) adsorbed per unit weight of adsorbent (mg g⁻¹), C_e is the concentration of U(VI) in solution at equilibrium (mg L⁻¹), b is the *Langmuir* constant and related to adsorption capacity and energy of adsorption (L mg⁻¹) and Q_0 is attained concentrations corresponding to monolayer coverage. The experimental results were also fitted to the *Freundlich* isotherm [17, 22, 24]. The empirical *Freundlich* equation is a suitable model for describing the surface heterogeneity, exponential distribution of active sites and infinite surface coverage. *Freundlich* equation was applied for the experimental data at optimum conditions as shown in following equation [24]:

$$\log q_e = \log k + \frac{1}{n} \log C_e$$

by plotting $\log q_e$ versus $\log C_e$, the coefficients k and n can be determined if a straight line is obtained.

Figure 5 shows the *Freundlich* adsorption isotherm data for U(VI) adsorption by PW and WS. *Freundlich* model was fitted better than *Langmuir* model for describing the U(VI) adsorption by PW and WS. For both of adsorbents, the *Freundlich* isotherm was followed over the entire range of concentration. These results are in conformity with U(VI) and Cr(III) adsorption onto sawdust [20, 24]. Correlation coefficients values and isotherms constant were calculated using *Langmuir* and *Freundlich* equations as shown in Table 1.

The values of $1/n$ were 0.79 and 0.68 for PW and WS, respectively. The fractional value ($0 < 1/n < 1$) of the

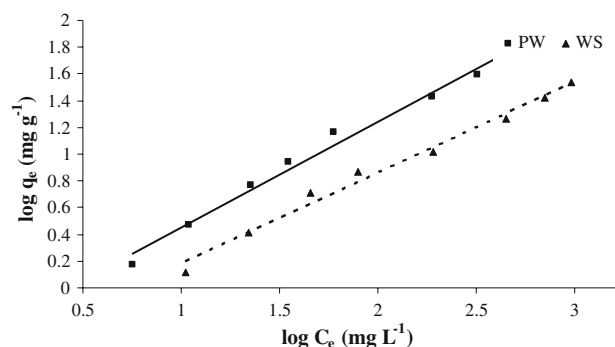


Fig. 5 *Freundlich* isotherm for PW and WS

Table 1 Langmuir and Freundlich constants for PW and WS

Adsorbents	Langmuir model			Freundlich model		
	R^2	Q_0 (mmole g^{-1})	b (L g^{-1})	R^2	k	$1/n$
PW	0.91	0.42	2.63	0.99	0.461	0.79
WS	0.87	0.20	2.25	0.99	0.346	0.68

constant $1/n$ shows the heterogeneous nature of the surface. The higher the fractional value the higher is the heterogeneity of the surface and vice versa [31]. It is deduced from the higher value of constant $1/n$ that the surface of PW and WS is heterogeneous in nature. Also, the surface of PW is more heterogeneous in comparison with WS.

Adsorption kinetics

For kinetic modeling of U(VI) onto PW and WS we used Lagergren pseudo-first order [32, 33], Lagergren pseudo-second order [32, 33] and Elovich model [32, 34–36]. The Elovich model, an empirical chemisorption model, was originally developed to describe the kinetics of heterogeneous chemisorption of gases on a solid surface. The Elovich model has been used to describe the kinetics of sorption and desorption of various inorganic materials on many adsorbents. The Elovich model may describe a number of different processes, including bulk and surface diffusion, as well as activation and inactivation of catalytic surfaces [34–36]. The Elovich equation is as follows [32]:

$$\frac{dq_t}{dt} = \alpha \exp(-\beta q_t)$$

By integrating this equation with the boundary conditions of $q_t = 0$ at $t = 0$ and $q_t = q_t$ at $t = t$, the following linear equation can be obtained [32]:

$$q_t = \left(\frac{1}{\beta}\right) \ln(\alpha\beta) + \left(\frac{1}{\beta}\right) \ln(t + t_0)$$

where, α and β are the parameters of the Elovich rate equation; t is equal to $1/(\alpha\beta)$. If $\alpha\beta t \gg 1$, this equation can further be simplified as [32]:

$$q_t = \left(\frac{1}{\beta}\right) \ln(\alpha\beta) + \left(\frac{1}{\beta}\right) \ln t$$

therefore, by plotting q_t versus $\ln t$, α ($mg\ g^{-1}\ min^{-1}$) and β ($g\ mg^{-1}$) can be determined [23].

For the pseudo-first-order process, the Lagergren equation is expressed as [32]:

$$\frac{dq_t}{dt} = k_1(q_e - q_t)$$

Integrating this Equation with the conditions ($q_t = 0$ at $t = 0$ and $q_t = q_t$ at $t = t$), gives [32]:

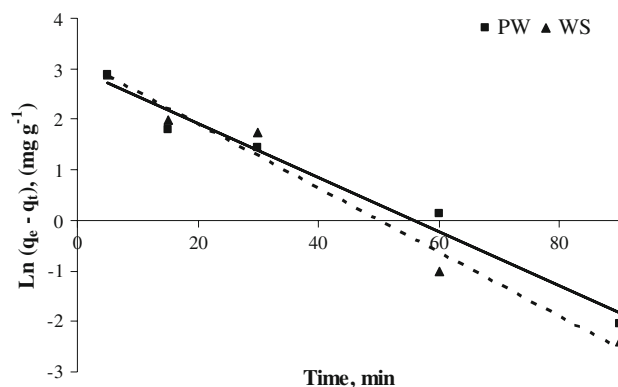


Fig. 6 Pseudo-first order model for PW and WS

$$\ln(q_e - q_t) = \ln(q_e) - k_1 t$$

where q_t ($mg\ g^{-1}$) is the amount of adsorbed U(VI) on the adsorbent at time t , q_e , the equilibrium sorption uptake, is extrapolated from the experimental data at time $t = \infty$ and k_1 (min^{-1}) is the rate constant of first-order adsorption.

Therefore, by plotting $\ln(q_e - q_t)$ versus t , k_1 (min^{-1}) and q_e ($mg\ g^{-1}$) values can be determined (Fig. 6).

We also chose pseudo-second order equation [23, 24, 32, 33]. The pseudo-second order process can be expressed as [33]:

$$\frac{t}{q_t} = \frac{1}{k_2(q_e)^2} + \frac{t}{q_e}$$

If the initial adsorption rate, h ($mg\ g^{-1}\ min^{-1}$) is [23]:

$$h = k_2 q_e^2$$

then Lagergren pseudo second order become [23]:

$$\frac{t}{q_t} = \frac{1}{h} + \frac{1}{q_e}(t)$$

where q_e ($mg\ g^{-1}$) is the U(VI) concentration at equilibrium and q_t ($mg\ g^{-1}$) is the U(VI) concentration at time t . Therefore, by plotting t/q_t versus t , the second order rate constant k_2 ($g\ mg^{-1}\ min^{-1}$) and q_e values can be determined (Fig. 7). A predominantly second-order mechanism suggests the chemisorption step might be rate determining and controlling the adsorption processes [33].

Correlation coefficients (R^2) were determined using the least square regression of measured values versus predicted values. Standard errors (SE) were calculated by:

$$SE = \sqrt{\sum \frac{(K_m - K_p)^2}{n - 2}}$$

where K_m and K_p represent the measured and predicted amount of U(VI) adsorption, respectively, and n is the number of data points evaluated. The data obtained separately for each of the kinetic models from the slopes of

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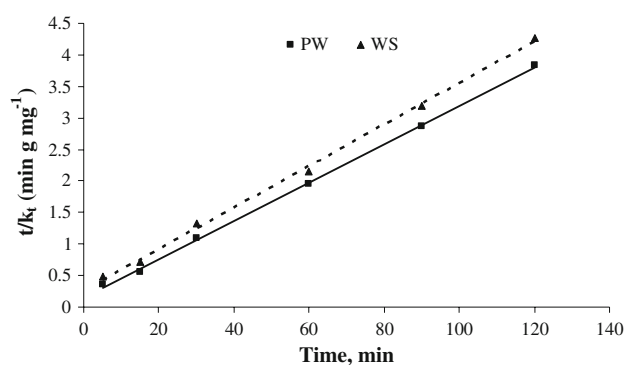


Fig. 7 Pseudo-second order model for PW and WS

plots show a good compliance with the pseudo second-order equation. The R^2 values for the linear plots being 0.999 and 0.997 for PW and WS, respectively. According to these results, the kinetic data followed the pseudo-second order adsorption kinetic equation for both adsorbents (Table 2).

As illustrated in Table 2, the initial sorption rate (h) and the rate constant of second order adsorption (k_2) of PW were $6.19 \text{ (mg g}^{-1} \text{ min}^{-1}\text{)}$ and $5.72 \times 10^{-3} \text{ (g mg}^{-1} \text{ min}^{-1}\text{)}$, respectively. These values for WS were $3.7 \text{ (mg g}^{-1} \text{ min}^{-1}\text{)}$ and $3.99 \times 10^{-3} \text{ (g mg}^{-1} \text{ min}^{-1}\text{)}$, respectively. A greater initial sorption rate (h) and k_2 values for PW may be attributed to a greater pore size and a greater penetrability of the adsorbent in comparison with WS.

Demirbas et al. concluded that pseudo-second order were the best-fitted equations used to describe Cr(VI) adsorption by low-value agricultural waste products [23]. Ahmad reported that the sorption of Cr(III) ions by sawdust obeys Reichenberg, Morris-Webber and Lagergren equations [24]. Öztas et al. also found that a second-order mechanism is predominant during iron adsorption by clinoptilolite samples [33]. As an optimum model in this study for the adsorption kinetics of U(VI) on the PW and WS, Lagergren pseudo-second-order were widely used to

Table 2 Parameters of three kinetic models for PW and WS

Model type	Parameter	PW	WS
Elovich	R^2	0.852	0.926
	$\alpha \text{ (mg g}^{-1} \text{ min}^{-1}\text{)}$	16.92	9.60
	$\beta \text{ (g mg}^{-1}\text{)}$	0.192	0.179
	SE	2.91	2.11
Pseudo-first order	R^2	0.976	0.978
	$k_1 \text{ (min}^{-1}\text{)}$	0.053	0.063
	SE	1.65	1.63
Pseudo-second order	R^2	0.999	0.997
	$k_2 \text{ (g mg}^{-1} \text{ min}^{-1}\text{)}$	5.72×10^{-3}	3.99×10^{-3}
	$h \text{ (mg g}^{-1} \text{ min}^{-1}\text{)}$	6.195	3.714
	SE	0.05	0.08

model the other adsorption kinetics resulting with very accurate fitting results [32, 33].

Desorption experiments

In order to estimate the reversibility of U(VI) sorption onto PW and WS, desorption experiments using five different desorptive solutions were performed. Firstly, PW and WS were loaded with U(VI), equilibrating the adsorbent with the U(VI) solutions ([U(VI)] concentrations for PW and WS was 200 and 100 mg L^{-1} , respectively, pH of solutions for PW and WS was 8 and 7, respectively, mass of adsorbents = 0.3 g, $V = 10 \text{ mL}$, shaking time = 1 h, temperature = $28 \text{ }^\circ\text{C}$). Secondly, solid residue was treated with the 10 mL of each leaching solution in thermostated shaker batch, GFL-1083 model, for 1 h at $28 \text{ }^\circ\text{C}$ (Table 3).

The results showed that U(VI) desorption from PW was higher compared to WS when HNO_3 and EDTA were used, while alkaline solutions (Na_2CO_3 and NaOH) released more U(VI) from WS compared to PW. The maximum U(VI) desorption for PW and WS was achieved in 1 M HNO_3 and 1 M Na_2CO_3 , respectively. In order to acquire the best conditions for U(VI) desorption, HNO_3 and Na_2CO_3 were used for next experiments.

Effect of desorption time

The U(VI) desorption from loaded PW (mass = 0.3 g, desorptive solution = 10 mL of 1 M HNO_3) and WS (mass = 0.3 g, desorptive solution = 10 mL of 1 M Na_2CO_3) was investigated as a function of shaking time in the range of 5–120 min. The amounts of desorbed U(VI) from PW and WS increased to 56 and 27% during the first 5 min of contacting time and then remained nearly constant until the end of experiment. Five minutes shaking time was used for the next of experiments.

Effect of desorptive reagent concentrations

Uranium desorption from loaded PW and WS (0.3 g of adsorbents and 10 mL of desorptive solutions) were studied

Table 3 Effect of elution reagents on U(VI) desorption from loaded PW and WS

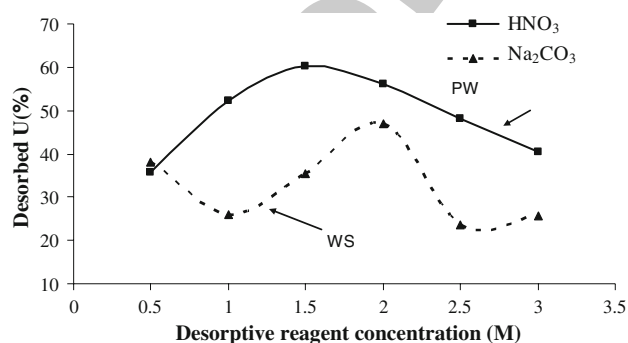
Reagent	Desorption (%)	
	PW	WS
1 M HNO_3	52	21
1 M NaOH	13	17
0.1 M EDTA	43	15
1 M Na_2CO_3	21	26
H_2O	2	1

400 by 0.5, 1, 1.5, 2, 2.5 and 3 M of HNO₃ and Na₂CO₃ solu-
401 tions, respectively. The maximum U(VI) desorption by PW
402 was observed at 1.5 M HNO₃, while for WS, it was
403 occurred at 2 M Na₂CO₃ (Fig. 8). These reagent concentra-
404 tions were employed for the next experiments.

405 Effect of desorption stages

406 The U(VI) desorption from loaded adsorbents was studied
407 as a function of desorption stages. Solid residue (0.3 g)
408 which was obtained from adsorption of U(VI) onto PW and
409 WS, was treated with the 10 mL of leaching solutions
410 (1.5 M HNO₃ for PW and 2 M Na₂CO₃ for WS) in
411 thermostated shaker batch, GFL-1083 model, for 5 min at
412 28 °C. After separation of solid and liquid phase, the new
413 portion (10 mL) of desorptive reagents was added to solid
414 residue. Desorption cycles were repeated several times to
415 determine the reversibility of the reactions and reusability
416 of PW and WS.

417 It was observed that the U(VI) desorption for both
418 adsorbents was decreased continuously with increasing the
419 desorption stages. According to desorption data, more than
420 half of the adsorbed U(VI) on PW was released at the first
421 desorption stage. Also, maximum desorption yield for WS
422 was occurred at the first desorption stage. After two
423 desorption stages, 74 and 60% of the initially adsorbed
424 U(VI) were desorbed on PW and WS, respectively, and
425 also, 84 and 77% of loaded U(VI) were recovered after
426 three and five stages for PW and WS, respectively. These
427 results revealed that U(VI) recovery from loaded PW and
428 WS was easy, owing to its low affinity on both adsorbents.
429 It seems that the fraction of adsorbed U(VI) which is not
430 recoverable by regeneration, probably represents U(VI)
431 that is bound through strong interaction and, consequently,
432 this may suggest that, aside from ion exchange, some other
433 mechanisms are involved in the adsorption and desorption
434 process of U(VI) onto PW and WS.



435 **Fig. 8** The effect of desorptive reagent concentration on U(VI)
436 desorption from loaded PW and WS

435 Conclusions

436 The pH of solution was an important factor in U(VI)
437 adsorption onto PW and WS. The maximum U(VI)
438 adsorption was accomplished at pH 8 and 7 for PW and
439 WS, respectively. It was observed that *Freundlich* equation
440 was more suitable than *Langmuir* equation for describing
441 the U(VI) adsorption behavior of PW and WS. The sorp-
442 tion of U(VI) ions onto PW and WS follows pseudo-second
443 order equation over entire range of concentration. Appli-
444 cation of the adsorption isotherm revealed that U(VI)
445 adsorption mechanisms by both adsorbent could be multi-
446 layer sorption of the surface. The presence of other foreign
447 anions, cations or complexing agents may affect the sorp-
448 tion of U(VI). Therefore, this needs further investigations
449 to study the utilization of these adsorbents for U(VI)
450 removal from more complex systems. The experimental
451 results showed that HNO₃ and Na₂CO₃ were successful
452 solutions for desorption of uranium from loaded PW and
453 WS, respectively. Taking into account the low cost and the
454 easy accessibility of the studied adsorbents as well as their
455 relatively high sorption capacity, sawdust and wheat straw
456 could be considered as effective adsorbents for the removal
457 of U(VI) from aqueous solutions.

458 **Acknowledgements** The authors gratefully acknowledge the sup-
459 port provided by Ferdowsi University of Mashhad. We would like to
460 express our special regards and appreciation to Prof. Dr. Sema Akyil
461 in Ege University, Institute of Nuclear Sciences, for his advice and
462 valuable suggestions. We also wish to thank Mr. Ali Moghimi and
463 Mr. Abolfazl Darroudi for their useful suggestions.

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