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Modeling adsorption of hexavalent chromium using a low-cost Jordanian olive stone waste adsorbent

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ABSTRACT

Olive stone waste (OSW) manifests as one of materials generated in Mediterranean countries. In Jordan produced thousands of tons of this natural waste. For removing the Cr(VI) ions from industrial liquid solutions, olive stone waste was employed as a natural adsorbent. The optimal conditions for removal processes were determined by sets of experiments. The contact time was 360 minutes, pH was 2.7, the adsorbent dosage was 4 g/L and the temperature was 25 °C. Results of adsorption mechanism data analysis for different Cr(VI) initial concentrations of 0.3, 2.7, 4.5, 9, 18 and 60 mg/l removed by OSW adsorbent fitted the Freundlich adsorption isotherm $R^2 = 1$, and near very close to pseudo second-order kinetics also $R^2 = 0.998$. It was found that the adsorption of Cr(VI) depended on concentration. Hexavalent chromium can be effectively removed from liquid industrial wastewater using olive stone waste.

Keywords: hexavalent chromium, adsorption, olive stone waste, adsorption kinetics models.

INTRODUCTION

Water pollution is a major and essential problem encountered everywhere (Awad 2024). Jordan is considered as one of the poorest countries in water. Jordan's water shortage issues illustrate the primary obstacles the nation has faced and will continue to confront in the years to come (Odeh, 2019). Water is very important and essential for human beings and societies to live. Water and the environment are affected by contamination from different sources, especially industrial wastewater which harms the natural sources (Crini and Lichtfouse, 2019). Numerous industrial pollution sources have an impact on the environment and water, including the production of batteries, electroplating, machining, textile dyeing, and the use of biocide in cooling fluids (Bai and Abraham, 2001; Visa et al., 2012; Saadh et al., 2024). Heavy metals are very toxic for the environment and pollute water and wastewater with small quantities and low concentrations (Shen and Wang, 1994; Bohli et al., 2015). But because these heavy metals are not biodegradable, they build up in the

ent oxidation numbers varying from -2 to +6 such as (CrO_4^{-2}) called chromate or $(Cr_2O_7^{-2})$ called dichromate (Shen and Wang, 1994). The most toxic chromium compounds toward the environmental system are the hexavalent chromium and the trivalent chromium (Acosta Rodríguez et al., 2013). These compounds existed in different water and wastewaters sources, especially industrial. As a result, water bodies and environmental systems get Cr (VI) effluents from several sources, including the materials dyeing and electroplating sectors (Aymen Awad, 2014; Bai and Abraham, 2001). Numerous attempts have been made to use various methods to treat wastewater and water that contain hexavalent chromium contamination. Chemical reduction, coagulation and filtration, precipitation, ion exchange, reverse osmosis (RO), and adsorption utilizing active carbon are the most widely used processes and techniques

bodies of the organisms and in environmental sys-

tems (Raji and Pakizeh, 2013). One of the most

heavy metals that contaminate and has significant

environmental concerns is chromium metals (Cr)

(Gandhi et al., 2013). Cr exists in nature in differ-

for treating Cr (VI) from liquid solutions (Bohli et al., 2015). These approaches and procedures are characterized as costly, poisonous, producing hazardous byproducts, and producing large amounts of residuals both during and after treatment for a variety of reasons and drawbacks (Şahin and Öztürk, 2005). In order to remove heavy metal pollutants in the form of ions from aqueous solutions, scientists and researchers concentrated on developing new, inexpensive materials to utilize as biosorbents (Volesky and Holan, 1995).

In the Mediterranean countries, the olive tree is a fundamental crop, there are more than 12 million hectares of this crop (95% of the world's cultivated olive area) (Rugini et al., 2016). One of the new solid waste byproducts and recently generated as agricultural waste is olive stone waste (Bohli et al., 2013). The point source of this industrial biowaste is the olive oil industry. This industry also is dominated in the Mediterranean Sea countries such as Jordan, Syria, Lebanon and Palestine. Therefore, industries in these countries produce huge quantities of wastewater polluted with olive stone materials and consequently need to be treated for discharging or reuse. Numerous researchers have examined olive waste, which is regarded as an inexpensive adsorbent and a natural substance similar to industrial and agricultural biowaste (Bailey et al., 1999; Fu and Wang, 2011). In 2007, Park et al. studied the organic materials that are generated from natural biomaterials and used as biosorbents. Phosphoric acid $(H_{A}PO_{A})$ was used to create activated carbon from surplus of olive stone for use as a biosorbent (Bohli et al., 2015). The activated carbon of olive stone waste is considered an effective adsorbent because of its high adsorption surface area, its deep microspores and heterogeneous surface functional groups (Bohli et al., 2013).

The most popular technique for removing pollutants from aqueous solutions is adsorption techniques (Bansal et al., 2009; Gupta and Babu, 2009). The most effective and widely spread adsorbent is activated carbon, but with a high cost, which convinced researchers and scientists to search for low-cost effective natural adsorbents. Recent studies and investigations were focused on natural lignocellulosic waste materials and other agricultural residuals (Gupta et al., 2009; Mohan et al., 2011). Biosorbents were used to remove Cr (VI), and it was confirmed that this was accomplished by combining adsorption and reduction mechanisms (Park et al., 2007). Today, regulations are more restricted in applying the effluent standards of pollutants' discharging to environment (Nieto et al., 2010; Rodríguez et al., 2008). Activated carbon, a biosorbent material made from residual olive stone, can be utilized for absorbing harmful metals from wastewater, including aluminum and arsenic (Awad 2024).

Adsorption isotherms represent the properties and equilibrium data which reveal the mechanisms of how the pollutants are removed by adsorbent materials (Piccin et al., 2011; Awad, 2014). The most commonly used models and equations for analyzing the system of hexavalent chromium metal pollutants removed by olive stone waste are the Langmuir model, Freundlich model, Temkin, and Dubinin-Radushkevich model (Crini and Badot, 2008; Awad, 2014).

Even though there are many ecological benefits that could be achieved when using natural waste as source of energy or a raw source for manufacturing of active carbon. Therefore, it is good for the environment to use such biowaste as adsorbent for removal of industrial waste such as heavy metals (Nieto et al., 2010). Consequently, different studies and many investigations have indicated that the biosorbent made from olive stone waste could be used to eradicate industrial pollutants such as phenols (Stasinakis et al., 2008) (Akar et al., 2009). Different investigations also approved that olive stone waste is an effective adsorbent that could be used to remove heavy metals contaminants like Cd (II), Pb (II), Ni (II) and done by the following researchers (Gharaibeh et al., 1998; Pagnanelli et al., 2002; Blázquez et al., 2005; Fiol et al., 2006).

Due to its high efficiency, cheap treatment costs, and minimal residual generation, adsorption technology has been considered beneficial and good for the removal of industrial pollutants, including heavy metals (Awad, 2024; Al-Shaweesh et al., 2023). Solid residuals of olive mill products (SROOMP) have been employed by various researchers as an adsorbent to treat wastewater containing trace concentrations of heavy metals such as Cr (III), Ni (II), Pb (II), Cd (II), and Zn (II). The results indicated significant removal of these metals (Demirbas et al., 2004; Awad, 2024).

Using the residual of olive stone as an absorbent, this study examined the adsorption of hexavalent chromium metal ions. Investigations of Cr(VI) adsorption in relation to various initial metal concentrations versus contact time were conducted using batch system studies. The Langmuir, Freundlich, Tempkin, and Dubinin-Radushkevich models were used to study equilibrium isotherms and kinetics for the removal of Cr (VI) (Mohamed Al-Meshragi, 2008; Kharabsheh et al., 2025).

MATERIALS AND METHODS

Materials

Olive stone waste was collected from different sites in Jordan (olive extraction oil plants and factories). Firstly, OSW was mixed, dried, washed with distilled water, and then socked in diluted phosphoric acid H_3PO_4 for two hours. Secondly, the washed stone was dried and crushed to particle size and sieved between 300–800 microns. Thirdly, the homogenous OSW was treated thermally at 104°C for 3 hours to eliminate the excess acid and evaporate the VOC in the adsorbent (Blázquez et al., 2014) (Awad 2024).

A standard hexavalent chromium solution of 3000 mg/l concentration was prepared using the desired amount of solid chromium trioxide $Cr_2O_7^{-2}$ (K₂Cr₂O₇) dissolved in 250 ml of distilled water. Cr (VI) solutions with the adsorbent amount of 4 g/l were taken in conical flasks and shaken on an electrical bench shaker for a time of 360 minutes at 25 °C and pH of 2.7.

A spectrophotometer DR5000 Hach, USA, was used to evaluate samples collected during testing to determine the quantities of the residual Cr (VI). Every time, the adsorbent was weighed using a digital balance (Mettler AE200, USA) with an accuracy of 0.1 mg and a capacity of 200 grams.

METHODS

Different experiments were done firstly to fix the parameters of pH, adsorbent dosage, mixing or contact time affecting adsorption rate. For the purposes of adsorption isotherms and removal kinetics investigations a tests group upon initial concentrations testing were done. Testing procedures were thus developed using the following initial metal concentrations of Cr(VI) solutions: 0.3, 2.7, 4.5, 9, 18, and 60 mg/l. Using a prober dilution factor for each desired concentration, stock solution was utilized to provide the necessary beginning concentrations. Each sample was tested starting at the initial concentration (Ci) until the concentration of the metal that remained after adsorption was roughly fixed at a point that represents the sorbent's equilibrium concentration (Ce) [Cr(VI)]. The concentration decrease over time was observed during the test. At the end of each experiment the equilibrium concentration of Cr(VI) was estimated calorimetrically by diphenyl carbazide test method and directly measured with spectrophotometer type of DR 5000 HACH-USA manufacturer). Using the following formula, the percentage of chromium removed from aqueous solution was estimated (Gupta et al., 2009; Awad 2024):

$$Removal of chromium =
 = \frac{(c \text{ initial - } c \text{ final})}{c \text{ initial}} \times 100
 \tag{1}$$

RESULTS AND DISCUSSION

Experiments were carried out at temperature (298 K). Equilibrium adsorption isotherms generated at equilibrium states. Adsorption isotherms are calculated from the results of batch experiments studies at different initial concentrations as shown in (Tables 1 and 2) and (Figure 1) (Mohamed Al-Meshragi, 2008; Piccin et al., 2011; Crini and Badot, 2008). These isotherms represent the adsorption capacity of the adsorbent in terms of metal uptake (milligrams of adsorbate per grams of adsorbent) and could be fitted to suitable correlation (adsorption model) (Crini and Badot, 2008; Wong et al., 2004). There are different forms of mathematical models describing the adsorption isotherms, based on physical bases or empirical hypotheses to represent data achieved experimentally. Four models were fitted to experimental equilibrium data in this study in order to determine which one best describes the removal process. The data was fitted using the Langmuir, Freundlich, Temkin, and Dubinin-Radushkevich adsorption isotherm models (Togue Kamga, 2019; Temkin, 1940).

Removal percentage versus initial concentration of Cr(VI)

At a pH of 2.7, the five initial concentrations of the salt solutions, and an adsorbent dosage of 4 g/L at room temperature (about 25 °C), the tests for this part of the investigation were conducted in 250 ml conical flasks and then combined at a continuous speed of 150 rpm.

Time (Min)	Concentration of hexavalent chromium (mg/l).									
0	0.30	2.70	4.50	9.0	18.0	60				
2	0.04	0.46	1.00	3.5	4.4	18				
4	0.03	0.32	0.90	2.1	2.4	16				
8	0.03	0.25	0.46	1.0	2.3	14				
90	0.02	0.23	0.43	0.9	2.2	13				
180	0.01	0.21	0.41	0.8	2.1	12				
270	0.01	0.15	0.32	0.8	2.1	12				
360	0.01	0.15	0.32	0.8	2.1	12				

Table 1. Effects of hexavalent chromium Cr(VI) initial concentrations of metal ions solutions in a batch reactor using olive stone waste adsorbent pH of 2.7 (processes temperature is 25 ± 1 °C, adsorbent dose of 4 g/L, mixing speed is 150 rpm, and solutions volumes of 0.25 liter)



Figure 1. Removal efficiency of Cr(VI) metal ions removed by olive stone waste at different initial concentrations versus time at an initial pH's of 2.7

The results of adsorption experiments of Cr(VI) at different initial concentrations ranging from 0.3-60 ppm received at the best acidity value of 2.7, the adsorbent dosage was (4g/L), while the mixing time was elapsed to (360 min) and the mixing speed was 150 rpm. Table 1 represents the results of Cr(VI) initial concentrations effects on adsorption of the metals in batch reactor. (Figure 1) shows the removal efficiency of Cr(VI) metal ions removed by the adsorbent (OSW) at 0.3, 2.7, 4.5, 9, 18, and 60 mg/l of Cr(VI) initial concentrations versus time. It is obvious that the percentage removal is increased when the adsorbate concentration is decreased and ranged from 80 percent up to 96 percent. Site restrictions on the adsorbent's surface may be the source of this, as they can result in a poor removal percentage at high concentrations.

Adsorption isotherms models

Table 2 contains a tabulation of the adsorption experiments' results at equilibrium states. The

computed parameters for plotting the liner forms of the adsorption models are displayed in Table 2.

Langmuir isotherm

Usually, to describe the removal mechanism of liquid molecules by solid material the Langmuir Isotherm is used to test for applicability, Irving Langmuir in 1916 set the model to test the adsorption of gas by adsorbents under certain pressure (Langmuir, 1918). The adsorption behavior by using the Irving Langmuir model was found to describe the monolayer removal mechanism between liquid phase and solid in case of homogenous sites on adsorbent surface. The model describes the adsorption process quantitatively, monolayer with the same energy value of adsorption onto the outer surface of adsorbent and no other adsorption types (Mittal et al., 2007). Figure 2 illustrates the layers of adsorbate attached to the adsorbent (Maryanti et al., 2020).

The following equation describes the Langmuir isotherm model based on the previously stated assumptions:

Parameters of adsorption isotherm models plotting of lead ions – olive stone waste												
Со	Ce (mg/l)	q _e (mg/g)	Ce/qe	X (mg)	x/ms (mg/g)	log (X/M)	log (Ce)	In (Ce)	Ln (qe)	3	ε ²	R _L Separation Factor
0.3	0.01	0.073	0.138	0.003	0.003	-2.602	-2.000	-4.605	-2.624	11200	1.3E+08	0.935
2.7	0.15	0.638	0.235	0.038	0.038	-1.426	-0.824	-1.897	-0.450	4930	2.4E+07	0.616
4.5	0.32	1.045	0.306	0.080	0.080	-1.097	-0.495	-1.139	0.044	3430	1.2E+07	0.490
9	0.80	2.050	0.390	0.200	0.200	-0.699	-0.097	-0.223	0.718	1960	3.9E+06	0.325
18	2.10	3.975	0.528	0.525	0.525	-0.280	0.322	0.742	1.380	944	8.9E+05	0.194
60	12.00	12.000	1.000	3.000	3.000	0.477	1.079	2.485	2.485	194	3.8E+04	0.067

 Table 2. Adsorption isotherm parameters for: A - Langmuir, B - Freundlich, C - Pseudo second-order, D - Tempkin

 and E - Dubinin-Radushkevich of hexavalent chromium Cr(VI) adsorption onto olive stone waste



Figure 2. Adsorption layers of liquids on solid adsorbents (Maryanti et al., 2020)

$$q_e = \frac{Q_{max}K_L C_e}{1 + K_L C_e} \tag{2}$$

The Langmuir isotherm model has the following linear form:

$$\frac{C_e}{q_e} = \frac{C_e}{q_{max}} + \frac{1}{q_{max}K_L} \tag{3}$$

where: q_{max} is the maximum adsorbent capacity as a single layer on the adsorbent surface in mg/g, q_e (mg/grams) is the quantity of adsorbent removed by the adsorbent, C_e is the concentration of adsorbate at equilibrium in mg/L, and K_L is the adsorption isotherm constant in L/mg.

Plotting $(\frac{C_e}{q_e})$ and (C_e) of Equation 2 will yield a linear connection from which, as shown in Figure 3, q_{max} and K_L may be calculated from the plotting's slope and intercept, respectively. Equation 3 provides the separation factor RL value, which characterizes the Langmuir isotherm process (Weber and Chakravorti, 1974):

$$R_L = \frac{1}{1 + K_L C_o} \tag{4}$$

 C_0 represents the adsorbate's starting concentration [Cr(VI)]. where the adsorption process's separation factor, R_L , is unfavorable for values greater than 1, linear for values greater than 1,

and strong and irreversible for values equal to 0. Table 1 presents the results in tabular form. According to R_L values, pure adsorption is the only method of elimination.

Freundlich adsorption isotherm

In the case of a multilayer adsorption process, the heterogeneous adsorbent surface is assumed whenever the experimental data is fitted using the Freundlich isotherm model (Doan et al., 2023; Dada et al., 2012; Voudrias, 2018; Mohan and Karthikeyan, 1997). Freundlich explained the behavior of adsorbed molecules on the adsorbent surface and data are fitted with the following empirical linear form equation:

$$\log\left(q_e\right) = \log K_f + \frac{1}{n}\log C_e \tag{5}$$

where: *n* is the linearity constant characterizing the adsorption process with regard to adsorbate concentration, C_e is the equilibrium concentration of adsorbate in (mg/l), K_f is the Freundlich constant, and q_e is the metals uptake (mg/g) (Dada et al., 2012).

Plotting results for n values say that if n = 1 then the process of adsorption is linear adsorption process, if n is less than 1 the process is with

chemical reaction but if n is higher than 1 a physical mechanism is included in the adsorption process is attained. As a conclusion if 0 < 1/n < 1then the situation is favorable and it is cooperative when 1/n > 1. Fitting of the data is illustrated in Figure 4, with a correlation coefficient R² of 1 and the value of the adsorption relation constant n equals 1 which means that the adsorption is liner process.

Pseudo second-order adsorption isotherm

The liner version of this adsorption kinetic model is as follows (Mohamed Al-Meshragi, 2008; Ho and McKay, 2000):

$$\left(\frac{t}{q_t}\right) = \frac{1}{h} + \frac{1}{q_e}\left(t\right) \tag{6}$$

As seen in Equation 5, the plot of the term (t/qt) against time ought to produce a linear relationship. The line slope and intercept of the fitted line can be used to get the model's constants, qe and k2, respectively. If h (mg/g·min), the initial adsorption rate, is:

$$h = k_2 q_e^2 \tag{7}$$

The pseudo second-order adsorption model's rate constant (g/mg·min) is denoted by the constant k^2 . Figure 5 illustrates how the data fits at the

boundary conditions of t = 0 to t = t and qt = 0 to qt = qt. For all starting chromium concentrations, the produced straight line of the fitted data of $[t/q_t]$ vs [t] demonstrates a strong agreement between the observed data and the kinetic model form. Additionally, the results showed that the elimination of Cr (VI) through sorption exhibits pseudo-second-order adsorption kinetics. It produced discussions on the fittingness of a pseudo second-order adsorption model with good correlation coefficients. The computed constants and parameters derived from the isothermal models are listed in (Table 3). For the pseudo second-order kinetic model, the correlation coefficient is 0.999.

Tempkin adsorption isotherm

The equilibrium binding constant $A_{T}(L/g)$ is a quantity that illustrates the adsorption process by the adsorbent in this isotherm. This factor has to do with the energy required in J/mol for the adsorbent to adsorb the pollutant molecules (Ofomaja, 2008). The following nonlinear form equation (Temkin, 1940) establishes the model:

$$q_e = \frac{RT}{b_T} Ln(A_T C_e) \tag{8}$$

The linear form is given in the following formula:



Figure 3. Langmuir adsorption isotherm model for Cr (VI)-OSW system



Figure 4. Freundlich adsorption isotherm model for Cr (VI)-OSW system



Figure 5. Pseudo second-order adsorption model for Cr (VI)-OSW system

$$q_e = B_T Ln (A_T) + B_T Ln (C_e)$$
(9)

where: $B_T = \frac{RT}{b_T}$. *T* is the process temperature, typically at 298 K; *B* is a constant associated with the heat of sorption in (J/mol); *R* is the universal gas constant and equals 8.314 J/mol/K; *AT* is the isotherm equilibrium binding constant (L/g); and *bT* is the Tempkin isotherm constant. Plotting the metal uptake q_e against ln *Ce*, as illustrated in Figure 6, allowed for the determination of the constants from the slope and intercept of the model fitting.

Plotting of slope and interception are taken to calculate the constant and binding energy and they are found to be equal to $A_T = 18.642 \text{ L/}\mu\text{mol}$, $B_T = 1.532 \text{ J/mol}$, where B_T refers to amount of heat for sorption which is indicating a physical adsorption process and the $R^2 = 0.6851$. Therefore, the results of fitting said that this process of removal is not comply with this model with its hypothesis which means that just a small amount of energy is needed to achieve the removal of contaminants from solution, and this will support the removal by another adsorption model.

Dubinin-Radushkevich (D-R) isotherm

This isotherm model depends on temperature and a factor called adsorption potential constant (ϵ) which considers the energy required for adsorption according to the adsorbent micropore size on the surface of adsorbent and the liner form of the model is represented by the following equation (Günay et al., 2007) (Dubinin, 1960):

$$Ln(q_e) = Ln(Q_0) - K_{DR}\varepsilon^2$$
(10)

Dubinin-Radushkevich (D-R) model presents the required mean free energy for desorption of each molecule from its space site on the adsorbent surface and can be calculated by the following formula (Dubinin, 1960):

$$E = \frac{1}{\sqrt{2K_{DR}}}$$
(11)

The parameter ε can be calculated from the following formula (Dubinin, 1960):

$$\varepsilon = RT \, Ln \, \left(1 + \frac{1}{c_e} \right) \tag{12}$$

where: q_e stands for metal uptake at equilibrium conditions in (mg/g), *Qo* for theoretical isotherm saturation capacity in (mg/g), *KDR* for the Dubinin–Radushkevich isotherm constant in (mol2J-2), ε for the adsorption potential constant, *R* for the gas constant (8.314 J/mol/K), *T* for the absolute temperature (K), and *Ce* for the adsorbate equilibrium concentration (mg/L).

Figure 7 illustrates how the experimental data were fitted using the Dubinin-Radushkevich (D-R) model, which plots $Ln(q_c)$ versus ε^2 .

The slope of fitted data in Figure 7 corroding to this model is (-3.0X10⁻⁸), which represents the value of (-KDR) and consequently (KDR) equals to (3X10⁻⁸ mol²J⁻²); the intercept of the fitted line is 1.1441 which equals to (LnQ_o) then Qo is calculated and equals to 3.140 mg adsorbed/g of adsorbent used, $R^2 = 0.79$. The results achieved depend on this model again confirmed that the process of removal is independent of energy or temperature to certain limits. The value of mean free energy for desorption E = 4082 J/mol and this is very large value.

Trend revealed that sorption capacity of olive stone waste increases by decreasing the initial concentration of metal ions. This is because in case of low concentration of metal ion solutions there are more adsorbent sites available for metal ions to adsorb on it.

Isotherm model	Slope	Constants or variables		Value	Intercept	Constants or variables		Value	R ²	E
Langmuir	0.063	=1/q _m	q _m	15.92	0.272	= KL*qm	kL =	0.231	0.913	
Freundlich	1.000	= 1/n	n	1.00	-0.602	= ln (Kf)	Kf =	0.548	1.000	
Pseudo-second order	1.568	= 1/h	h	0.64	1.850	= 1/qe	qe=	0.541	0.999	
Temkin	1.532	=B _T	Β _τ	1.53	4.481	= B _T Ln (Af)	Af =	18.642	0.685	
Dubinin- Radushkevich	-3.0E+08	=-K _{DR}	K_{DR}	3E+08	1.144	= Ln(Q ₀)	Q _o =	3.140	0.790	4082

Table 3. Adsorption isotherms constants and variables of A - Langmuir, B - Freundlich, C - Pseudo second-order, D - Tempkin and E - Dubinin-Radushkevich of hexavalent chromium Cr(VI) adsorption onto olive stone waste



Figure 6. Tempkin adsorption isotherm model for Cr(VI) OSW system



Figure 7. Dubinin-Radushkevich adsorption isotherm model for Cr(VI) OSW system

CONCLUSIONS

This study demonstrated that a cheap waste product from Jordanian olive stones might be utilized as a natural adsorbent to extract the hazardous Cr(VI) from aqueous solution, potentially serving as a substitute for more expensive materials. With an initial concentration of 0.3 mg/L, this adsorbent has a good sorption efficiency, reaching a value of 96.67% for the removal of chromium from aqueous solutions. When the initial concentration of adsorbate increases to 60 mg/L, the sorption effectiveness drops to 80%. Waste from olive stones could be a valuable natural resource for efficiently removing the hexavalent chromium from wastewater. It could also be utilized to remove additional contaminants. For a range of initial Cr (VI) concentrations, the Freundlich adsorption isotherm model exhibits excellent agreement with experimental results and the removal mechanism for the adsorption of Cr (VI) onto OSW.

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