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Palladium recovery from spent Pd plating solutions using Lewatit TP 214 resin

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ABSTRACT

This study aims to explore the recovery of palladium (Pd(II)) ions using Lewatit TP 214 resins. Waste Pd(II) ions with ammonia complex procured from a precious metal plating were selected as the source solution. In the experimental studies, two stock solutions of 60 ppm Pd(II) with a pH value of 4.0 and 7.5 were prepared as initial solutions. The experiments were performed by altering four parameters: solution pH, time 15–180 min, temperature 25°C–60°C, and amount of resin 100–400 mg. It was proved that the recovery percentage increased with higher temperature and resin at lower pH values. The Pd(II) recovery percentage increased with a temperature rise, reaching 100% after 40 min at pH 4.0 and 60°C. On the other hand, a bit lower efficiency (95%) was attained after 180 min at pH 7.5 and 60°C. Using Lewatit TP 214, the computed activation energies for Pd(II) recovery are 17.73 and 15.62 kJ/mol at pH 4.0 and 7.5, respectively. Considering these activation energy values, a mixed mechanism dominated the recovery of Pd(II).

Keywords: Palladium recovery; Waste plating solution; Ion-exchange resin; Lewatit TP 214

1. Introduction

In the last decades, demand for the recycling of platinum group metals has increased. Studies have focused on the methods to balance the offer of these metals and convert metal materials into a valuable renewable resource, which includes plating solutions, spent automotive, chemical industry catalysts, military equipment, electronic scrap, ore dressing plant tailings, and exhausted nuclear fuel [1–3].

Ion exchange resins are critical for separating precious metals, that is, platinum group elements, silver, and gold beside liquid–liquid extraction, pyrometallurgy, etc.For this reason, selective ion exchange resins, consisting of chelating, anion, and cationic chelate groups, are preferred in the industry. Thus, basic ion exchange resins were applied for the separation, concentration, and adsorption of noble metal ions owing to their high affinity [4].

Many studies focus on commercial patents for the application of Lewatit resins and adsorption of palladium (Pd(II)) [1,4–7]. Other anion exchangers (strongly, medium and weakly basic of polystyrene acrylate and phenol formaldehyde skeletons) used by many studies were Duolite A6 [8], Duolite A7 [8], Duolite A 30 B [8], Varion AP [8], Lewatit M 600 (microporous or gel) [9], acrylic Amberlite

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IRA 458 (microporous or gel) [9], Amberlite IRA 958 (macroporous) [9], Amberlyst A26 (macroporous) [9], Lewatit MonoPlus 220 (chelating ion exchanger with bis-picolylamine functional groups) [10], Lewatit AF5 (carbon sorbent) [11], and Lewatit MP 62 [12].

Recent studies also focused on Lewatit TP 214, Lewatit MonoPlus TP 214, and compared them with other commercial resins in green chemistry [7,13–22]. A study focusing on Pd(II) adsorptions using Lewatit TP 214 showed that the recovery reached up to 98% in the combined medium of hydrochloric acid and perchloric acid [13]. Another study compared Pd(II) complexes with chelating ion exchangers, revealing that Lewatit TP 214 offered the highest performance, followed by Purolite S 920, Chelite S, and Duolite GT 73 [7].

A study compared Lewatit TP 214 with Amberlyst A21 to identify a better resin to recover Pd(II) from ELP (electroless plating) solutions, prepared synthetically. After comparing the results with the kinetic calculations, Lewatit TP 214 offered better performance than Amberlyst A21 as an adsorbent [16].

Another study focused on Pd(II) adsorption of commercial exchangers using the rhenium-containing sulfuric acid solutions. Several resins were used to investigate the Pd(II) adsorption performance. TP 214 was the best exchanger, followed by the D 4384, TP 207, AN 105, CS-PTFE, A170, MN 202, MP 62, and VP-14KR. Thus, recovered Pd(II) eluted from the 8% ammonia exchangers and/or 4 mol/L hydrochloric acids [22].

The present study aims to identify and characterize the adsorption behavior of Pd(II) ions in a commercial spent plating solution of a very well known trademark in the jewellery industry on the adsorbent resin Lewatit TP 214 including kinetic and isotherms studies at optimal conditions using atomic absorption spectrometer (AAS), Fourier-transform infrared spectroscopy (FTIR) analysis to indicate the profile and the molecular fingerprint of the resin before and after adsorption of Pd(II), finally scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analysis to monitorize the surface of the resin's microstructure before and after adsorption of Pd(II) in order to demonstrate the availability of the adsorption process which is a an environmentally friendly method for further indsutrial applications.

2. Materials and methods

In this study, the solutions were prepared at two different pHs; 4.0 and 7.5, respectively using the as-received solution – spent Pd solution of Heimerle + Meule GmbH – had a pH of 7.5 and of 600 ppm. This spent solution was provided "FANCY Silver Company, Turkey" for research purposes. The palladium concentration was found to be 600 ppm using an atomic absorption spectrometer. For the experimental studies, two stock solutions of 60 ppm Pd(II) and pH values of 4 and 7.5 were prepared, the hydrochloric acid used for dilution of the acid was of analytical grade (Hydrochloric acid fuming 37% Merck 100317 for analysis EMSURE® ACS, ISO, Reag. Ph Eur). Lewatit TP 214 (Lanxess Company, Germany) density of approx. 1.1 g/mL was chosen as the adsorbent resin for Pd(II) ions. Four parameters – time, temperature, amount of resin, and solution pH^- were examined using a 0.25 L glass boiling flask as a reactor. The glass boiling flask was immersed in a water bath to maintain a constant temperature for the homogenous bath temperature by tightly closing the glass boiling flask lid. The stirring speed of 150 rpm was kept constant. Fig. 1 shows the layout of the experimental procedure. The temperature reaction was adjusted using a digitally controlled hot plate. The volume of the solution was 150 mL. Aliquots of 2 mL were sampled every 15 min for the kinetic study to measure the Pd(II) solution concentration up to 180 min. Blank experiments were performed using Lewatit (100, 200, 300, and 400 mg). The chosen resin amount was added to the initial solution. The temperature was kept constant, and the variable was the sorbent from 100 to 400 mg with the pH ranged from 4 to 7.5. Table 1 gives the experimental parameters. All the chemicals with determined, analytical purity were used. TSB-28C Shaking Water Bath was used as the thermostatic shaker. HI2002-01edge® Dedicated pH/ORP Meter and wireless pH electrode were used to measure the pH. The yield of Pd(II) recovery (%) was established using an atomic absorption spectrometer (Analytik Jena AG, Germany). The tests were repeated three times, each AAS analysis was made in company with an arbitration specimen and run twice at once.

After each adsorption experiment, solid/liquid separation was performed using a filtering paper (Blue band, Sartorius).

The FTIR spectral analyses of TP 214 resins before and after the adsorption have been carried out between 400 and 4,000 cm^{-1} on the Perkin Elmer Spectrum 100.

The Lewatit TP 214 resins before and after Pd[II] adsorption process were dried under a vacuum at 80°C for 1 h. These specimens were used for scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDS) analysis by SEM-EDX (ZEISS EVO LS10, Japan).

The adsorption recovery efficiency (%) was calculated with the following equation:

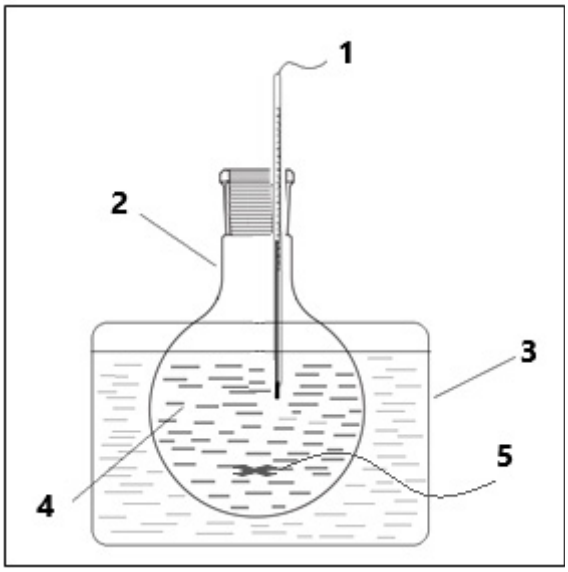

Fig. 1. Experimental setup: 1. Electronic thermometer, 2. Glass boiling flask, 3. Water bath, 4. Solution, 5. Magnetic stirring bar.

Table 1
The experimental parameters

Parameters	Value
Lewatit TP 214	100–400 mg
Temperature (°C)	25–40–50–60
pH	4.0 and 7.5

$$\text{Recovery}(\%) = \left[\frac{\left(\left[\text{Pd}\right]_o - \left[\text{Pd}\right]_t\right)}{\left[\text{Pd}\right]_o}\right] \times 100 \quad (1)$$

where $[Pd]_o$ is the initial palladium concentration in mg/L (ppm) solution; $[Pd]_t$ is the final palladium concentration in mg/L (ppm) after the experiment.

3. Results

Lewatit TP 214 was used for the Pd(II) recovery. The results emphasize the primary factors and optimal conditions for the maximum adsorption yields, that is, time, temperature, amount of Lewatit TP 214, and pH solution, which are given below.

3.1. Effect of amount of resin

The aliquots were taken every 15 min (15, 30, 45, 60, 75, 90, 120) for 120 min. Two experimental series were performed at 50°C at pH 4 and 7.5 solutions. Figs. 2 and 3 show the change in Pd(II) recovery (%) with an increase in the resin quantity and time.

The 400 mg of resin and 50°C provided 100% Pd(II) recovery from the pH 4 solution and 70% Pd(II) recovery from the pH 7.5 solution. However, 100 mg of the resin and 50°C provided 40% Pd(II) recovery from the pH 4 solution and 50% recovered from the pH 7.5 solution. The results showed that an increase in the amount of resin increased the Pd(II) recovery with a rise in the resin/metal ratio. On the surface, the total of effective sites was enhanced, thermodynamically more convenient, as stated by a previous study [17].

Table 3 (Constant equations calculated for Pd(II) ion adsorption onto Lewatit TP 214 at a pH value of 4.0 and 7.5)

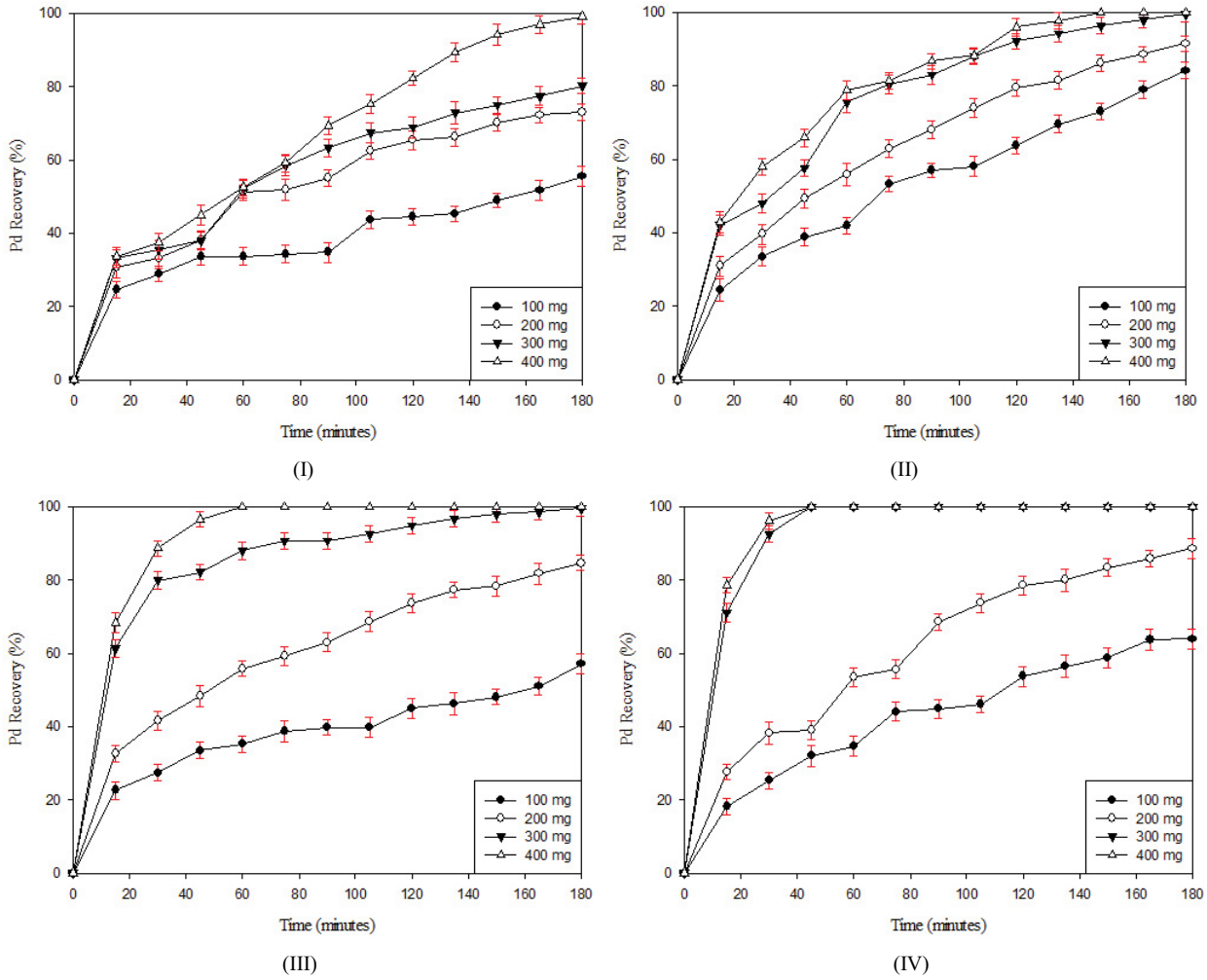

Fig. 2. The effect of the amount of resin on Pd(II) recovery in relation to the time (I) 25°C, (II) 40°C, (III) 50°C, (IV) 60°C, 100 rpm, solution pH of 4.0 and 2 mL of 60 mg/L.

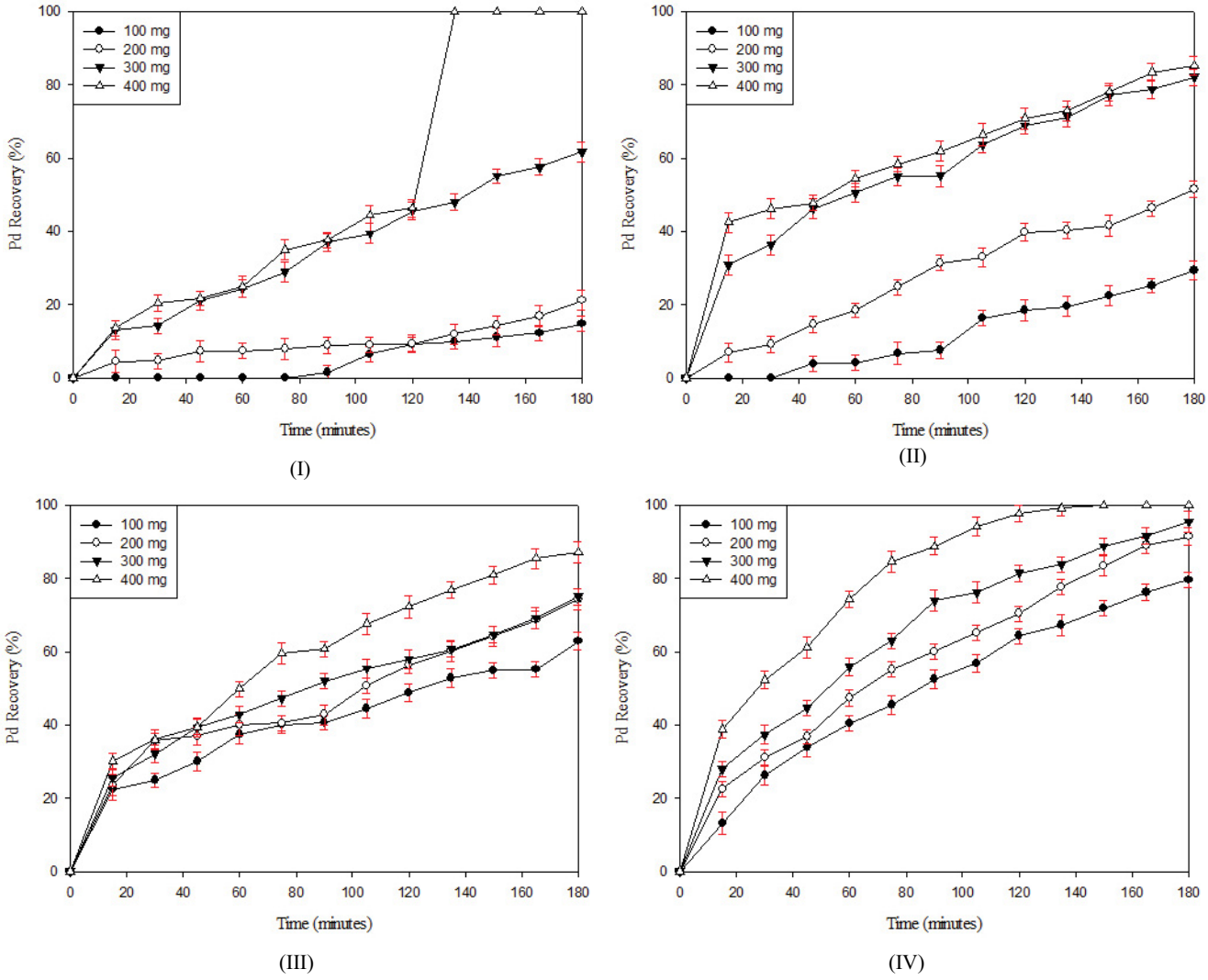

Fig. 3. The change in Pd(II) recovery with the amount of resin in relation to the time (I) 25°C, (II) 40°C, (III) 50°C, (IV) 60°C, 100 rpm, solution pH of 7.5 and 2 mL of 60 ppm.

has been given to express the mg Pd adsorbed per gr Lewatit TP 214.

3.2. Effect of time

Figs. 2 and 3 show the effects of time on the Pd(II) recovery. The experiments were performed for 180 min between 25°C and 60°C. Shaking was kept constant (100 rpm). A 100, 200, 300, and 400 mg of resin were added to the pH 4 and pH 7.5 solutions. As shown in Figs. 3 and 4, Pd(II) recovery was positively affected at different pH solutions, resin quantity, and temperatures. Depending on the other three parameters, the time to reach the maximum efficiency percentage naturally changed.

3.3. Effect of temperature and time

Many experiments were performed to reveal the effects of temperature and time on the kinetics of Pd(II) recovery. The experiments were performed using Lewatit TP 214 of 400 mg and 2 mL of aliquots were taken every 15 min for 180 min at temperatures between 25°C and 60°C, where the pH of the solution was kept constant either at 4.0 or at 7.5. The agitation rate was set to 100 rpm.

As shown in Fig. 4, Lewatit TP 214 showed better performance at pH 4.0 than at pH 7.5. At the pH 4.0, Pd(II) recovery percentage was found to be almost 100% after 40 min at 60°C. At pH 7.5, a recovery efficiency of 95% was attained at 60°C after 180 min. At pH 4.0, a similar performance was obtained at 40°C after 180 min. Thus, it was concluded that the Pd(II) recovery was effected significantly by the solution pH.

3.4. Adsorption kinetics

According to the experimental results, three models were investigated to determine the adsorption mechanism. Table 2 shows various kinetic models.

The kinetics models were remarkable for the reaction mechanism and the steps. Of all computed kinetic

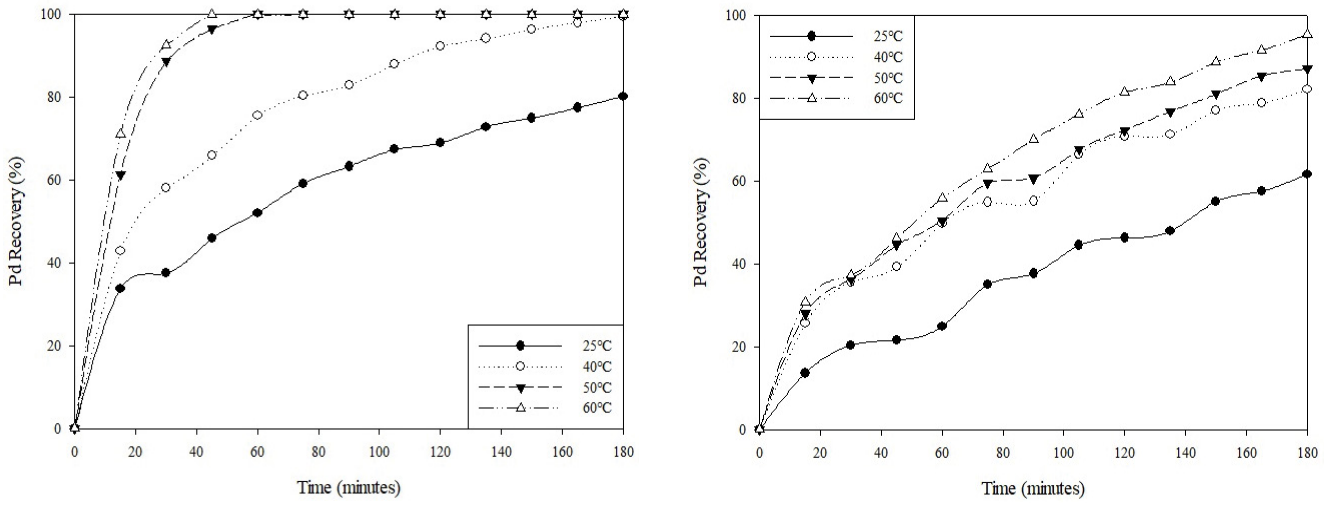

Fig. 4. The change in Pd(II) recovery in relation to the time and temperature (I) pH 4.0, (II) pH 7.5, Lewatit TP 214 of 400 mg, 100 rpm, 2 mL of 60 mg/L for each aliquot.

equations, the pseudo-second-order model was the best model for the Pd(II) recovery using Lewatit TP 214 resin. Figs. 5 and 6 show the adsorbed Pd(II) by Lewatit TP 214 for pH 4, and 7.5, respectively. Table 3 shows all the constants' values calculated for Pd(II) ion adsorption on Lewatit TP 214 at pH 4.0 and 7.5. According to the correlation coefficients, pseudo-second-order is closer to 1.00 than the pseudo-first-order. The correlation coefficients for intraparticle diffusion (R^2 = 0.96–0.98) were lower than the pseudo-second-order. The result reveals that the system follows the intraparticle diffusion model [23–26].

3.5. Effect of pH

As shown in Fig. 4, the pH solution is critical for Pd(II) recovery and Lewatit TP 214 performance. The Pd(II) recovery percentage increases aggressively, at pH 4 level, it reaches 100% in 40 min. This behavior is stable at pH 7.5. Hence, the Lewatit TP 214 performed better at lower pH levels.

3.6. Adsorption isotherms

With Lewatit TP 214, the isotherms of Pd(II) adsorption were investigated based on four different resin quantities and different temperature levels, keeping other parameters constant. The amount of Pd(II) recovered at equilibrium (q_e, mg Pd(II)/g) was computed by Eq. (2):

$$q_e = \frac{\left(C_0 - C_e\right) \times V}{m} \tag{2}$$

where C_0 and C_e (mg/L) are the initial and equilibrium Pd(II) quantities; V is the solution volume, and m is the mass of the resin.

Freundlich and Langmuir isotherm models are applied to investigate sorption equilibrium parameters. Freundlich model is employed for the adsorption multilayer. However, the Langmuir isotherm model is better for the adsorption of the monolayer on the surface. Table 4 displays the investigated isotherms.

Fig. 7 provides the Langmuir and Freundlich isotherm model at 60°C. Table 5 shows k_F, k_L, Q_{max}, and n, computed using the slope and the line intersection.

k_F is the Freundlich constant and an indicator of the adsorption resin capability. Thus, n is the divergence magnitude from the adsorption linearity. The Freundlich isotherm is used for heterogeneous systems [24,25,27].

The Langmuir constant k_L indicates free energy of adsorption. According to the Langmuir model, adsorbed molecules cannot bind other molecules using lateral interaction. Therefore, the adsorption process is limited to the adsorbent surface. Since Q_{max} (the maximum capacity of the adsorbent) is computed by the Langmuir isotherm, the total capacity must be computed by the Langmuir [24,25,27].

The outcome of the correlation coefficients showed that the Langmuir isotherm ($R^2 \geq 0.98$) was more suitable for pH 4.0 and pH 7.5 than the Freundlich isotherm ($R^2 \leq 0.96$). Thus, the Pd(II) adsorption with Lewatit TP 214 is monolayer adsorption at both pHs [24,25,27].

3.7. Adsorption thermodynamics

Another approach was to apply kinetic models to compute the activation energy of the adsorption process in the range of 298, 313, and 323 K. The best-fitting kinetic model was the first-order kinetics at pH 4.0 and one-dimensional diffusion at pH 7.5, as shown in Eq. (3) [25]:

$$k_t = \left(\frac{C_0 - C_t}{C_0}\right) \tag{3}$$

The activation energy for this recovery was established by the Arrhenius equation (4), [25]:

Table 2
Studied kinetic models [23–26]

Adsorption model	Kinetics equation
Pseudo-first-order model/ Lagergren model	$\frac{dq_t}{dt} = k_1\left(q_e - q_t\right)$
Pseudo-second-order model	$\frac{dq_t}{dt} = k_2\left(q_e - q_t\right)^2$
Intraparticle diffusion model	$q_t = k_p\sqrt{t} + C$

$$k = Ae^{-E_a/RT} = RT \text{ or } \ln k = \ln A - \frac{E_a}{RT} \quad (4)$$

where E_a is the activation energy; k is the rate constant, T is the temperature (K), and R is the gas constant.

Fig. 8 shows the Arrhenius plot for the Pd(II) adsorption at both pHs. Table 6 shows the temperatures of 25°C (298 K), 40° (313 K), and 50°C (323 K), k, and ln(k) values. The computed activation energies for Pd(II) recovery by Lewatit TP 214 are 17.73 and 15.62 kJ/mol at pH 4.0 and 7.5, respectively. Considering the activation energy values, the Pd recovery is dominated by a mixed mechanism [25]. The result indicates that the Pd(II) adsorption using Lewatit TP 214 includes both diffusion and chemical reaction-controlled processes, which depends on the pH solution, coherent with the adsorption kinetics.

3.8. FTIR spectrum of resin

The molecular structure combined with PS and thiourea of the Lewatit TP 214 was shown in Fig. 9. As a result of FTIR analysis shown in Fig. 10, the asymmetric and symmetrical stretching bonds of –NH_2 groups of thiouronium in the wavelength band 3,200–3,400 cm^{-1} (3,358.44 and

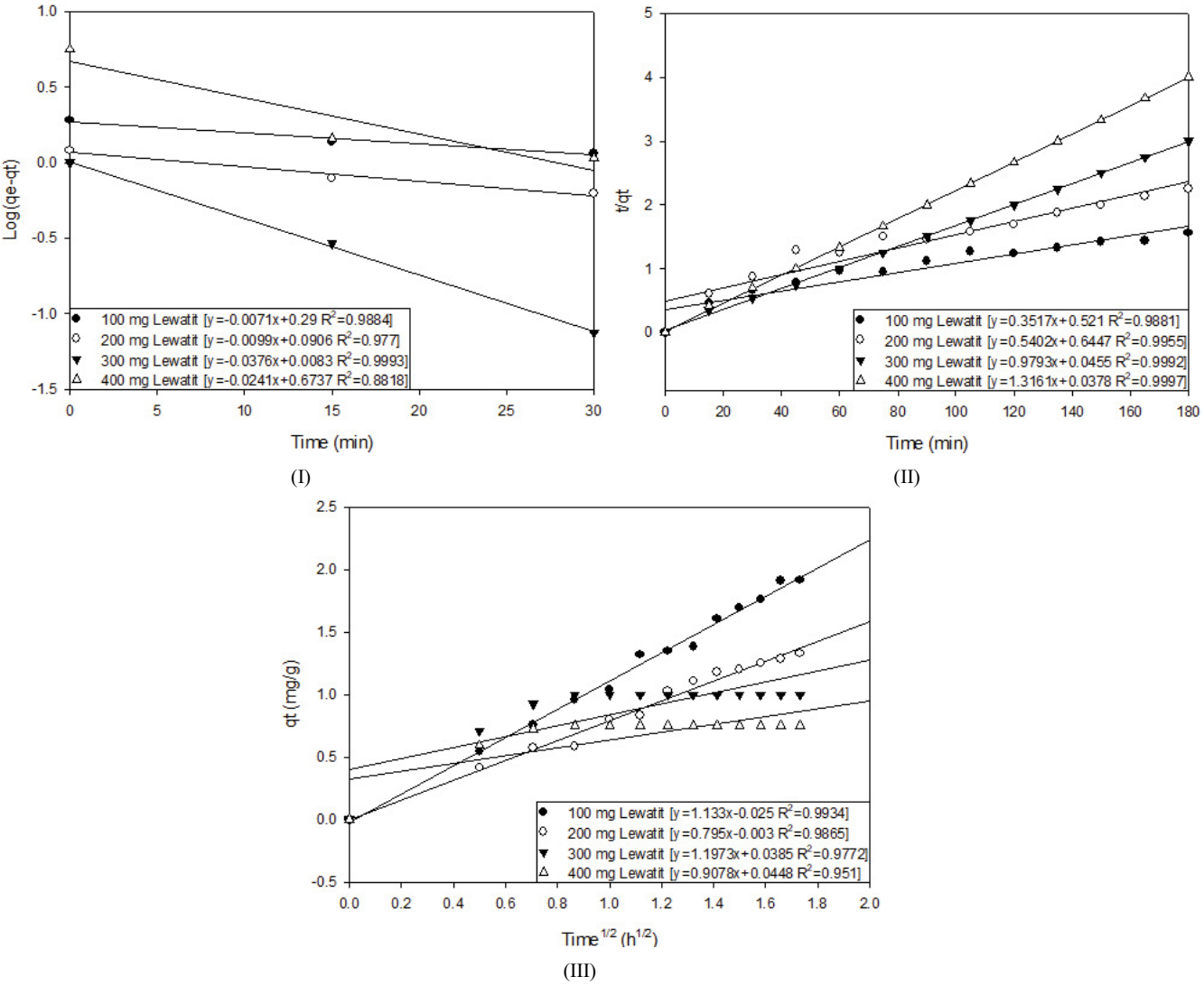

Fig. 5. Equation of Pd(II) recovered by Lewatit TP 214 for pH 4.0 (I) pseudo-first-order model, (II) pseudo-second-order model and (III) intraparticle diffusion model (60°C, 100 rpm, and 2 mL of 60 ppm solution).

Table 3
Constant equations calculated for Pd(II) ion adsorption onto Lewatit TP 214 at a pH value of 4.0 and 7.5

Rate constants for the pseudo-first-order model						
Resin, mg	pH 4.0			pH 7.5		
	k_1 (min^{-1})	q_e/mg g^{-1} (experimental)	R^2	k_1 (min^{-1})	q_e/mg g^{-1} (experimental)	R^2
100	0.0071	1.91	0.9884	0.0085	1.93	0.9781
200	0.0099	1.20	0.9501	0.0059	1.34	0.9734
300	0.0376	1.00	0.9976	0.0075	0.96	0.9749
400	0.0241	0.75	0.8818	0.0083	0.75	0.9587
Rate constants for the pseudo-second-order model						
Resin, mg	pH 4.0			pH 7.5		
	k_2 (min^{-1})	q_e/mg g^{-1} (experimental)	R^2	k_2 (min^{-1})	q_e/mg g^{-1} (experimental)	R^2
100	0.3517	1.91	0.9881	0.2246	1.93	0.9873
200	0.5402	1.20	0.9955	0.3715	1.34	0.9934
300	0.9793	1.00	0.9992	0.6977	0.96	0.992
400	1.3161	0.75	0.9997	1.0713	0.75	0.9929
Rate constants of the intraparticle diffusion model						
Sorbent, mg	pH 4.0			pH 7.5		
	k_p (min^{-1})	R^2		k_p (min^{-1})	R^2	
100	1.133	0.9934		3.3131	0.9904	
200	0.795	0.9865		0.8778	0.9927	
300	1.1973	0.9772		0.5715	0.9892	
400	0.9078	0.9510		0.4801	0.9812	

Table 4
Linear forms of the isotherm models [23–28]

Isotherm models	Linear form equation
Freundlich	$q_e = k_F C_e^{1/n}$
Langmuir	$q_e = Q_{\max} \frac{k_L C_e}{1 + K_L C_e}$

Table 5
Recovery of Pd(II) by Lewatit TP 214 at 60°C, based on Langmuir and Freundlich isotherm constant at pH values

Langmuir			
pH	$Q_{\max}$ (mg/g)	k_L (L/g)	R^2
4.0	2.431	0.165	0.9926
7.5	2.113	0.401	0.9810
Freundlich			
pH	N	k_F (mg/g)	R^2
4.0	0.413	5.384	0.9413
7.5	0.263	2.041	0.9545

Table 6
Rate constants based on various temperatures at pH 4.0 and 7.5 (300 mg resin, 180 min, 100 rpm, pH 4.0 and 7.5, 2 mL of 60 ppm solution)

pH	T (°K)	k (min^{-1})	ln$k$	E_a	R^2
4.0	298	0.0091	–4.700	17.73	0.9933
	313	0.0228	–3.781		
	323	0.0257	–3.61		
7.5	298	0.0022	–6.119	15.62	0.9956
	313	0.0029	–5.843		
	323	0.0036	–5.627		

3,266.33 cm^{-1}, respectively) were observed before and after adsorption on Lewatit TP 214 resin with thiouronium functional groups containing sulfur and nitrogen atoms [8,14]. Beside the asymmetric stretching bonds of –CH_2 (C–H) groups at 2,922.22 cm^{-1} were present. N–H stretching of the unused Lewatit TP 214 were also observed in the wave range of 1,620 cm^{-1}. [8,14]. The bands related to the functional group of Lewatit TP 214 were additionally present at 1,530–1,560 cm^{-1} indicating the stretch vibrations of C=C, the combination of C–N and C–S bonds in the range of 1,427 cm^{-1}, finally the wavelength of the deformation bands of –NH_2 groups between 1,200–1,080 cm^{-1} [8,14].

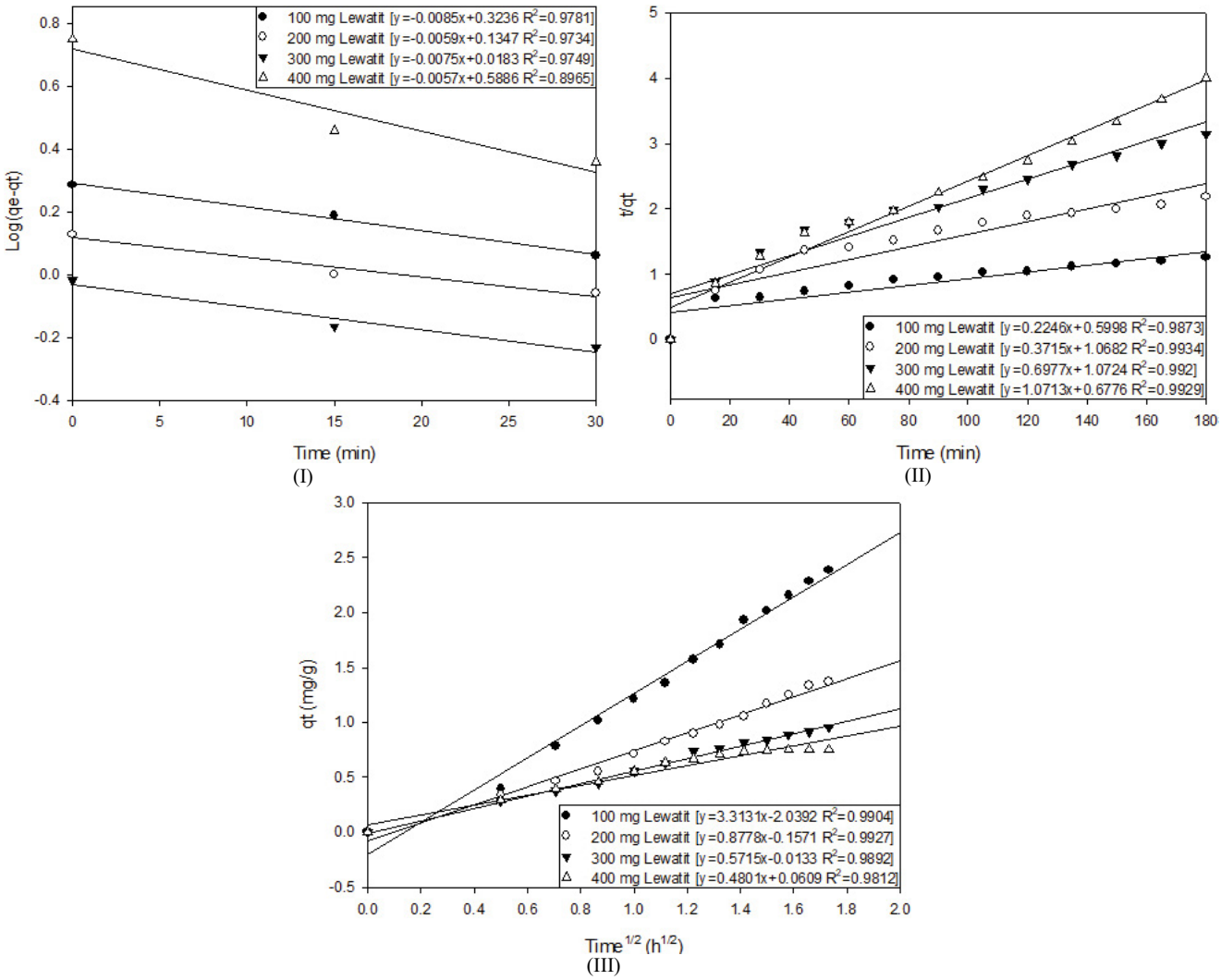

Fig. 6. Equation plots for Pd(II) recovered by Lewatit TP 214 for pH 7.5 (I) pseudo-first-order model, (II) pseudo-second-order model and (III) intraparticle diffusion model (60°C, 100 rpm, and 2 mL of 60 ppm solution).

3.9. SEM and EDS analysis of resin before and after Pd(II) adsorption

As shown in Figs. 11 and 12, SEM and EDS analysis to monitorize the surface of the resin's microstructure before and after adsorption of Pd(II) in the selected areas 1. The results showed the successful adsorption of Pd(II) on the Lewatit TP 214, probably on sulfur bands sites. Because sulphur has affinity towards precious metals and plays active role to capture Pd(II) ions.

4. Conclusion

Based on the Pd(II) recovery by Lewatit TP 214, as the resin/metal ratio increased, the amount of Lewatit TP 214 increased the palladium recovery (%). The most effective sites on the surface were enhanced, thermodynamically more appropriate as stated in similar studies. The effect of time on the Pd(II) recovery was explored via 4 parameters: time 15–180 min, pH 4 and 7.5, temperature 25°C, 40°C, 50°C, and 60°C, and the amounts of resin 100, 200, 300, and 400 mg. Depending on the other three parameters, that is, solution pH, amount of resin, and temperatures, the time required to reach the maximum efficiency percentage changed.

The Pd(II) recovery percentage increased aggressively, reaching 100% after 40 min at pH 4.0 and 60°C. However, a bit lower efficiency (95%) was attained after 180 min at pH 7.5 and 60°C. Hence, the Lewatit TP 214 performed better at lower pH levels since palladium is complex with ammonia at higher pH levels.

The outcome of the correlation coefficients shows that the Langmuir isotherm ($R^2 \geq 0.98$) is more suitable for both pH 4.0 and pH 7.5 than the Freundlich isotherm ($R^2 \leq 0.96$). Therefore, the Pd(II) adsorption with Lewatit TP 214 is monolayer adsorption at both pHs. Considering the correlation coefficients, the pseudo-second-order kinetics are closer to 1.00 than the pseudo-first-order. The correlation coefficients for intraparticle diffusion (R^2 = 0.96–0.98) were lower than the pseudo-second-order kinetics.

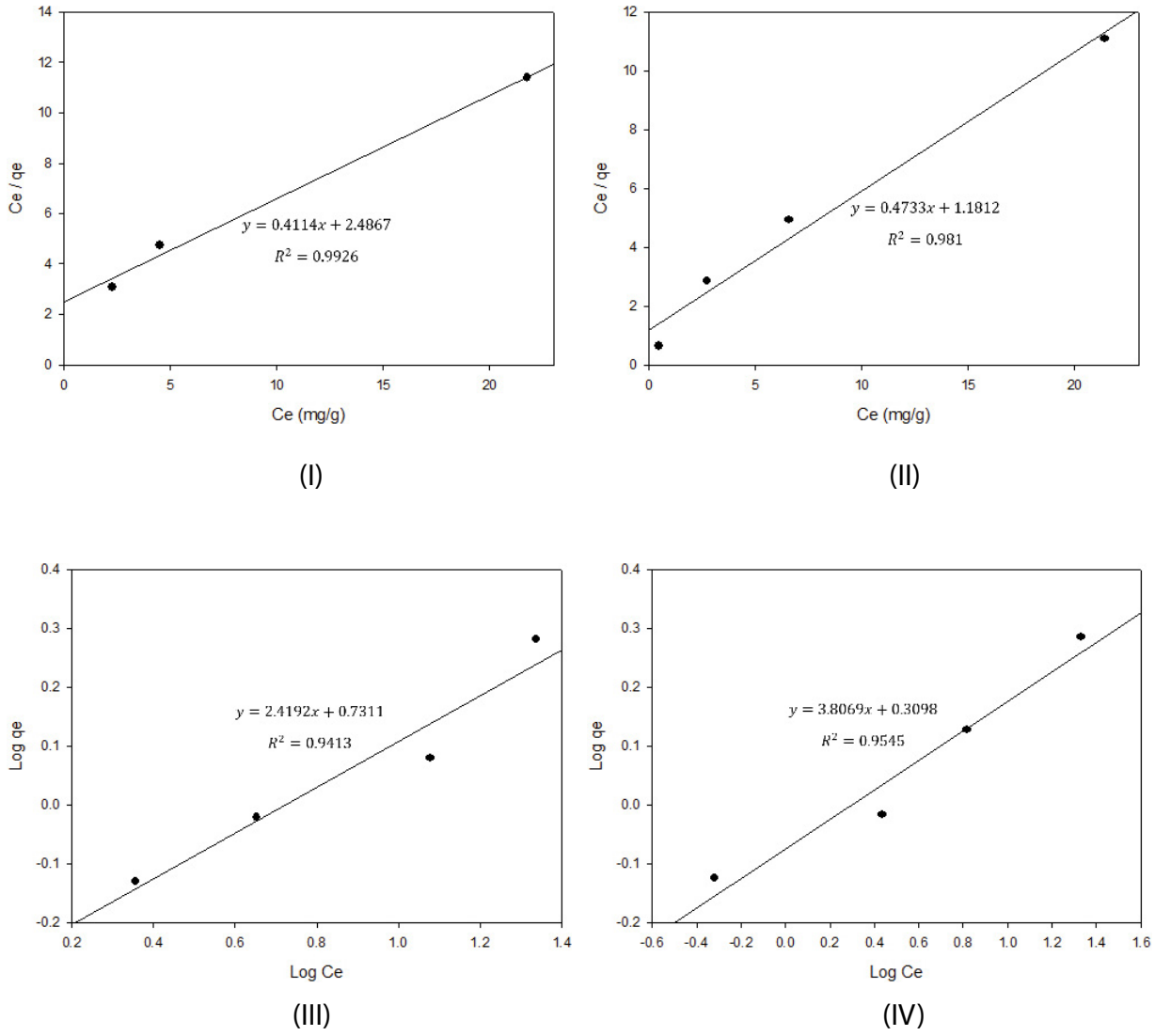

Fig. 7. The isotherms of Langmuir and Freundlich at 60°C (180 min, 100 rpm, pH 4.0 and 7.5, 2 mL of 60 ppm solution) (I) Langmuir – pH: 4.0, (II) Langmuir – pH: 7.5, (III) Freundlich – pH: 4.0 and (IV) Freundlich – pH: 7.5.

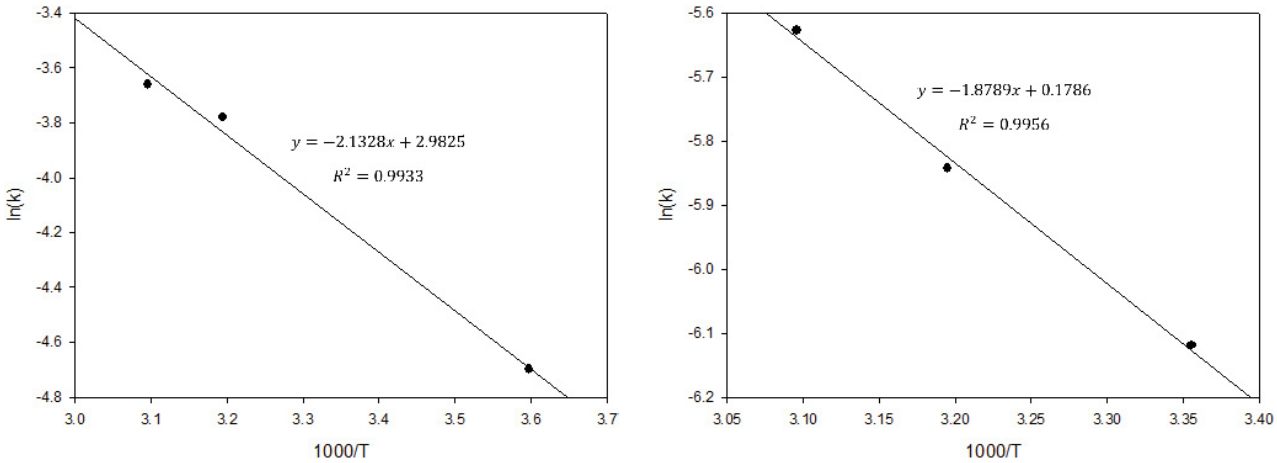

Fig. 8. Ln(*k*) vs. inverse temperature based on the Arrhenius equation (300 mg resin, 180 min, 100 rpm, pH 4.0 and 7.5, 2 mL of 60 ppm solution): (I) pH 4.0 and (II) pH 7.5.

Several kinetic models were investigated. The best-fitting kinetic model was the first-order kinetics at pH 4.0 and one-dimensional diffusion at pH 7.5. The activation energy for Pd(II) recovery with the resin amount was computed to be 17.73 and 15.62 kJ/mol at pH 4.0 and 7.5, respectively. Hence, the computed activation energy levels prove that a mixed mechanism dominated the recovery process.

Acknowledgment

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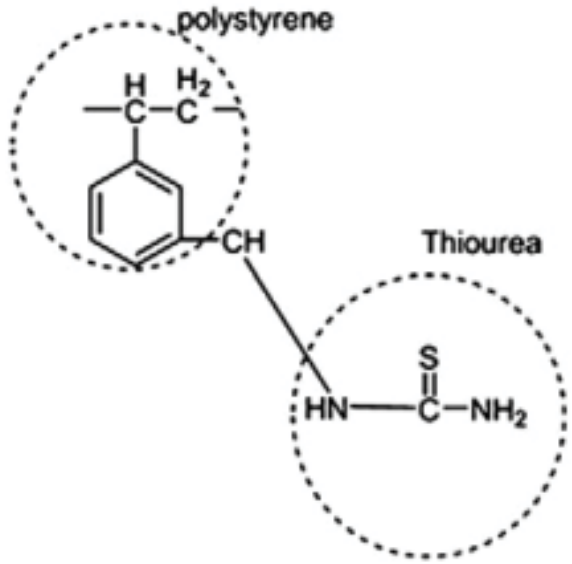

Fig. 9. The molecular structure combined with PS and thiourea of the Lewatit TP 214 [13].

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Conflicts of interest

The authors declare no conflict of interest.

Symbols

C_0	—	Initial Pd(II) concentration in the solution, mg/L
C_t	—	Final Pd(II) concentration in the solution at the end of the experiment, mg/L
t	—	Adsorption time, min
q_t	—	Adsorption amount at time t, mg/g
q_e	—	Adsorbed amount of Pd(II) per unit mass of the sorbent, mg/g
k_1	—	Pseudo-first-order rate constant, min^{-1}
k_2	—	Pseudo-second-order rate constant, g/mg min
k_p	—	Intraparticle diffusion rate constant, mg/g $min^{1/2}$
R^2	—	Correlation coefficients
V	—	Volume, L
m	—	Mass, g
C_e	—	Equilibrium Pd(II) concentration, mg/L
E_a	—	Activation energy, kJ/mol
k_F	—	Freundlich constant, mg/g
k_L	—	Langmuir constant, L/g
n	—	Dimensionless exponent of Freundlich equation
k	—	Rate constant
R	—	Gas constant
T	—	Temperature, K
A	—	Frequency or pre-exponential factor
q_m	—	Maximum amount of the adsorbed Pd(II) per unit mass of sorbent, mg/g
Q_{max}	—	Maximum adsorption capacity of a material

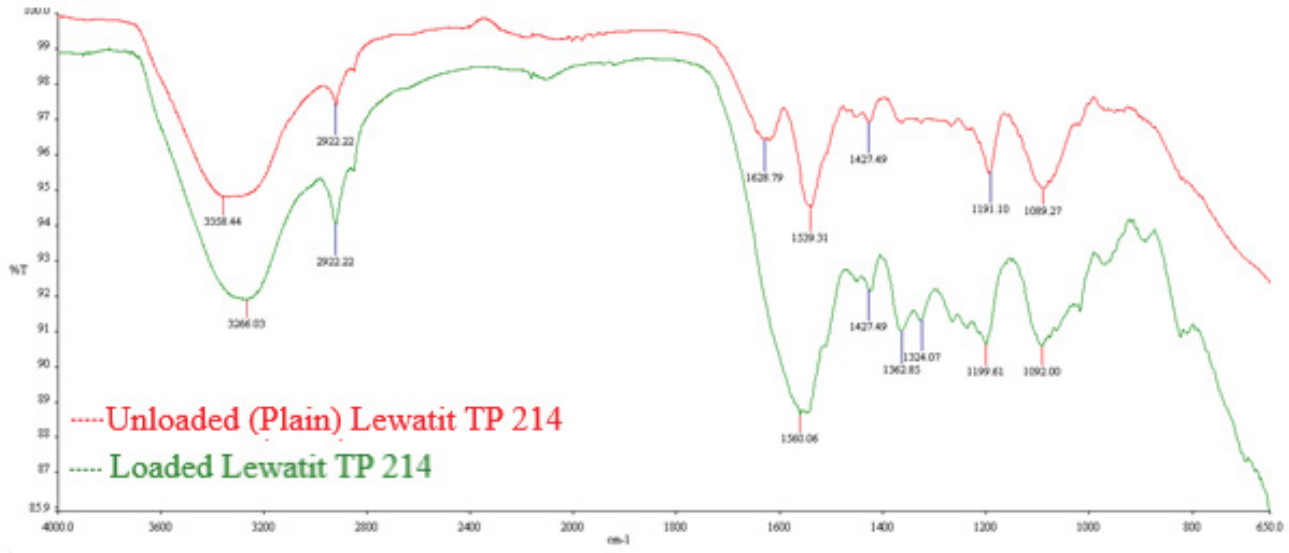
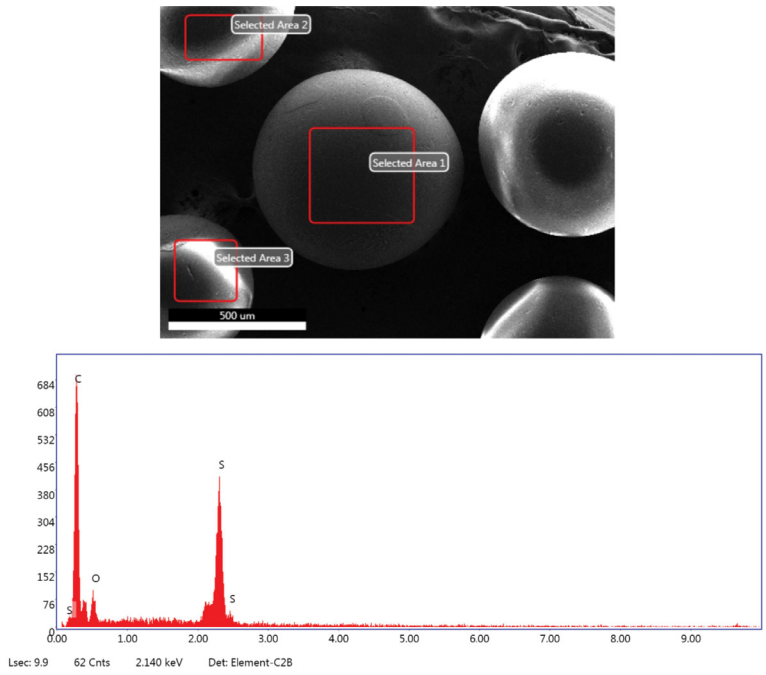
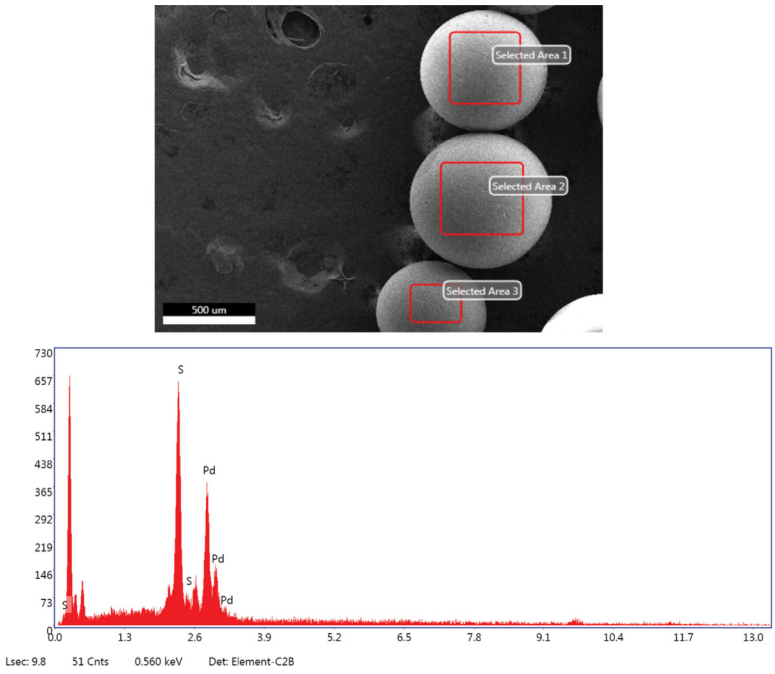


Fig. 10. FTIR spectrum of unloaded (plain) and loaded Lewatit TP 214.



Element	Weight %	Atomic %
C K	73.32	84.26
O K	9.82	8.48
S K	16.86	7.26

Fig. 11. SEM and EDS analysis of the Lewatit TP 214 commercial resin as-taken, before adsorption.



Element	Weight %	Atomic %
S K	40.13	68.99
Pd K	59.87	31.01

Fig. 12. SEM and EDS analysis of the Lewatit TP 214 commercial resin after Pd(II) adsorption.

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