Supplementary Information

A functionalized activated carbon adsorbent prepared from waste amidoxime resin by modifying with H3PO4 and ZnCl2 and its excellent Cr(VI) adsorption

*Chunlin He*1,2,5),🖂, *Yun Liu*1,2), *Mingwei Qi*1,2), *Zunzhang Liu*1,2), *Yuezhou Wei*3,4), *Toyohisa Fujita*1,2), *Guifang Wang*1,2), *Shaojian Ma*1,2), *and Wenchao Yang*1,2)

1) School of Resources, Environment and Materials, Guangxi University, Nanning 530004, China

2) State Key Laboratory of Featured Metal Materials and Life-cycle Safety for Composite Structures, Guangxi University, Nanning 530004, China

3) School of Nuclear Science and Technology, University of South China, Hengyang 421000, China

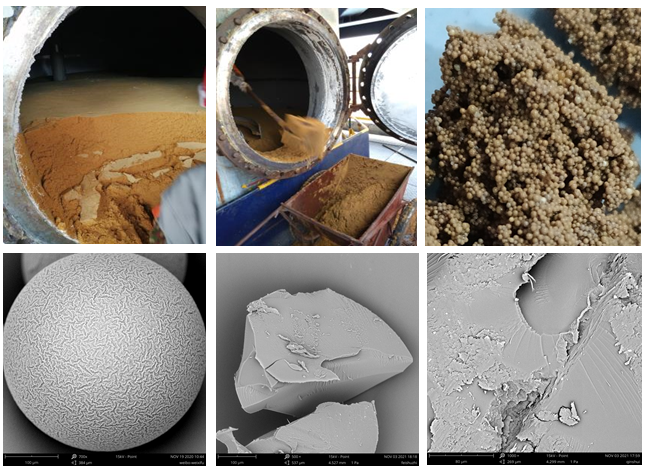
4) School of Nuclear Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

5) Key Laboratory of New Low-carbon Green Chemical Technology, Education Department of Guangxi Zhuang Autonomous Region, Nanning 530004, China

🖂 Corresponding author: Chunlin He E-mail: [helink1900@126.com](mailto:helink1900@126.com)

**Supplementary material S1**

**S1-1.** The waste amidoxime resin (PR) was provided from Guangxi Branch of Aluminum Corporation of China Limited.



**Fig. S1.** Waste amidoxime resin.

**S1-2.** Preparation of sorbent

**1. Adsorbent PPR-Z:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, 5 g PR and 50 ml 40% H3PO4 were put into a 100 ml beaker, and stired it in a 40°C thermostatic water bath at 500 r/min for 4h, and subsequently being washed with deionized water for three times, and dried in an oven at 50°C for 24h. Third, ZnCl2 and dried resin with a mass ratio of 1:1 was put into 50 ml water and soaked it for 30 min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (500°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.1 L/min. Finally, the material after slow pyrolysis was washed with 0.1mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PPR-Z.

**2. Adsorbent PR:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (500°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.1 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PR.

**3. Adsorbent PR-4P:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, 5 g PR and 50 ml 40% H3PO4 were put into a 100 ml beaker, and stired it in a 40°C thermostatic water bath at 500 r/min for 4h, and subsequently being washed with deionized water for three times, and dried in an oven at 50°C for 24h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (500°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.1 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PR-4P.

**4. Adsorbent PR-5N/ZnCl2=1:1:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, 5 g PR and 50 ml 50% HNO3 were put into a 100 ml beaker, and stired it in a 40°C thermostatic water bath at 500 r/min for 4h, and subsequently being washed with deionized water for three times, and dried in an oven at 50°C for 24h. Third, ZnCl2 and dried resin with a mass ratio of 1:1 was put into 50 ml water and soaked it for 30 min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (500°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.1 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PR-5N/ZnCl2=1:1.

**5. Adsorbent PR/NiCl2:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, NiCl2 and dried resin with a mass ratio of 1:1 was put into 50 ml water and soaked it for 30 min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (500°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.3 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PR/NiCl2.

**6. Adsorbent PR+Fe(NO3)3:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, 0.1 mol/L Fe(NO3)3 and dried resin with a mass ratio of 1:1 was put into 50 ml water and soaked it for 30 min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (800°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.3 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PR+Fe(NO3)3.

**7. Adsorbent PR+20% KOH:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, 20% KOH and dried resin with a mass ratio of 1:1 was put into 50 ml water and soaked it for 30 min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (500°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.5 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PR+20% KOH.

**8. Adsorbent PR-T400:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (400°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.1 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new materialPR-T400.

**9. Adsorbent PR-Mn:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, 0.1 mol/L KMnO4 and dried resin with a mass ratio of 1:1 was put into 50 ml water and soaked it for 30 min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (500°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.3 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PR-Mn.

**10. Adsorbent PR+FeCl3:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, 0.3 mol/L FeCl3 and dried resin with a mass ratio of 1:1 was put into 50ml water and soaked it for 30 min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (600°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.3 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PR+FeCl3.

**11. Adsorbent PR/ZnCl2=1:1:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. ZnCl2 and dried resin with a mass ratio of 1:1 was put into 50 ml water and soaked it for 30 min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (500°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.1 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PR/ZnCl2=1:1.

**12. Adsorbent PPR-T40:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, 5 g PR and 50 ml 40% H3PO4 were put into a 100 ml beaker, and stired it in a 40°C thermostatic water bath at 500 r/min for 4h, and subsequently being washed with deionized water for three times, and dried in an oven at 50°C for 24h. Third, ZnCl2 and dried resin with a mass ratio of 1:1 was put into 50ml water and soaked it for 30min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (400°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.1 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PPR-T40.

**13. Adsorbent PPR-T60:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, 5 g PR and 50 ml 40% H3PO4 were put into a 100 ml beaker, and stired it in a 40°C thermostatic water bath at 500 r/min for 4h, and subsequently being washed with deionized water for three times, and dried in an oven at 50°C for 24h. Third, ZnCl2 and dried resin with a mass ratio of 1:1 was put into 50 ml water and soaked it for 30 min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (600°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.1 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PPR-T60.

**14. Adsorbent PPR-N4:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, 5 g PR and 50 ml 40% H3PO4 were put into a 100 ml beaker, and stired it in a 40°C thermostatic water bath at 500 r/min for 4h, and subsequently being washed with deionized water for three times, and dried in an oven at 50°C for 24h. Third, ZnCl2 and dried resin with a mass ratio of 1:1 was put into 50 ml water and soaked it for 30 min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (500°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.4 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PPR-N4.

**15. Adsorbent PPR-N7:** First, waste resin (PR) was washed with deionized water for three times and dried for 24h in an oven at 50°C. Second, 5 g PR and 50 ml 40% H3PO4 were put into a 100 ml beaker, and stired it in a 40°C thermostatic water bath at 500 r/min for 4h, and subsequently being washed with deionized water for three times, and dried in an oven at 50°C for 24h. Third, ZnCl2 and dried resin with a mass ratio of 1:1 was put into 50 ml water and soaked it for 30 min, and then put it into an 80°C oven for curing for 12h. Next, the resin was put into the tubular furnace for slow pyrolysis with heating rate of 3 °C/min for 2h (500°C), and then it is naturally cooled. The process of pyrolysis was in N2 atmosphere with a gas flow of 0.7 L/min. Finally, the material after slow pyrolysis was washed with 0.1 mol/L hydrochloric acid (HCl), and then washed with deionized water until the pH reached neutral. After that, the sample was dried at 80°C for 24h to prepare a new material PPR-N7.

**Supplementary material S2**

1. Adsorption experiments

The static adsorption experiment is used to investigate the adsorption performance of PPR-Z on Cr(Ⅵ) by controlling variables, such as pH (1–10), adsorption time (10–720 min), initial concentration of chromium in solution (400–5000 mg/L) and temperature (293 K, 303 K, 313 K, 323 K). The adsorption experiment was carried out in a water bath shaker with vibration frequency of 140 r/min. After adsorption, solution was separated by a 0.45 um syringe filter and measured concentration of chromium by inductively coupled plasma emission spectrometer (ICPS-7510). Three parallel experiments were set up to ensure the accuracy of experimental data. The calculation formulas of adsorption capacity (*Q*) and adsorption efficiency (*E*) are shown in Eqs. (S1) and (S2), respectively:

(S1)

(S2)

where *Q* (mg/g) represents the adsorption capacity of the adsorbent on Cr(Ⅵ); *C*o(mg/L) and *C*e(mg/L) represent the initial concentration of Cr(Ⅵ) before adsorption and the equilibrium concentration of Cr(Ⅵ) after adsorption, respectively; *V* represents the volume of Cr(Ⅵ) solution used in the experiment and *m* (mg) represents the mass of the adsorbent.

Adsorption is the process of migration of ion from the liquid phase to binder to the adsorbent by physical or chemical action, which contains three rate-limiting steps: internal diffusion, external diffusion and surface reaction. The adsorption kinetics is often used to demonstrate the adsorption mechanism and rate control steps, and provide a reference for the optimization of adsorption experiments. In order to reveal the possible adsorption mechanism, quasi-first order kinetics (Eq. (S3)), quasi-second order kinetics (Eq. (S4)) and Weber Morris intra particle diffusion model (Eq. (S5)) were applied to fit the data.

|  |  |
| --- | --- |
|  | (S3) |
|  | (S4) |
|  | (S5) |

where *k*1(min−1) and *k*2(g·mg−1·min−1) are the quasi-first order kinetics, quasi-second order kinetics rate constants, respectively. *Q*e(mg/g) and *Qt* (mg/g) represent the amount of metal ions adsorbed per unit of adsorbent at equilibrium and *t* time, respectively. *k*p is the intraparticle diffusion rate constant (mg·(g·min1/2)−1), and *F* is the boundary resistance.

Adsorption isotherm refers to the dynamic equilibrium of the concentration of metal ions in the solution at the solid–liquid interface of the adsorbent under specific pH and temperature environment. It is used to study the change of the adsorption capacity of the adsorbent for metal ions at a certain temperature with the concentration of metal ions, and to characterize the surface properties and adsorption capacity of the adsorbent. Langmuir (Eq. (S6)) and Freundlich (Eq. (S7)) adsorption isotherm models are most commonly used to illustrate the adsorption equilibrium characteristics. The linear forms are as follows:

|  |  |
| --- | --- |
|  | (S6) |
|  | (S7) |

where *C*e(mg/L) is the concentration of metal ion at adsorption equilibrium, *Q*e(mg/g) and *Q*m(mg/g) represent the adsorption capacity at actual equilibrium and the saturated adsorption capacity, respectively. *K*L(L/mg) is the constant of the Langmuir adsorption isotherm equation, *K*f(mg/g) and *n* are Freundlich constants related to the adsorption capacity.

The Temkin isotherm contains a factor that explicitly takes into account of the adsorbent-adsorbate interactions. In this equation, it is assumed that, because of these interactions and ignoring very low and very large concentration values, the heat of adsorption of all molecules in the layer would decrease linearly with the coverage. This isothermal equation is applicable to chemical adsorption where the adsorption heat decreases linearly with the change of surface coverage; Dubinin-Radushkevich (D-R) model is based on the assumption that the adsorption is related to the surface porosity and pore volume. To investigate the adsorption from an energetic perspective. The equation (Eq. (S9)) of Dubinin-Radushkevich (D-R) model is given below.

(S8)

(S9)

(S10)

(S11)

where *Q*e (mg·g−1) and *Q*m (mg·g−1) are the equilibrium and computed maximum adsorption capacities. *C*e (mmol·L−1) stands for equilibrium ions concentration. *R* is the ideal gas constant (8.31447 J·mol−1·K−1) and *T* is the temperature. The mean free energy *E* (J·mol−1) represents the energy change of Cr from solution to adsorbent. *β* (mol2·J−2) is a constant related to adsorption energy. *ε* is the Polanyi potential (J·mol−1). When the energy higher than 8 kJ·mol−1, the process dominated by chemical adsorption, on the contrary, the process dominated by physical adsorption.

The changes in the adsorption capacity of the adsorbent at 298, 308, and 318 K were investigated and the values of the thermodynamic parameters such as Gibbs free energy change (Δ*G*, kJ/mol), enthalpy change (Δ*H*, kJ/mol) and entropy change (Δ*S*, J/(mol·K)) were calculated from the experimental data as shown in the following equations:

(S12)

(S13)

(S14)

where *K*D is the dispersion coefficient, *R* (8.314 J/(mol·K)) is the general thermodynamic constant and *T* (K) is the absolute temperature during the adsorption process.

The distribution coefficient (*K*dM, mL/g), separation factor SFA/B were calculated by Eqs. (S11) and (S12), respectively：

(S15)

(S16)

where *C*oM(mmol/L) and *C*eM(mmol/L) represent the initial and equilibrium concentration of ion in mixed solution, respectively; *m* (mg) is the mass of adsorbent used; *V* (mL) means the volume of the mixed solution.

**Table S1.**  Preparation of different adsorbents

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Number | Name | Temperature / °C | N2 flow speed / (L·min−1) | Processing reagents |
| 1 | PPR-Z | 500 | 0.1 | H3PO4, ZnCl2 |
| 2 | PR | 500 | 0.1 | — |
| 3 | PR-4P | 500 | 0.1 | H3PO4 |
| 4 | PR-5N/ZnCl2 = 1:1 | 500 | 0.1 | HNO3, ZnCl2 |
| 5 | PR/NiCl2 | 500 | 0.3 | NiCl2 |
| 6 | PR + Fe(NO3)3 | 800 | 0.3 | Fe(NO3)3 |
| 7 | PR + 20%KOH | 500 | 0.5 | KOH |
| 8 | PR-T400 | 400 | 0.1 | — |
| 9 | PR-Mn | 500 | 0.3 | KMnO4 |
| 10 | PR + FeCl3 | 600 | 0.3 | FeCl3 |
| 11 | PR/ZnCl2 = 1:1 | 500 | 0.1 | ZnCl2 |
| 12 | PPR-T40 | 400 | 0.1 | H3PO4, ZnCl2 |
| 13 | PPR-T60 | 600 | 0.1 | H3PO4, ZnCl2 |
| 14 | PPR-N4 | 500 | 0.4 | H3PO4, ZnCl2 |
| 15 | PPR-N7 | 500 | 0.7 | H3PO4, ZnCl2 |

**Table S2.**  Surface area and pore size analysis

|  |  |  |  |
| --- | --- | --- | --- |
| BET analysis | Surface area / (m2·g−1) | Pore volume / (cm3·g−1) | Pore size / nm |
| Langmuir | 1427.58 | — | — |
| BET | 1188.58 | — | — |
| Adsorption | — | 0.094616 | 3.3704 |
| Desorption | — | 0.10245 | 2.8808 |

**Table S3.**  Elemental contents before and after PPR-Z adsorption

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Element | Original | | Adsorption | |
| at% | wt% | at% | wt% |
| C | 64.85 | 60.08 | 51.49 | 43.87 |
| N | 26.58 | 28.72 | 26.37 | 26.20 |
| O | 8.14 | 10,04 | 19.92 | 22.61 |
| P | 0.06 | 0.15 | 0.09 | 0.19 |
| Cl | 0.37 | 1.01 | 0.60 | 1.51 |
| Cr | — | — | 1.52 | 5.62 |

**Table S4.** pH value and composition of electroplating wastewater Cr(VI) solutions and its adsorption capacity.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| pH | Ion type | Ions | Ion concentration / (mg·L−1) | *Q* / (mg·g−1) |
| 2.4 | Metal ion | Cr6+ | 243.58 | 71.59 |
| Ni2+ | 25.57 | 0.5816 |
| Cu2+ | 15.75 | 1.86 |
| Fe2+ | 34.24 | 1.52 |
| Anion | Cl− | 200.26 | — |
| NO3− | 25.23 | — |
| SO4− | 200.51 | — |

**Table S5.**  PPR-Z adsorption kinetics obtained by PFO, PSO and W-M models

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Temperature / K | PFO | | | PSO | | | W-M | | |
| *Q*e / (mg·g−1) | *K*1 / (min−1) | *R*2 | *Q*e / (mg·g−1) | *K*2 / (g·mg−1·min−1) | *R*2 | *R*12 | *R*22 | *R*32 |
| 293 | 138.5 | −0.00946 | 0.9493 | 138.5 | 0.00693 | 0.9999 | 0.9799 | 0.8963 | 0.8861 |
| 313 | 140.1 | −0.00664 | 0.9175 | 140.1 | 0.00707 | 0.9999 | 0.9901 | 0.9979 | 0.9968 |
| 323 | 143.8 | −0.00975 | 0.8915 | 143.8 | 0.00721 | 0.9999 | 0.9902 | 0.9455 | 0.9594 |

**Table S6.**  Isothermal adsorption model fitting table

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Metal ion | *T* / K | Langmuir | | | Freundlich | | |
| *Q*m / (mg·g−1) | *K*L / (L·mg−1) | *R*2 | *K*f / (mg·g−1) | *n* | *R*2 |
| Cr(Ⅵ) | 293 | 241.04 | 0.0143 | 0.9907 | 78.5158 | 8.6562 | 0.9481 |
| 303 | 253.52 | 0.0145 | 0.9917 | 76.9611 | 7.8996 | 0.9687 |
| 313 | 254.15 | 0.0196 | 0.9931 | 83.2460 | 8.0183 | 0.9754 |
| 323 | 255.68 | 0.0274 | 0.9976 | 95.8994 | 9.3741 | 0.9785 |

**Table S7.** Isothermal adsorption model fitting table

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Metal ion | *T* / K | TemKin | | | Dubin Radushkevich | | |
| *A* | *B* | *R*2 | *β* / (mol2·J−2) | *E* / (kJ·mol−1) | *R*2 |
| Cr(Ⅵ) | 293 | 16.6333 | 31.3754 | 0.8913 | 0.00829 | 7.7640 | 0.6163 |
| 303 | 15.6805 | 18.7993 | 0.9173 | 0.00745 | 8.1923 | 0.6471 |
| 313 | 15.0581 | 19.5024 | 0.9306 | 0.00508 | 9.9209 | 0.6225 |
| 323 | 10.7329 | 23.2168 | 0.9457 | 0.00528 | 9.7312 | 0.7818 |

**Table S8.** Thermodynamic parameters

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Cr(Ⅵ) concentration / (mg·L−1) | Δ*H* / (kJ·mol−1) | Δ*S* / (kJ·mol−1·K−1) | Δ*G* / (kJ·mol−1) | | | | *R*2 |
| 293 K | 303 K | 313 K | 323 K |
| 400 | 16.050 | 0.06332 | −2.503 | −3.136 | −3.769 | −4.402 | 0.9694 |
| 800 | 5.202 | 0.01303 | 1.384 | 1.254 | 1.124 | 0.993 | 0.9812 |
| 1000 | 4.686 | 0.00821 | 2.281 | 2.199 | 2.117 | 2.034 | 0.9940 |
| 2000 | 2.891 | −0.00579 | 4.589 | 4.647 | 4.705 | 4.763 | 0.9065 |
| 3000 | 2.067 | −0.01258 | 5.754 | 5.880 | 6.006 | 6.132 | 0.9127 |
| 4000 | 3.248 | −0.01136 | 6.576 | 6.690 | 6.804 | 6.917 | 0.9812 |
| 5000 | 1.640 | −0.01852 | 7.068 | 7.253 | 7.438 | 7.623 | 0.7431 |