

Study on the preparation of carboxyl-functionalized ordered mesoporous silica and its adsorption performance for Cu(II)

LIU Yang¹, LIN Muyao¹, YANG Shuyuan², ZHANG Yibo^{*,1}, HU Jianglei^{*,3}

1. The Innovation Laboratory for the Manufacturing and Application of New Carbon Materials, Jilin Vocational College of Industry and Technology, School of Chemical Engineering, Jilin 132013, China;

2. School of Chemical Engineering, East China University of Science and Technology, Shanghai 200237, China;

3. School of Chemical Engineering, Changchun University of Technology, Changchun 130012, China

Received: March 16, 2026; Accepted: April 14, 2026; Published online: May 27, 2026

SBA-15 shows great potential as a carrier for heavy metal adsorbents. However, the lack of effective adsorption active sites on its surface limits its further application in the field of adsorption. To address this issue, 3-phosphonopropionic acid was used as a functionalizing reagent to prepare carboxyl-functionalized SBA-15 (denoted as SBA-15C and SBA-15C-g) *via* one-step co-condensation as well as post-grafting modification, respectively. The results showed that the carboxyl-functionalized SBA-15 retained an ordered two-dimensional hexagonal mesoporous structure, and the surface of the SBA-15 was successfully functionalized with carboxyl groups. SBA-15, SBA-15C-2 and SBA-15C-g were used as adsorbents to study their adsorption performance on Cu(II) in solution. Under the optimized conditions, the adsorption capacity of Cu(II) by SBA-15, SBA-15C-2 and SBA-15C-g reached 30.4, 65.7 and 44.9 mg·g⁻¹, respectively. Adsorption kinetics and isotherm analysis indicated that the adsorption of Cu(II) onto the three materials was better described by the pseudo-second-order kinetic model and the Langmuir adsorption isotherm model. In addition, SBA-15C-2 maintained a high adsorption capacity of Cu(II) after five cycles. These results provide a theoretical basis for the carboxyl functionalization modification and practical application of SBA-15.

mesoporous materials; SBA-15; adsorption; carboxyl-functionalization; Cu(II)

Citation: LIU Y., LIN M. Y., YANG S. Y., ZHANG Y. B., HU J. L., Study on the preparation of carboxyl-functionalized ordered mesoporous silica and its adsorption performance for Cu(II), J. Mol. Sci. 42, 26020607 (2026), <https://doi.org/10.3724/jmolsci.2026030003>

1. Introduction

Ordered mesoporous silica has attracted the attention of researchers due to its important applications such as catalysis^[1-2], adsorption of heavy metals from aqueous solutions^[3-5], removal of organic pollutants^[6], capture of volatile organic compounds^[7], and medical applications^[8]. Among various mesoporous silica, SBA-15 demonstrates superior suitability as a carrier for heavy metal adsorption benefiting from its large specific surface area, tunable pore size, and excellent hydrothermal stability^[9-10].

However, the surface of pure SBA-15 contains only Si—OH groups and lacks effective active sites for adsorbing Cu(II), resulting in poor adsorption performance. Surface modification is required to introduce functional groups^[11-12]. The main methods for introducing functional groups into

mesoporous silica are co-condensation and post-grafting. Co-condensation enables uniform functional group distribution and strong bonding within the material framework. Post-grafting offers simplicity and flexibility yet suffers from uneven functional group distribution and limited grafting efficiency.

In current studies, carboxyl groups exhibit strong chelating ability toward Cu(II), making them ideal adsorbent functional groups^[13]. Carboxyl-functionalized SBA-15 combines the advantages of mesoporous mass transfer with the high adsorption activity of carboxyl groups, offering enhanced selectivity and adsorption capacity for Cu(II).

Herein, 3-phosphonopropionic acid was employed as a carboxyl-functionalizing reagent to prepare carboxyl-functionalized SBA-15 *via* a co-condensation followed by post-grafting, addressing the issue of insufficient active sites for Cu(II) adsorption in pure SBA-15. Through material characterization, adsorption kinetics, isotherm modeling, and evaluation of cycling performance, the adsorption mechan-

*Corresponding author. zhangyb0130@outlook.com (ZHANG Yibo);
hujl863@163.com (HU Jianglei)
Executive editor: CHANG Yingfei

ism of carboxyl-functionalized SBA-15 toward Cu(II) was elucidated, providing both theoretical and experimental references for its modification and application.

2. Experimental section

2.1 Materials

Triblock copolymer P123 ($\text{EO}_{20}\text{PO}_{70}\text{EO}_{20}$), $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$, 3-phosphonopropionic acid, and tetraethyl orthosilicate (TEOS), were purchased from Sigma-Aldrich. HCl (36%–38% by mass) was purchased from Beijing Chemical Works.

2.2 Synthesis of materials

SBA-15 was prepared on the basis of Ref.[14]. The synthesis of the co-condensed SBA-15C was carried out as follows. Firstly, 7.5 mL of distilled water and 60 mL of $2 \text{ mol} \cdot \text{L}^{-1}$ HCl were added to 2 g of P123 and continuously stirred by a magnetic stirrer until completely dissolved; then, 4 g of TEOS and different doses of 3-phosphonopropionic acid (0.23, 0.37, and 0.52 g, respectively) were added to the above-mentioned mixture, which was continuously stirred at 35 °C for 24 h; subsequently, the mixture was transferred to a PTFE-lined autoclave and aged at 100 °C for 24 h; after the reactor was naturally cooled, the reaction product was filtered and washed several times with distilled water and ethanol, followed by drying in a vacuum oven at 60 °C for 12 h. Finally, the carboxyl-functionalized SBA-15 was treated under refluxing conditions to 400 mL of the ethanol-hydrochloric acid solution (containing 5 mL of HCl) and refluxed at 80 °C for 24 h to remove P123. The product was washed several times with ethanol and distilled water, and dried in a vacuum oven at 60 °C for 12 h^[15]. The white powder obtained was denoted as SBA-15C-*x* (*x* = 1, 2 and 3, corresponding to 3-phosphonopropionic acid additions of 0.23, 0.37 and 0.52 g, respectively).

The synthesis of the post-grafting modification SBA-15C was carried out as follows. First, 0.5 g of SBA-15 was added to 20 mL of an ethanol/water mixture with a volume ratio of 95/5. Subsequently, 0.16 g of 3-phosphonopropionic acid was added. The mixture was then subjected to ultrasonic treatment for 0.5 h, followed by refluxing at 80 °C for 2 h. The resulting product was separated by centrifugation and washed three times with ethanol. Finally, the modified SBA-15 was dried in a vacuum oven at 60 °C for 24 h. The obtained white solid was denoted as SBA-15C-g.

2.3 Adsorption experiment

A total of 40.0 mg of adsorbent was added to 40.0 mL of Cu(II) solution with initial concentrations of 20, 40, 60, 100, and 140 $\text{mg} \cdot \text{L}^{-1}$; followed by pH adjustment. Place all flasks in an automatic shaker with a water bath and agitated at 20, 25, 30, 35, and 40 °C for 300 min to achieve ad-

sorption equilibrium. Subsequently, the solid adsorbent was removed by filtration through a syringe filter, and the Cu(II) concentration was determined by atomic absorption spectra.

The adsorption capacity q_e ($\text{mg} \cdot \text{g}^{-1}$) is calculated using Equation (1)^[16]

$$q_e = \frac{(c_0 - c_e) \times V}{m}, \quad (1)$$

where c_0 and c_e are the initial and final concentrations at adsorption equilibrium of Cu(II) ($\text{mg} \cdot \text{L}^{-1}$), respectively; V is the volume of the suspension (L); and m is the mass of the adsorbent (g).

The percentage removal (R) of Cu(II) at adsorption equilibrium is calculated by

$$R = \frac{c_0 - c_e}{c_0} \times 100\%. \quad (2)$$

3. Results and discussion

3.1 Characterization of SBA-15C and SBA-15C-g

The low-angle XRD pattern of the sample was shown in Figure 1a. Three characteristic diffraction peaks were observed at approximately 0.88°, 1.51°, and 1.73°, corresponding to the (100), (110), and (200) crystal planes, which were basically consistent with the positions of the characteristic peaks of SBA-15 in the literature, suggesting that the material prepared in this experiment had a typical ordered 2D hexagonal mesoporous structure^[17]. As shown in Figure 1b, all samples exhibited a broad diffraction peak in the range of 15°–30°. This characteristic diffraction peak was attributed to amorphous silica^[18], indicating that the pore structure of SBA-15 remained unchanged.

As shown in Figure 1c, the N_2 adsorption-desorption isotherms of all samples were type IV isotherms with H1-type hysteresis loops. However, with the functionalization of the carboxyl group on the surface of SBA-15, the adsorption capacities of SBA-15C-1, SBA-15C-2, SBA-15C-3, and SBA-15C-g decreased, but still maintained the type IV isotherm with H1 hysteresis loop. The pore sizes of all four adsorbents were reduced, which could be attributed to 3-phosphonopropionic acid was involved in the formation of SBA-15, partially occupying the pore channels.

The FTIR spectra of the samples were shown in Figure 1d. In the spectra, the peaks at 470, 800, and 1087 cm^{-1} belonged to the bending vibration, symmetric stretching, and asymmetric stretching of the Si–O–Si, respectively; the peaks at 962 and 1630 cm^{-1} belonged to the bending vibration of Si–OH and O–H, respectively^[19–20]. For SBA-15C-1, SBA-15C-2, and SBA-15C-3, a new characteristic peak appeared at 1720 cm^{-1} , which corresponded to the stretching vibration of the –COOH group^[21]. In contrast, for SBA-15C-g, the intensity of the characteristic peak at 1720 cm^{-1} was weaker, which may be attributed to the lower grafting degree of 3-phosphonopropionic acid.

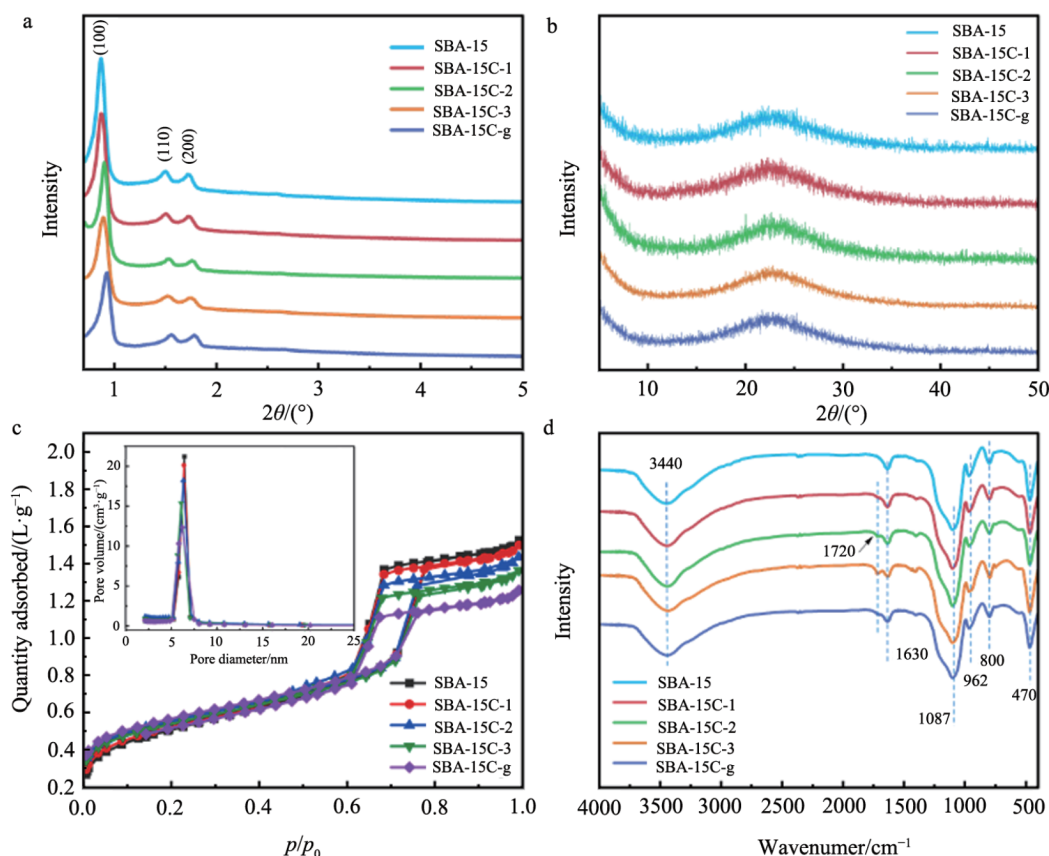


Figure 1 Low-angle (a) and wide-angle (b) XRD spectra, N₂ adsorption-desorption isotherms and pore size distribution (c), and FTIR spectra (d) of samples

The morphological characterization of the samples is shown in Figure 2. The SEM images of both SBA-15 and SBA-15C-2 reveal short rod-like structures, indicating that carboxyl functionalization did not alter the morphology of SBA-15. In contrast, the TEM images reveal regularly ordered alternating bright and dark channels, confirming that SBA-15C-2 retains an ordered two-dimensional hexagonal mesoporous structure.

3.2 Adsorption performance

First, the effect of pH on the adsorption of Cu(II) was investigated. As shown in Figure 3a, the adsorption capacities of SBA-15, SBA-15C-2, and SBA-15C-g for Cu(II) increased with the increasing pH in the range of 1–6. When the pH increased from 6.0 to 7.0, the adsorption capacities of all adsorbents increased sharply. This was attributed to the precipitation of Cu(II) as hydroxide at pH above 6.0^[22]. Therefore, pH = 5.0 was selected for subsequent adsorption experiments.

Secondly, the effect of adsorption time on the adsorption capacity of Cu(II) was investigated. As shown in Figure 3b, the adsorption capacities of SBA-15, SBA-15C-2 and SBA-15C-g for Cu(II) increased rapidly in the initial stage, and equilibrium was reached within 30 min. Meanwhile, the adsorption of Cu(II) by the three adsorbents remained nearly constant. Compared to SBA-15C-g, during the synthesis of

SBA-15C-2, 3-phosphonopropionic acid participated in the formation of the SBA-15 framework. This resulted in the uniform dispersion and greater quantity of carboxyl groups on the surface of SBA-15C-2. Consequently, upon reaching equilibrium, SBA-15C-2 exhibited a higher adsorption capacity for Cu(II). To ensure adsorption equilibrium, the adsorption time was selected as 120 min for the subsequent experiments.

The effect of solution temperature on Cu(II) adsorption was shown in Figure 3c. For SBA-15, SBA-15C-2, and SBA-15C-g, the adsorption capacities of Cu(II) increased slightly with increasing temperature. These results indicated that elevated adsorption temperatures enhance the mobility of Cu(II) in the solution, thereby facilitating the adsorption process. However, considering energy consumption, 25 °C was selected as the optimal temperature for subsequent adsorption experiments.

Finally, the influence of initial concentration c_0 on Cu(II) adsorption was investigated. As shown in Figure 3d, the adsorption capacities of SBA-15, SBA-15C-2 and SBA-15C-g for Cu(II) increased with increasing c_0 . When c_0 exceeded 100 mg·L⁻¹, the adsorption capacity of all three adsorbents for Cu(II) reached equilibrium and remained essentially unchanged. However, the three materials exhibit differing adsorption capacity for Cu(II). This was because carboxyl groups possess superior adsorption capacity for Cu(II) relative to silanol groups, resulting in SBA-15C-2 de-

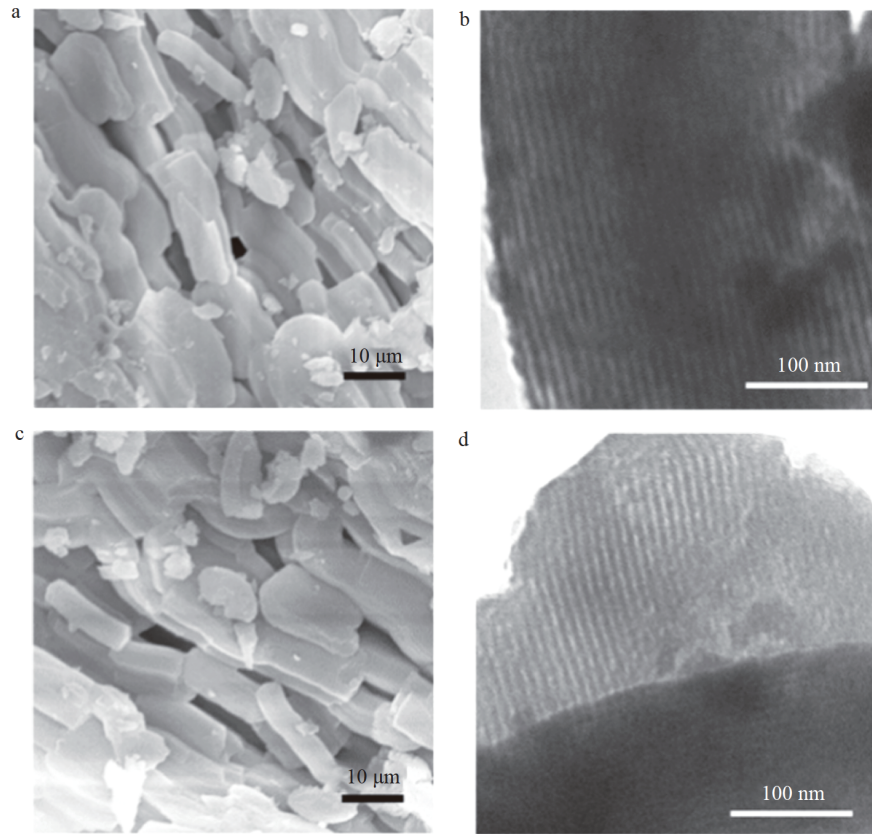


Figure 2 SEM (a) and TEM (b) images of SBA-15; SEM (c) and TEM (d) images of SBA-15C-2

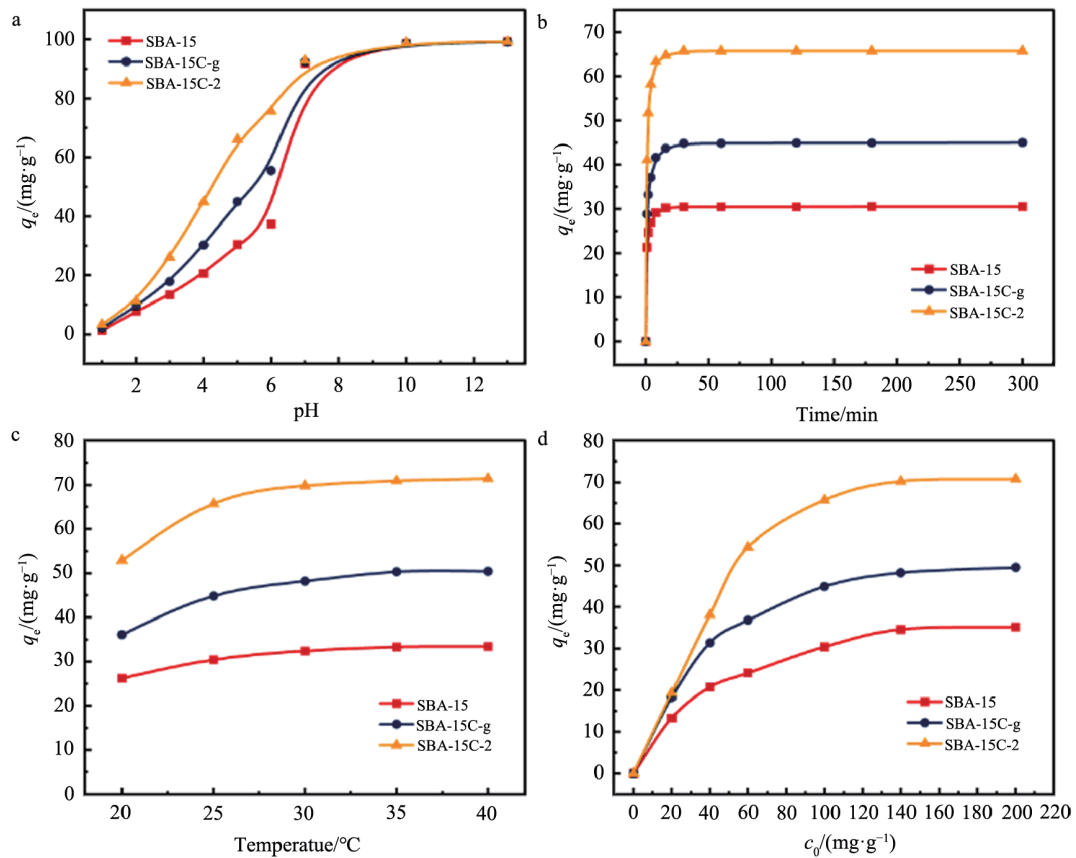


Figure 3 The influence of pH (a), time (b), temperature (c), and initial concentration (d) on the adsorption capacity of Cu(II) by SBA-15, SBA-15C-2, and SBA-15C-g

monstrating a higher adsorption capacity for Cu(II).

Table 1 presented the adsorption capacities of Cu(II) by SBA-15, SBA-15C-2, and SBA-15C-g under optimal conditions. As shown in Table 1, the carboxyl-functionalized SBA-15 synthesized *via* the co-condensation achieved a Cu(II) adsorption capacity of $65.7 \text{ mg} \cdot \text{g}^{-1}$. This can be attributed to the involvement of 3-phosphonopropionic acid in the formation of the SBA-15 framework, which promotes uniform dispersion of carboxyl groups and increases their surface density on SBA-15. Moreover, the ordered mesoporous structure of SBA-15C-2 provided an optimal environment for Cu(II), thereby enhancing its adsorption capacity. Table 1 also compares the adsorption capacity of different SBA-15-based materials. It can be observed that SBA-15C-2 exhibited a relatively high adsorption capacity for Cu(II), although it remains lower than those of certain adsorbents functionalized with branched chelating ligands.

3.3 Adsorption kinetics and isotherm analysis

To further investigate the adsorption mechanism, pseudo-first-order and pseudo-second-order kinetic models were applied based on the experimental data, as shown in Equations (3) and (4):

$$\lg(q_e - q_t) = \lg q_e - \frac{k_1}{2.303} t, \quad (3)$$

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_e}, \quad (4)$$

where, q_e and q_t are the adsorption capacity at equilibrium and time t , k_1 and k_2 are the rate constants of the pseudo-first-order and pseudo-second-order kinetic models, respectively.

The fitted pseudo-first-order and pseudo-second-order adsorption kinetic curves were shown in Figures 4a and 4b, respectively.

Table 1 Adsorption capacity of Cu(II) by different SBA-15 materials

Materials	$q_e/(\text{mg} \cdot \text{g}^{-1})$	Conditions		Reference
		pH	Temperature/ $^{\circ}\text{C}$	
SBA-15C-2	65.7	5	25	This study
SBA-15C-g	44.9	5	25	This study
SBA-15	30.4	5	25	This study
NH ₂ -SBA-15-f	19.8	6	30	[23]
G-SBA-15-NN-E	53.1	Unmentioned	25	[24]
MDA-SBA-15	78.3	4.0	25	[25]
SA-SBA-15	57.2	4.8	Room temperature	[26]

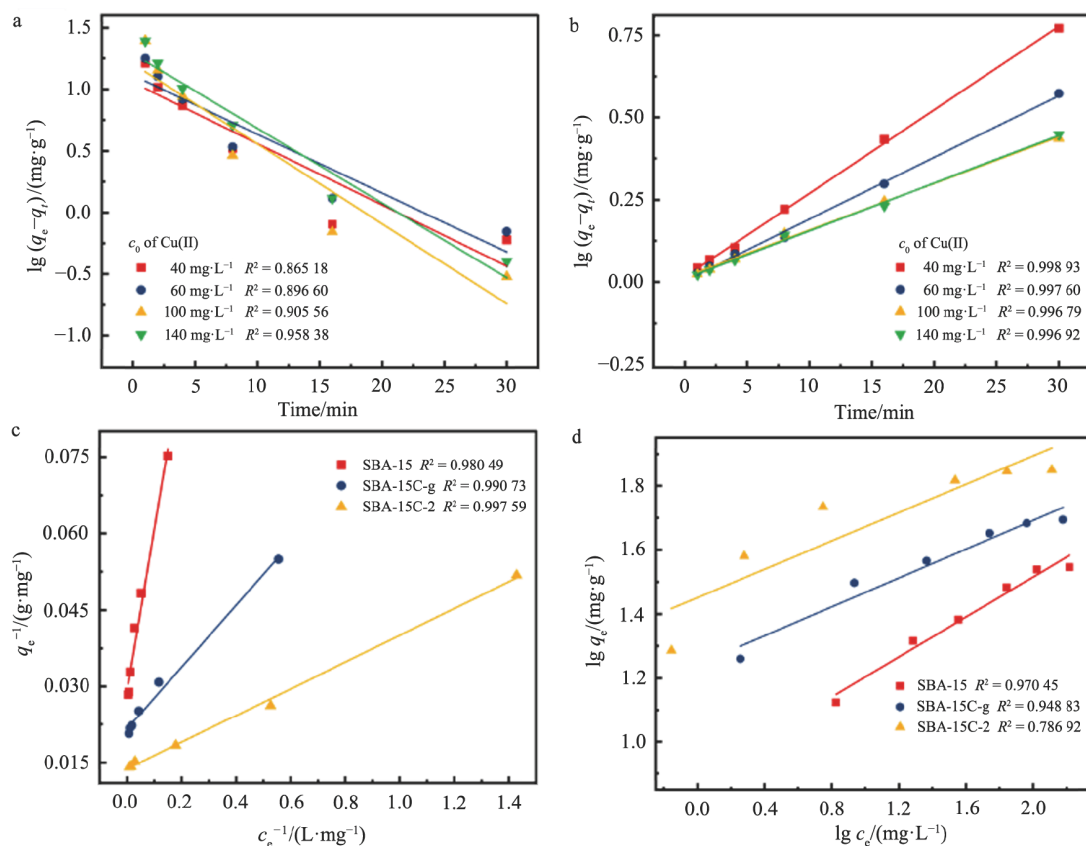


Figure 4 Linear fitting plots of the pseudo-first-order kinetic model (a) and pseudo-second-order kinetic model (b) for SBA-15C-2, isotherm fitting plots of the Langmuir model (c) and Freundlich model (d) for Cu(II) adsorption on different adsorbents

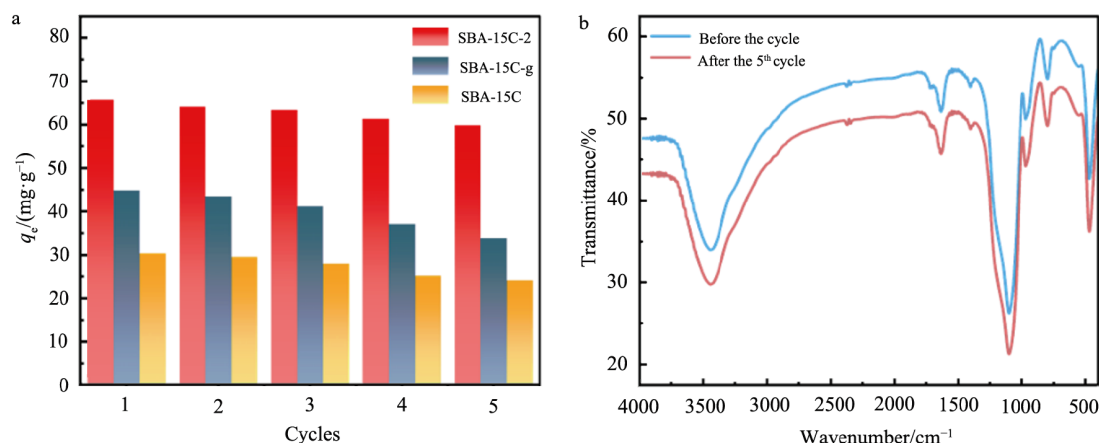


Figure 5 Reusability of SBA-15, SBA-15C-2 and SBA-15C-g for Cu(II) adsorption (a) and FTIR spectra of SBA-15C-2 before and after cycling (b)

For the pseudo-second-order adsorption kinetic model, its correlation coefficient (R^2) was significantly higher than that of the pseudo-first-order adsorption kinetic model. Consequently, the adsorption experimental data for SBA-15C-2 were better fitted by the pseudo-second-order kinetic model. According to the assumptions of the pseudo-second-order kinetic model, the adsorption of metal ions by adsorbents may represent a chemical adsorption process between the metal ions and the adsorbent. This chemical adsorption was attributed to covalent forces arising from electron exchange or sharing^[27].

To further elucidate the adsorption mechanism, Langmuir model and Freundlich isotherm model were applied, as shown in Equations (5) and (6):

$$\frac{1}{q_e} = \frac{1}{Q_0 K_L c_e} + \frac{1}{Q_0}, \quad (5)$$

$$\lg q_e = \lg K_F + \frac{1}{n} \lg c_e, \quad (6)$$

where Q_0 is the saturated adsorption capacity, and K_L and K_F are the adsorption equilibrium constants for Langmuir model and Freundlich isotherm model, respectively. n is the adsorption intensity parameter reflecting the favorability of the adsorption process.

The results were shown in Figures 4c and 4d. The Langmuir adsorption isotherm model more accurately described the adsorption process of Cu(II) than the Freundlich adsorption isotherm model. According to the theory of the Langmuir adsorption isotherm model^[28], the active adsorption sites were likely uniformly distributed across its surface, resulting in monolayer adsorption. Meanwhile, the carboxyl groups grafted onto SBA-15 interact with Cu(II) through coordination bonds.

3.4 Reusability study

Finally, the reusability of SBA-15, SBA-15C-2, and SBA-15C-g was evaluated. As shown in Figure 5a, after five cycles, the adsorption capacity of SBA-15C-2 decreased from 65.7 to 59.9 mg·g⁻¹; the adsorption capacity of SBA-

15C-g decreased from 44.9 to 33.9 mg·g⁻¹; and the adsorption capacity of SBA-15 decreased from 30.4 to 24.1 mg·g⁻¹. As shown in Figure 5b, for SBA-15C-2, the intensity of the characteristic peak at 1720 cm⁻¹ remained essentially unchanged after five cycles. This stability was attributed to 3-phosphonopropionic acid participates in the formation of SBA-15, which led to the stable immobilization of carboxyl functional groups on the surface of SBA-15C-2. Consequently, SBA-15C-2 maintained a relatively high adsorption capacity after repeated use.

4. Conclusion

Carboxyl-functionalized SBA-15 was successfully prepared via one-step co-condensation and post-grafting modification. The modified material retained their ordered mesoporous structure and high specific surface area, with the successful introduction of carboxyl groups. Under optimized conditions, SBA-15C-2 exhibited the highest adsorption capacity for Cu(II). The adsorption process followed pseudo-second-order kinetics and the Langmuir monolayer adsorption model, and SBA-15C-2 maintained high adsorption capacity even after five adsorption-desorption cycles. This study provided new insights into the adsorption mechanism of carboxyl-functionalized SBA-15, enriching the theoretical understanding of mesoporous materials for heavy metal adsorption. Furthermore, it presented a highly efficient and stable Cu(II) adsorbent, offering a technical reference for the treatment of Cu(II)-containing wastewater. In the future, the adsorption capacity of the material for other heavy metals such as Pb(II) and Cd(II) will be further investigated.

Acknowledgements This work was supported by the Project of Education Department of Jilin Province, China (JJKH20251816KJ, JJKH20261574KJ).

References

- PANPRANOT J, GOODWIN J G Jr, SAYARI A. [J]. *J Catal*, 2002, 211(2): 530-539. DOI: 10.1006/jcat.2002.3761.
- DAS D, SAYARI A. [J]. *J Catal*, 2007, 246(1): 60-65. DOI: 10.1016/j.

- jcat.2006.11.020.
- 3 PÉREZ-QUINTANILLA D, SÁNCHEZ A, SIERRA I. [J]. *J Colloid Interface Sci*, 2016, 472: 126-134. DOI: 10.1016/j.jcis.2016.03.048.
 - 4 YANG W, SHIRAZIAN S, SOLTANI R, et al. [J]. *npj Clean Water*, 2024, 7: 49. DOI: 10.1038/s41545-024-00340-7.
 - 5 EZZEDDINE Z, BATONNEAU-GENER I, GHSSEIN G, et al. [J]. *Water*, 2025, 17(5): 669. DOI: 10.3390/w17050669.
 - 6 WALCARIUS A, MERCIER L. [J]. *J Mater Chem*, 2010, 20(22): 4478-4511. DOI: 10.1039/b924316j.
 - 7 SERNA-GUERRERO R, SAYARI A. [J]. *Environ Sci Technol*, 2007, 41(13): 4761-4766. DOI: 10.1021/es0627996.
 - 8 POURSHAHRESTANI S, ZEIMARAN E, ADIB KADRI N, et al. [J]. *J Mater Chem B*, 2016, 4(1): 71-86. DOI: 10.1039/c5tb02062j.
 - 9 AGUADO J, ARSUAGA J M, ARENCIBIA A. [J]. *Microporous Mesoporous Mater*, 2008, 109(1/2/3): 513-524. DOI: 10.1016/j.micromeso.2007.05.061.
 - 10 LIANG B, ZHU P, GU J, et al. [J]. *Molecules*, 2024, 29(15): 3543. DOI: 10.3390/molecules29153543.
 - 11 WANG S, WANG K, DAI C, et al. [J]. *Chem Eng J*, 2015, 262: 897-903. DOI: 10.1016/j.cej.2014.10.035.
 - 12 ZHANG S, HUANG Q, CHEN L, et al. [J]. *J Hazard Mater*, 2024, 467: 133741. DOI: 10.1016/j.jhazmat.2024.133741.
 - 13 DEKA J R, LEE M H, SAIKIA D, et al. [J]. *Dalton Trans*, 2019, 48(23): 8227-8237. DOI: 10.1039/c9dt00248k.
 - 14 ZHAO D, FENG J, HUO Q, et al. [J]. *Science*, 1998, 279(5350): 548-552. DOI: 10.1126/science.279.5350.548.
 - 15 CHEN C S, LAI Y T, LAI T W, et al. [J]. *ACS Catal*, 2013, 3(4): 667-677. DOI: 10.1021/cs400032e.
 - 16 GOURMAND C, BERTAGNOLLI C, PRELOT B, et al. [J]. *Dalton Trans*, 2024, 53(8): 3690-3701. DOI: 10.1039/d3dt03210h.
 - 17 YU Z, ZHANG L, HAN Y, et al. [J]. *Mater Lett*, 2021, 282: 128841. DOI: 10.1016/j.matlet.2020.128841.
 - 18 YU Z, CHEN X, ZHANG Y, et al. [J]. *Chem Eng J*, 2022, 430: 133059. DOI: 10.1016/j.cej.2021.133059.
 - 19 RATCHADAPIBAN K, PRASERTHDAM P, TUNGASMITA D N, et al. [J]. *Catalysts*, 2018, 8(9): 360. DOI: 10.3390/catal8090360.
 - 20 QI Z, LIU C, SHEN P, et al. [J]. *Mater Today Commun*, 2025, 44: 112188. DOI: 10.1016/j.mtcomm.2025.112188.
 - 21 VATANPOUR V, RABIEE H, DAVOOD ABADI FARAHANI M H, et al. [J]. *Chem Eng Res Des*, 2020, 156: 240-250. DOI: 10.1016/j.cherd.2020.01.029.
 - 22 TONG X J, LI J Y, YUAN J H, et al. [J]. *Chem Eng J*, 2011, 172(2/3): 828-834. DOI: 10.1016/j.cej.2011.06.069.
 - 23 LEE J Y, CHEN C H, CHENG S, et al. [J]. *Int J Environ Sci Technol*, 2016, 13(1): 65-76. DOI: 10.1007/s13762-015-0841-y.
 - 24 AGUADO J, ARSUAGA J M, ARENCIBIA A, et al. [J]. *J Hazard Mater*, 2009, 163(1): 213-221. DOI: 10.1016/j.jhazmat.2008.06.080.
 - 25 SHAHBAZI A, YOUNESI H, BADIEI A. [J]. *Chem Eng J*, 2011, 168(2): 505-518. DOI: 10.1016/j.cej.2010.11.053.
 - 26 MURESEANU M, REISS A, STEFANESCU I, et al. [J]. *Chemosphere*, 2008, 73(9): 1499-1504. DOI: 10.1016/j.chemosphere.2008.07.039.
 - 27 YANG Y, CAO X, MA Z, et al. [J]. *Desalin Water Treat*, 2021, 213: 358-370. DOI: 10.5004/dwt.2021.26718.
 - 28 TAPASWI P K, MOORTHY M S, PARK S S, et al. [J]. *J Solid State Chem*, 2014, 211: 191-199. DOI: 10.1016/j.jssc.2013.12.028.

羧基功能化有序介孔二氧化硅的制备 及其对Cu(II)的吸附性能研究

刘杨¹, 林慕尧¹, 杨舒源², 张毅博^{*,1}, 胡江磊^{*,3}

1. 吉林工业职业技术学院化学工程学院新型碳材料制造与应用创新实验室, 吉林 吉林 132013;

2. 华东理工大学化工学院, 上海 200237;

3. 长春工业大学化学工程学院, 吉林 长春 130012

摘要 SBA-15 作为重金属吸附剂载体具有良好应用前景, 但其表面缺乏有效的吸附活性位点, 限制了其在吸附领域的进一步应用。为此, 本研究以3-膦酰基丙酸为功能化试剂, 分别通过一步共缩聚法和后接枝改性法制备了羧基功能化的SBA-15 (分别记为SBA-15C和SBA-15C-g)。表征结果表明, 羧基功能化后的SBA-15仍保持有序的二维六角介孔结构, 且羧基成功引入载体表面。以SBA-15、SBA-15C-2和SBA-15C-g为吸附剂, 研究其对溶液中Cu(II)的吸附性能。在优化条件下, 三者对Cu(II)的吸附容量分别达到30.4、65.7和44.9 mg·g⁻¹。吸附动力学和吸附等温线分析表明, Cu(II)在各吸附剂上的吸附行为更符合准二级动力学模型和朗格缪尔吸附等温模型。此外, SBA-15C-2在5次循环后仍保持较高的Cu(II)吸附容量。上述结果为SBA-15的羧基功能化改性及实际应用提供了理论依据。

关键词 介孔材料; SBA-15; 吸附; 羧基功能化; Cu(II)