Synthesis of a magnetic C@Co material via the design of a MOF precursor for efficient and selective adsorption of water pollutants

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Abstract

3D metal-organic frameworks (MOFs) can be appropriate templates for the fabrication of nanomaterials due to they have active sites exposed on the channel or surface, which thus provide them with improved catalytic performance. In this study, a 3D cobalt-based MOF $[\text{Co}(\text{H}_2\text{bpta})]_n$ (Co-MOF), where H_4bpta denotes 2,2',4,4'-biphenyltetracarboxylic acid, has been constructed with the use of a ligand with a high carbon content. On this basis, a 2D magnetic carbon-coated cobalt nanoparticle composite (C@Co) was prepared by using the title MOF. Magnetic C@Co can readily absorb dye from the solution and can thus act as an inexpensive and fast-acting adsorbent. Moreover, we have explored the adsorption isotherms, kinetics and thermodynamics of the anion dyes in detail. The adsorption capacity of the C@Co for investigated methyl orange (MO) and congo red (CR) dyes were 773.48 and 495.66 mg g^{-1} , respectively. It is noteworthy that MO adsorption is higher in existing materials. Thermodynamic studies suggest that the adsorption processes are spontaneous and exothermic. This study opens a new insight into the synthesis and application of carbon-based materials that enable the selective removal of organic dyes.

1. Introduction

With the growth of the printing, textile, and other industries in recent years, the discharge of dye wastewater has increased each year.^{1–4} Methyl orange (MO) and Congo red (CR) are two common anionic dyes which have been widely used in the industries and research laboratories.^{5, 6} Nowadays, a variety of methods such as oxidation, ozonation or degradation have been exploited to remove anionic dyes from wastewater.^{7–10} However, aforementioned techniques have poor selectivity and are relatively expensive because they cannot be reused. Therefore, there is an urgent need for an efficient way to selectively remove anionic dyes.

Carbon-based materials are regarded as ideal candidates for the adsorption heavy metal ions and organic pollutants because of their good stabilities and high specific surface areas.^{11–14} However, these materials have only offered modest anionic dye removal performance.^{15–18} Therefore, achieving selective, efficient, and reversible anionic dye adsorption and desorption using a carbon-based material continues to pose a daunting challenge.

Metal-organic frameworks (MOFs) as sacrificial precursors or templates for preparing highly dispersed inorganic, organometallic, and composite materials with good stabilities and high specific surface areas after the calcined or pyrolysis process have been widely used.^{19–22} Notably, MOF-derived materials can remain the original morphologies of the MOFs under appropriate conditions. Among them, Co-doped carbon-based materials synthesized by the pyrolysis of Co-containing MOF precursors are considered as good adsorbents.^{23–26} Carbon-coated cobalt composites (C@Co) have been regarded as adsorbents for the removal of organic and inorganic pollutants from solutions, and they have been found to offer performances comparable to commercial adsorbents.^{27–31} Furthermore, the outstanding adsorption capabilities of C@Co relative to other adsorbents may be caused by strong interactions between C@Co

and the targeted compounds through $\pi - \pi$ interactions, which result from the presence of delocalized electrons in hexagonal arrays of carbon atoms that thus facilitate adsorption onto the surfaces of C@Co materials.^{32, 33}

In this work, $[\text{Co}(\text{H}_2\text{bpta})]_n$ (Co-MOF), where H_4bpta denotes 2,2',4,4'-biphenyltetracarboxylic acid, was synthesized under solvothermal conditions (Tables S1 and S2). The Co-MOF was thermally annealed under an N_2 atmosphere to form carbon-based composites (C@Co) (Scheme 1). The dye adsorption performances of the Co-MOF and C@Co have been studied. Moreover, the kinetics and thermodynamics parameters of the dye adsorption on the C@Co were investigated in detail to gain insight regarding the adsorption mechanism.

2. Experimental Section.

2.1 Materials and Methods.

The ligand 2,2',4,4'-biphenyltetracarboxylic acid (H_4bpta) was synthesized by the methods described in the literature.³⁴ All other reagents and solvents were reagent grade, which employed from commercial sources and used without further purification.

2.2. Synthesis of $[\text{Co}(\text{H}_2\text{bpta})]_n$ (Co-MOF).

A mixture of $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ (0.048 g, 0.2 mmol), H_4bpta (0.052 g, 0.15 mmol), CH_3CN (3 mL), and H_2O (3 mL) were placed in a 20 mL Teflon-lined autoclave and kept at 120°C for 96 h. Then, it was cooled to room temperature and obtained purple cubic crystals of $[\text{Co}(\text{H}_2\text{bpta})]_n$. (0.064 g, 58% yield based on Co). Calcd for $\text{C}_{16}\text{H}_8\text{CoO}_8$ (%): C, 48.33; H, 2.52. Found (%): C, 48.25; H, 2.24. FT-IR (KBr, cm^{-1}): 3437 (m), 2395 (m), 1905 (w), 1619 (s), 1572 (s), 1559 (s), 1416 (s), 1370 (s), 1244 (s), 1131 (m), 805 (w), 696 (s).

2.3. Synthesis of the carbon-based composites of $[\text{Co}(\text{H}_2\text{bpta})]_n$ (C@Co).

Firstly, the Co-MOF complex was placed in a quartz boat and situated in a tubular furnace. Secondly, the furnace temperature was increased to 800°C under the N_2 flow (200 mL/min, 99.999% purity) with the heating rate of $20^\circ\text{C min}^{-1}$. Thirdly, the carbon-based material was prepared with N_2 (200 mL min^{-1}) for 60 min. Finally, it was cooled to room temperature with N_2 flow, the carbon-based material had been synthesized.

2.4. Characterization.

The elemental analyses (C, H, and N) of the samples were performed with a Perkin-Elmer 240C elemental analyzer. FT-IR spectra (KBr pellets) were recorded with a Varian 640-IR spectrometer over the spectral from 500 to 4000 cm^{-1} . Powder X-ray diffraction (PXRD) data was collected using a Rigaku diffractometer with $\text{CuK}\alpha$ radiation. Meanwhile, the morphology of the carbon-based material was

characterized via scanning electron microscopy (SEM, Nova Nano SEM 430) and high-resolution transmission electron microscopy (HRTEM, JEOL2010 at 200 kV). The thermal stabilities of Co-MOF and the carbon-based composite of C@Co were measured with a thermogravimetric analyzer (NETZSCH STA 449C). The specific surface area and pore structure of C@Co was measured by an automatic volumetric sorption analyzer (ASAP 2020 M) using N₂ as the adsorbate at - 196°C. UV–Vis absorption spectra were recorded using an SP–1900 UV–Vis spectrophotometer.

3. Results And Discussion

3.1. Preparation and characterization of the cobalt-coated carbon-nanoparticle composite (C@Co).

It should be noted that the Co-MOF is the same that had been reported previously by Pan and co-workers.³⁵ According to reported research, the MOF-derived carbon-based materials could improved the energy conversion and storage capabilities as well as the adsorption properties of the resultant composite materials.³⁶ As a result, researchers have investigated the *in situ* growth carbon-based composites using MOFs as precursors, which is an efficient strategy for enhancing the properties of the MOF-derived materials.^{37, 38} On this basis, the C@Co was synthesized via the chemical vapor deposition (CVD) method with the use of Co-MOF as a precursor. The morphology of the C@Co was observed by SEM and TEM characterization. After calcined, the Co-MOF formed Co nanoparticles, and the surrounding organic ligands were pyrolyzed into a Co-doped carbon skeleton which surrounded the nanoparticles. It can be seen that C@Co maintains a 2D layered structure, and Co particles are loading on the carbon surface (Fig. 1). The diameter of the Co particles is in the range of 30 – 40 nm, and the Co nanoparticles in the carbon matrix are well dispersed without exhibiting significant agglomeration. The FT-IR spectrum of the C@Co was recorded in the frequency range of 500 – 4000 cm⁻¹, as shown in Fig. 2a. The band at 3437 cm⁻¹ corresponds to the stretching and bending vibrations of the hydroxyl groups of C@Co, while the peaks observed at 1653 cm⁻¹ correspond to the asymmetric and symmetric vibrations of the carboxyl groups of C@Co.^{37, 38} Moreover, we have investigated the thermal stability and the components in C@Co by thermogravimetric analysis (TGA) measurements in air at temperatures reaching up to 800°C (Fig. 2b), and found that the weight loss of C@Co occurred via a single step. This weight loss of 25% in the range of 220–310°C is the decomposition of amorphous carbon. Moreover, the residual catalyst content is 74% after oxidation, suggesting that the majority of the catalyst residue remains in the sample. The PXRD pattern of the C@Co material prepared via the calcine of Co-MOF is demonstrated in Fig. 2c. The materials show metallic Co and weak CoO and Co₃O₄ diffraction peaks, the latter two sets of peaks can be attributed to the oxidation of the surface Co nanoparticles undergoing oxidation in the air.³⁹ Additionally, the cobalt particles gradually aggregate and separate from the carbon layer, then they are oxidized during the high temperature. Meanwhile, the C@Co sample has a specific surface area of 340.54 m² g⁻¹ and a pore size distribution from 2 to 10 nm, suggesting that it possesses mesoporous structures

(Fig. 2d). It is well known that the pores with variety of sizes is an appropriate way to increase active centers and can yield high-efficiency sorbents.⁴⁰

3.2. Dye adsorption properties of Co-MOF and C@Co.

MOFs are excellent adsorbents and are generally used on account of their specific surface areas, diverse range of functional groups, and controllable channel sizes.^{41, 42} Herein, the adsorption properties of dyes from wastewater brought about widespread attention.^{43, 44} In this study, three cationic dyes [methylene blue (MB), rhodamine B (RhB) and gentian violet (GV)] and two anionic dye (MO and CR) were chosen as models to investigate the adsorption properties of Co-MOF. More details of adsorption experiments are given in the supporting information. As illustrated in Fig. 3, the adsorption capacities of the Co-MOF for MB, RhB, CR, and GV at room temperature are 44.93, 3.92, 81.4, and 10.10 mg g⁻¹ at 360 min, respectively. However, Co-MOF exhibited an adsorption capacity of 235.64 mg g⁻¹ for MO in only 10 min, thus demonstrating it is highly selective toward MO and offers rapid and efficient capture of this dye (Fig. 3). According to the literatures, the mechanism of dye adsorption is host-guest interactions with electrostatic interaction, hydrogen bonding or π - π stacking.⁴⁵

However, the existing dye adsorption techniques are expensive due to their poor recyclabilities. It is of great significance to find an inexpensive adsorbent with reversible adsorption capabilities. On this basis, we have synthesized C@Co using the Co-MOF as a combined catalyst and precursor via the CVD method. At time intervals of 360 min, the dye concentration was measured via UV-Vis spectroscopy (Figs. 4a – 4e). The dye adsorption capacities of the C@Co adsorbent for MB, RhB, MO, CR, and GV at room temperature are 65.35, 50.88, 773.48, 495.66, and 43.62 mg g⁻¹, respectively (Fig. 4f). In comparison with other adsorbents, the adsorption capacities of the C@Co for MB, RhB and GV are not the highest.⁴⁶ However, we note that the adsorption capacities of our C@Co adsorbent for CR and MO are much higher than those of other dyes. The presence of –OH and –COOH in the C@Co and amino groups of MO and CR might promote the formation of numerous hydrogen bonding interactions.⁴⁷ Moreover, the favorable adsorption of MO and CR could be attributed to the electrostatic attraction between the negatively charged aqueous solution of MO and CR and the positively charged surfaces of the C@Co.⁴⁸ At the same time, π - π interaction between the surface of the carbon-based material and the aromatic compounds of dyes was considered to be the main contributor of the adsorption mechanism. Hence, these features demonstrate that the title C@Co can be a highly effective sorbent for the selective removal of dye species from water. Interestingly, the magnetic separation of C@Co was further tested with a magnet (Fig. S1). C@Co quickly to external magnetic fields and can be absolutely isolated from an aqueous solution by a magnet. This feature facilitates the recycling of this adsorbent.

3.3. Effect of contact time on adsorption performance.

The effect of contact time on the adsorption of MO and CR by C@Co is displayed in Fig. 4f. The initial concentration of MO and CR are 40 and 80 mg L⁻¹, respectively, at room temperature. It can be seen that

the adsorption capacities of C@Co for MO and CR increase rapidly as the contact time is increased from 0 to 180 min, due to the large number of vacant adsorption sites and the large surface area of this adsorbent. The adsorption rate began to slow down gradually during 180 min, mainly due to the lower MO and CR concentration, resulting in a weaker adsorption driving force while the number of surface active adsorption sites also decreased. After 360 min, the adsorption capacity reached equilibrium, and the equilibrium adsorption capacities were 733.33 and 495.66 mg g⁻¹ for MO and CR, respectively.

3.4. Effect of temperature on adsorption performance.

Temperature is one of the significant factors influencing the adsorption process. In particular, it affects the physical and chemical properties of the adsorbent and the diffusion rate of the adsorbed molecules and determines the adsorption capacity.⁴⁹ In this experiment, the effect of temperature on the adsorption of MO and CR by C@Co was studied at 298, 303, 313, and 323 K, respectively. It can be seen that the initial concentration of MO and CR is 40 and 80 mg L⁻¹ and the adsorption capacity reaches 733.33 and 495.66 mg g⁻¹ (Figs. 5 and S2). These results show that the adsorption capacity increases at higher temperatures. It may be caused by the electrostatic interactions between C@Co and dye molecules at higher temperatures. The results suggest that the adsorption of MO and CR on C@Co is an endothermic process.⁵⁰

3.5. Effect of concentration on adsorption performance.

The initial concentration of the solution is another crucial factor affecting the adsorption process. It affects adsorption by changing the adsorbent and the protonation of the adsorbent's surface functional groups. The effect of the concentration of the solution on the MO and CR adsorption capacity of C@Co is shown in Figs. 6 and S3, and it can be seen that the adsorption capacity increases at higher dye concentrations. As the concentration of the dyes is increases, eventually the adsorption sites on C@Co become occupied, so that a certain adsorption capacity is eventually reached.

3.6. Adsorption isotherms.

Many mathematical models have been used to describe the relationship between the adsorption capacity of adsorbents and the residual concentration in solution. The choice of isotherm model depends on the properties and types of adsorbents and adsorbates under investigation.⁵¹ In this work, the Langmuir and Friedrich models were used to further investigate the adsorption performance of C@Co and the reaction between adsorbents and adsorbates. The Langmuir model assumes that happens uniformly on the surface to form a monolayer of the adsorbed complex on the surface of C@Co, and all adsorption sites are identical and independent of each other. By linear fitting the scatter plot of the above equation, a linear curve can be obtained (Figs. S4 and S5). According to the slope and intercept of the curve in the figures, the values of q_{max} and k_L can be obtained (Tables 1 and S3). The maximum of MO theoretical adsorption capacities at 298, 303, 313, and 323 K are 772.75, 772.95, 773.09 and 773.33 mg g⁻¹ respectively, while the maximum theoretical adsorption capacities of CR are 476.86, 483.20, 491.15 and

495.66 mg g⁻¹, respectively. The decision coefficient of the Langmuir equation (R^2) is > 0.99. These results show that the adsorption of MO and CR onto C@Co are in accordance with the Langmuir model, thus suggesting that they are adsorbed in the form of a monolayer. As shown in Table 1, all R_L values are between 0 and 1, indicating that C@Co has a higher adsorption capacity for MO and CR than for the other dyes.⁵²

Table 1

The adsorption isotherm constants of the Langmuir and Freundlich models for the adsorption of MO onto C@Co.

Temperature (K)	Langmuir model				Freundlich model		
	q_{max} (mg g ⁻¹)	k_L (L mg ⁻¹)	R^2	R_L	k_F (L mg ⁻¹)	$1/n$	R^2
298	772.875	2.68×10 ⁻⁴	0.9687	0.0362–0.0447	6.9566	0.6432	0.8197
303	772.951	2.63×10 ⁻⁴	0.9698	0.0368–0.0455	6.9141	0.6178	0.8003
313	773.092	2.56×10 ⁻⁴	0.9721	0.0378–0.0472	6.9177	0.6127	0.8026
323	773.339	2.49×10 ⁻⁴	0.9734	0.0388–0.0489	6.9208	0.6078	0.8145

As shown in Figs. S6 and S7, the values of K_F and $1/n$ can be respectively determined from the slope and intercept of a Freundlich plot. The decision coefficient of Freundlich equation is $R^2 > 0.99$, thus suggesting that the adsorption of MO and CR by C@Co is in accordance with the Freundlich model (Table 1). The Langmuir and the Freundlich isotherm charts and parameters indicate that the adsorption conformed to the two models. According to the calculations performed via the Langmuir equation, the biggest adsorption capacity of C@Co reaches 773.33 and 495.66 mg g⁻¹ for MO and CR, respectively, which indicates that C@Co is an excellent adsorbent calculated by the Freundlich equation, $1/n$ is less than 1 which indicates that it is conducive to the adsorption reaction.⁵³

3.7. Adsorption kinetics.

Several kinetic models, such as the quasi-first-order kinetic model, the quasi-second-order kinetic model and the internal particle diffusion model, are often used to evaluate adsorption data.⁵⁴ As shown in Table 2, the values of k_1 and q_e can be determined from the intercept and slope of the plots shown in Fig. 7. Although the coefficient of determination (R^2) is close to 1, there is a significant difference between the calculated q_e (2.97 and 0.97 mg g⁻¹) and the experimental q_e values (773.33 and 495.66 mg g⁻¹),

indicating that the quasi-first-order kinetic model is unsuitable for this experiment. A plot of t/q_t versus t is shown in Figs. 7c and d, and the values of k_2 and q_e are acquired from the slope and intercept of this plot. The determination coefficients are 0.9723 and 0.9641 for MO and CR, respectively, and the calculated q_e values (773.33 and 495.66 mg g⁻¹) are very close to the experimental q_e values (773.33 and 495.66 mg g⁻¹), thus indicating that the quasi-second-order kinetic model can accurately describe the kinetics of MO and CR adsorption onto C@Co. Therefore, the adsorption rate is controlled by chemical adsorption, and the adsorbent and the adsorbed material exchange electrons through shared electrons or covalent forces.⁵⁴

Table 2
The parameters of the pseudo-first-order, pseudo-second-order, and intra-particle diffusion models.

Kinetic model	Parameters	MO	CR
		(40 mg L ⁻¹)	(80 mg L ⁻¹)
Pseudo-first-order model	k_1 (min ⁻¹)	-0.00427	-0.00625
	q_e (mg g ⁻¹)	2.97978	2.39548
	R^2	0.98130	0.96398
Pseudo-second-order model	k_2 (g mg ⁻¹ min ⁻¹)	0.00169	0.00196
	q_e (mg g ⁻¹)	0.05196	0.08215
	R^2	0.97230	0.96416
Intra-particle diffusion model	k_{id} (mg g ⁻¹ min ^{-1/2})	-239.70	-258.33
	C (mg g ⁻¹)	32.8970	32.9037
	R^2	0.98510	0.98923

The internal particle diffusion model is usually used to determine the rate control steps in porous structures.⁵⁴ As shown in Fig. S8 and described in Table 2. The determination coefficients R^2 of the internal particle diffusion model are 0.98510 and 0.98923, which are higher than those of the quasi-second order equation. The curve is nonlinear and the intercept is unequal to zero and does not pass through the origin, which indicates that the internal particle diffusion is the only rate determining step, and the adsorption of MO and CR on C@CO are simple process.⁵⁵

3.8. Adsorption thermodynamics.

Due to the impact of temperature on the adsorption of MO and CR by C@Co, the thermodynamic parameters of C@Co, MO, and CR were studied at different temperatures. The values of ΔH and ΔS are calculated according to the slope and intercept of the corresponding van't Hoff plot (Fig. S9).⁵⁶ ΔG is negative, suggesting that the adsorption process is spontaneous (Tables 3 and S4). Additionally, as the temperature is ranged from 298 to 323 K, the ΔG of MO cut down about 2.00 kJ mol⁻¹, while the ΔG of CR reduces from - 5.47 to - 5.99 KJ mol⁻¹, suggesting that a higher temperature is more beneficial for adsorption. Otherwise, the negative value of ΔH (3.87 and 0.79 kJ mol⁻¹) indicated that the interactions between C@Co and MO or CR are endothermic processes. The positive ΔS suggests that the randomness of the system increases as the MO and CR are adsorbed onto C@Co.⁵⁶

Table 3

Thermodynamic arguments at various temperatures.

$T(K)$	$\Delta G(kJ\ mol^{-1})$	$\Delta H(kJ\ mol^{-1})$	$\Delta S(kJ\ mol^{-1}\ K^{-1})$
298	-19.97	3.87	0.08
303	-20.37		
313	-21.17		
323	-21.97		

3.9. Comparison of adsorption efficiencies with other adsorbents.

Table 4 shows the adsorption efficiencies of the C@Co nanocomposite and those of other adsorbents reported in the literatures.⁵⁷⁻⁷² The results demonstrate that the C@Co shows a higher adsorption capacity than the other MOF-based and carbon-based adsorbents. In spite of some adsorbents may have demonstrated competitive adsorption efficiency, their removal conditions such as adsorbent amount are quite high. The enhanced dye adsorption performance of the magnetic C@Co material indicates that it can afford a selective and high-efficient adsorbent for the remove of wastewater. Sum up, the magnetic properties of the C@Co nanocomposite is an excellent adsorbent for wastewater treatment in demanding conditions.

Table 4
Adsorption capacities of different adsorbents for MO.

Absorbent	Adsorption capacity (mg/g)	Ref.
Carbon nanotubes	64.70	57
λ -Fe ₂ O ₃ /MWCNTs/chitosan	66.10	58
QPEI/SiO ₂	105.00	59
Ni-containing ordered mesoporous carbon	107.10	60
Chitin/alginate magnetic nano-gel beads (MCAs)	107.50	61
MIL-101 (Fe)	117.70	62
Acid modified carbon coated monolith	132.70	63
MIL-100(Fe)	145.70	64
Alkali-activated multiwalled carbon nanotubes	149.00	65
carbon nanotubes (CNTs-A)	149.00	65
GO/MIL-101 (Fe)	186.20	63
Calcined layered double hydroxides	200.00	66
Mesoporous carbon CMK-3	294.10	67
Cu@Cu ₂ O	344.80	68
Mesoporous magnetic Co-NPs/carbon nanocomposites	380.00	69
Mesoporous Y-Fe ₂ O ₃ /calcined SiO ₂ nanocomposites	476.00	70
Mn@Si/Al	571.00	71
C@Co	733.33	This work

4. Conclusions

In summary, a magnetic C@Co material was successfully synthesized with the use of Co-MOF as a catalyst precursor via the CVD method. The as-grown C@Co shown a highly selective adsorption capacity toward anionic dyes, and the adsorption capacities were 773.33 mg g⁻¹ and 495.66 mg g⁻¹ for MO and for CR, respectively. Moreover, a viable adsorption mechanism has been proposed, which suggests that non-covalent interaction (hydrogen bonding and π - π stacking interaction) is a key role in the adsorption process. The internal particle diffusion is the only rate determining step which the adsorptions of MO and CR on C@CO are simple processes. Thermodynamic studies suggest that the adsorption processes are

spontaneous and exothermic. The resulting C@Co was discovered to be an efficient adsorbent material for the removal of anionic dyes from aqueous solutions. This research may open up new routes toward.

Declarations

CRedit authorship contribution statement

Yu Liu and Yan Wang–Crystal synthesis, writing-original draft preparation. Xiao-Sa Zhang and Ai-Ai Yang–Formal analysis, investigation; Hong-Zhu Liu and Zhong-Gang Wang–Software; Wen-Ze Li and Jian Luan–Writing-review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

Figure 1

(a and b) SEM images of C@Co; (c and d) TEM images of C@Co.

Figure 2

(a) IR spectrum of C@Co; (b) TGA curve of C@Co; (c) PXRD pattern of simulated and fresh samples of C@Co; (d) Nitrogen adsorption and desorption isotherms of C@Co. The inset shows the pore distributions.

Figure 3

(a-e) UV-vis spectra of MB, RhB, MO, CR, and GV solutions after various adsorption times with Co-MOF; (f) The capacities of MB, RhB, MO, CR, and GV absorbed from aqueous solutions by Co-MOF under similar conditions.

Figure 4

(a–e) UV-vis spectra of MB, RhB, GV, MO, and CR solutions after different adsorption times with C@Co; (f) The amounts of MB, RhB, MO, CR, and GV adsorbed from aqueous solutions by C@Co under similar conditions.

Figure 5

Effect of the temperature on MO adsorbed by C@Co.

Figure 6

Effect of the concentration on MO adsorbed by C@Co.

Figure 7

Adsorption kinetics of MO and CR adsorbed by C@Co: (a and b) Pseudo-first-order models; (c and d) Pseudo-second-order models.

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