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MIL-88B(Fe)-NH₂: an amine-functionalized metal–organic framework for application in a sensitive electrochemical sensor for Cd²⁺, Pb²⁺, and Cu²⁺ ion detection†

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We propose here an electrochemical platform for multi-heavy metal ion detection in water based on MIL-88B(Fe)-NH₂, an amine-functioned metal–organic framework (MOF) for modifying the surface of a glassy carbon electrode (GCE). Herein, MIL-88B(Fe)-NH₂ with abundant functionalized amine groups can play the role of capture sites for the enrichment of metal ions before electrochemical oxidation sensing. MIL-88B(Fe)-NH₂ was synthesized under optimized conditions through a solvothermal method and characterized by X-ray diffraction (XRD), scanning electron microscopy (SEM), transition electron microscopy (TEM), Fourier-transform infrared spectroscopy (FT-IR), cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) techniques. MIL-88B(Fe)-NH₂ was then drop-casted on GCE to electrochemically determine the Cd²⁺, Pb²⁺ and Cu²⁺ ion concentrations by differential pulse voltammetry (DPV). The electrochemical sensor exhibits excellent electrochemical performance toward Cd²⁺, Pb²⁺ and Cu²⁺ ions in the large linear ranges of 0.025–1.000 μM, 0.3–10.0 μM and 0.6–10.0 μM with limits of detection that are 2.0 × 10^{−10} M, 1.92 × 10^{−7} M and 3.81 × 10^{−7} M, respectively. The fabricated sensor also shows high reliability and good selectivity. This MIL-88B(Fe)-NH₂ application strategy is promising for the evaluation of various heavy metal ions in water.

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1. Introduction

Metal–organic framework (MOF) is a unique class of porous materials constituting metal ions (or clusters) and organic ligands that link together *via* coordination bonds. Due to their unique structure, MOFs have high specific porosity and surface area,^{1,2} tunable chemical functionalization, reversible adsorption, and high catalytic ability.³ As a result, MOFs can be applied in various fields, such as gas storage and separation,^{4,5} drug delivery,^{6,7} chemical separation,⁸ catalysis,⁹ cell imaging,¹⁰ and sensing.^{11–13} In terms of the sensing domain, MOFs are considered as a promising material class for the detection of various contaminants, such as organic substances,^{14,15} antibiotics,^{16–19} inorganic and heavy metal ions,²⁰ owing to good physicochemical properties (*e.g.*, large surface area, sensitivity to target ions, and versatile structure). For the synthesis of MOF materials, linear organic linkers, such as terephthalic acid, have been widely used due to their ability to create open framework structures. The presence of functional groups in the organic linkers

leads to changes in the physicochemical behavior of the MOFs products, including the Brønsted/Lewis acid/base properties, the solubility of the starting materials, and the changes in the pore opening (flexibility) and in the adsorption selectivity to targets.^{21–23} On the organic linker molecule, the amino groups (–NH₂) have lone pair electrons and act as the Lewis base. They can form coordinate bonds with the heavy metal ions. Thus, using NH₂-functionalized MOFs as sensors to detect heavy metals is significant. In this study, we chose 2-aminoterephthalic acid (H₂N-BDC), which is the one of the simplest amino diacids as an organic linker for the synthesis of MIL-88B(Fe)-NH₂ (MIL: Materials of Institute Lavoisier), a common MOF whose structure is built up by Fe³⁺ clusters and 2-aminoterephthalate anionic ligands.²⁴ The outstanding advantages of MIL-88B(Fe)-NH₂ compared to other MOFs are its chemical stability, less toxicity, and abundant raw sources. Thus, it attracts considerable research in different applications including adsorption, sodium-ion batteries, and heterogeneous catalysis.^{25–29} However, the use of MIL-88B(Fe)-NH₂ in the fabrication of electrochemical sensors for the detection of heavy metal ions is a relatively new issue that requires further investigation.

Nowadays, the term “heavy metal” has been utilized to describe metallic elements that are harmful to the environment and humans. In recent decades, heavy metal pollution has

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become increasingly serious due to global population growth and industrial development. Transportation, farming activities, and industrial manufacturing like pesticides, metallurgy, oil refining, and chemicals have released an excessive amount of heavy metal (ions) into the environment. These contaminants cannot be degraded or demolished, leading to accumulation in the environment and the consequent contamination of food chains—a severe threat to human health and species. For instance, people who consume large quantities or get regularly exposed to cadmium (Cd) have a higher rate of prostate and lung cancers than others.³⁰ Furthermore, lead (Pb) is harmful to the digestive, cardiovascular, nervous, and kidney systems.³¹ Another example is copper (Cu), an essential trace metal for some biological functions. However, at elevated concentrations, it can destroy many red blood cells, or result in neurological symptoms, including behavioral abnormalities, tremors of the hands, unclear speech, and others.³² Thus, examining the concentration of the heavy metal (ions) is urgent and essential.

Among many methods used to detect heavy metal ions in the water environment, MOF-based sensors show great potential for application in practice by the possibility to build portable instruments, its high sensitivity, and the ability obtain quick results.²⁰ MOF-based sensors for heavy metal ion sensing are classified into optical sensors^{33,34} and electrochemical sensors.^{20,35–40} Furthermore, electrochemical sensors with its many advantages, such as high sensitivity and selectivity, wide linear response range, good stability and reproducibility, quick detection, ease of use, and reasonable cost, have many potential applications for the monitoring of heavy metal ions.^{20,36}

In this work, the metal–organic framework MIL-88B(Fe)-NH₂ was synthesized. The specific characteristics of the obtained MIL-88B(Fe)-NH₂ samples were investigated using a number of chemical-physical techniques in order to select the optimized synthesis conditions. Then, the MIL-88B(Fe)-NH₂ material was used to modify the glassy carbon electrode (GCE) to develop the sensitive electrochemical sensor for the detection of Cd²⁺, Pb²⁺, and Cu²⁺ ions in aqueous solutions.

2. Experimental

2.1. Chemicals and instrumentation

2-Aminoterephthalic acid H₂N-C₆H₃-1,4-(COOH)₂ (NH₂-TPA) (99 wt%), iron(III) chloride hexahydrate FeCl₃·6H₂O (99 wt%), methanol CH₃OH (MeOH) (anhydrous, 99.8 v/v%), sodium acetate CH₃COONa (99 wt%), acetic acid CH₃COOH (99.5 wt%), cadmium nitrate tetrahydrate Cd(NO₃)₂·4H₂O (99 wt%), lead nitrate Pb(NO₃)₂ (99 wt%), and copper sulfate pentahydrate CuSO₄·5H₂O (99 wt%) were purchased from Sigma-Aldrich. Cobalt sulphate heptahydrate (CoSO₄·7H₂O 99.5 wt%), nickel sulphate hexahydrate (NiSO₄·6H₂O 98.5 wt%), potassium dichromate (K₂Cr₂O₇ 99.8 wt%), and zinc chloride (ZnCl₂ 98 wt%) were supplied by Xilong Chemical Co., China. The appropriate amounts of sodium acetate and acetic acid were used to prepare acetate buffer solution 0.1 M (ABS) with pH 6.0. Dimethylformamide C₃H₇NO (DMF) (99.94 v/v%) was purchased from Fisher Chemical. Polyethylene glycol 2000 (H(OCH₂CH₂)_nOH, PEG 2000) was supplied by Alfa Aesar.

A Siemens D5005 diffractometer (Cu K_α radiation, λ = 1.54056 Å), a NICOLET iS50FT-IR spectrometer, a Hitachi S4800 scanning electron microscope (SEM), and a TECNAI F20-G2 high-resolution transmission electron microscope (TEM) were used to perform X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FT-IR), SEM, and TEM measurements, respectively. Electrochemical measurements were conducted using a PGSTAT302N AutoLab electrochemical workstation (Metrohm, Netherlands).

2.2. Optimization of the synthetic conditions of MIL-88B(Fe)-NH₂

Fig. 1 shows a typical process for the synthesis of MIL-88B(Fe)-NH₂ by the solvothermal method. To investigate the impact of the molar ratio between the metal ion and the ligand on the formation of MIL-88B(Fe)-NH₂, 1.15 mmol FeCl₃ and 1.15x (mmol) H₂N-C₆H₃-1,4-(COOH)₂ (wherein, x = 1.0; 1.2; 1.5 and 2.0, respectively) were mixed into 25 mL of DMF solvent using a magnetic stirrer until homogeneous solutions were obtained. The solutions were added into autoclaves, and then the reactions were performed hydrothermally at 150 °C. The obtained powder products were separately washed by DMF, methanol and distilled water, and were subsequently dispersed into distilled water overnight. The MIL-88B(Fe)-NH₂(x) materials were obtained by centrifuging and vacuum-drying at 170 °C within 12 hours. The same experiments were carried out to study the effect of the hydrothermal time on the crystalline phase formation of MIL-88B(Fe)-NH₂ at different periods, including 8, 12, 18, and 24 hours.

2.3. MIL-88B(Fe)-NH₂ modification of a glassy carbon electrode

Firstly, glassy carbon electrodes (GCE) were polished by 1 μm Al₂O₃ slurry on polishing cloth, and then washed with water and ethanol. A total of 3.0 mg of MIL-88B(Fe)-NH₂ and 3.0 mg of PEG-2000 were dispersed into 1 mL of deionized water using ultrasonication for 10 minutes. Then, 5 μL of this solution was dropped onto a freshly polished GCE, and dried in air to obtain the MIL-88B(Fe)-NH₂ modified GCE (GCE/MIL-88B(Fe)-NH₂).

2.4. Electrochemical measurements and electrochemical sensing of Cd²⁺, Pb²⁺, and Cu²⁺ ions

The three-electrode configuration consists of the GCE/MIL-88B(Fe)-NH₂ as the working electrode (WE), a Pt wire as the counter electrode (CE), and Ag/AgCl as the reference electrode (RE). Cyclic voltammetry (CV) and electrochemical impedance spectroscopy (EIS) measurements of the GCE and the GCE/MOFs in a solution containing 0.005 M K₃[Fe(CN)₆], 0.005 M K₄[Fe(CN)₆], and 0.1 M KCl were performed. CVs were studied at a scan rate of 25 mV s⁻¹. EIS spectra were recorded in a frequency range from 100 kHz to 0.1 Hz, E_{AC} = 5 mV, and E_{DC} = 160 mV. The fabricated GCE/MOFs sensor was used to detect cadmium, lead and copper ions (in ABS) using DPV measurements with a deposition potential of -1.2 V, a deposition time of 120 seconds, a pulse amplitude of 50 mV, a pulse width of 50



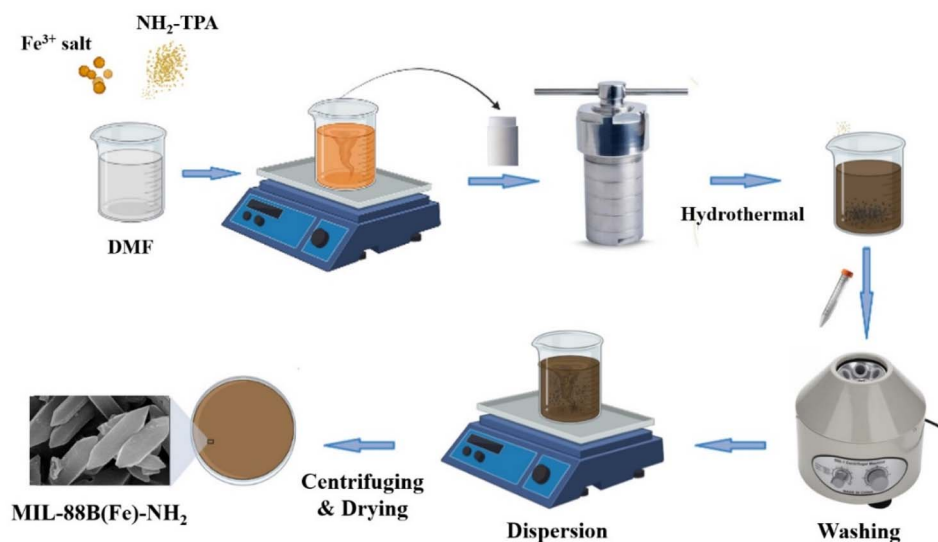


Fig. 1 Depiction of the MIL-88B(Fe)-NH₂ synthesis.

ms, a desorption potential of 0.4 V, and a desorption time of 60 seconds.

3. Results and discussion

3.1. Characterization of MIL-88B(Fe)-NH₂

3.1.1 X-ray diffraction (XRD) patterns. XRD patterns of the obtained MIL-88B(Fe)-NH₂ with the various x values (herein, x is the molar ratios of H₂N-C₆H₃-1,4-(COOH)₂/Fe(III) ions) are displayed in Fig. 2A. In particular, when $x = 1.0$ (line a) and 1.2 (line b), the formation of the MIL-88B(Fe)-NH₂ phase is observed, which are characterized by $2\theta \approx 9.3^\circ$ and 10.6° , corresponding to the (002) and (101) lattice faces, respectively (CCDC 647646). However, the γ -Fe₂O₃ crystalline phase also appears at $2\theta \approx 25.0^\circ$ and 29.0° (JCPDS 39-1346), which is caused by a residual amount of Fe(III) ions. At higher proportions with $x = 1.5$ (line c) and $x = 2.0$ (line d), the XRD pattern only shows the typical peaks of the MIL-88B(Fe)-NH₂ crystal. These characteristic peaks are very clear and sharp, indicating that the MIL-88B(Fe)-NH₂ crystals are completely formed. The average crystal size of the MIL-88B(Fe)-NH₂ is calculated by Scherrer formula for the lattice of (101):

$$D = \frac{0.9\lambda}{\beta_{hkl}\cos\theta} \quad (1)$$

where D is the average particle size in nm, k is the constant depending on the crystallite shape (0.9), λ is the wavelength of the copper K _{α} X-ray radiation, β is the FWHM of the most intense peak (in rad), and θ is the diffraction angle. The average crystallite size can be estimated around 22.8 and 23.3 nm for MIL-88B(Fe)-NH₂($x = 1.5$) and MIL-88B(Fe)-NH₂($x = 2.0$) samples, respectively. Fig. 2B manifests the XRD patterns of the MIL-88B(Fe)-NH₂(1.5) material at the different hydrothermal periods. The sample that performed for 8 hours forms the material phase, but the diffraction peaks of γ -Fe₂O₃ still exist. With the periods of 12, 18 and 24 hours, the characteristic peaks

of MIL-88B(Fe)-NH₂ appear and do not have any peaks of other materials, proving the purified phase of the MIL-88B(Fe)-NH₂. The calculated crystallinities of the materials are 86.80, 79.97 and 70.28% for the 12, 18 and 24 hours samples, respectively. It can be seen that increasing the reaction time causes a detrimental effect on the material's crystallinity. Recrystallization occurs under high temperature and pressure conditions, leading to the crystallinity reduction.⁴¹ Similar degradation phenomena have been observed in several other MOFs.^{42,43} Based on these findings, the MIL-88B(Fe)-NH₂ sample synthesized at $x = 1.5$ and hydrothermal treatment for 12 hours was selected for further investigations of the electrochemical behaviors and applications for electrochemical sensor developments.

3.1.2 FT-IR spectra. Fig. 2C shows the FT-IR spectra of the TPA-NH₂ ligand (curve a), MIL-88B(Fe)-NH₂(1.5) (curve b) and MIL-88B(Fe)-NH₂(2.0) (curve c). Namely, a peak appears at 3454 cm^{-1} owing to the stretching oscillation of the N-H bonds. The peaks at 1578 cm^{-1} and 1379 cm^{-1} are attributed to the presence of the C-O asymmetric and symmetric stretching oscillations, respectively. Another peak obtained at 1620 cm^{-1} represents a carbonyl group (C=O), but the peak is not clear due to the strong intensity of the C-O peak. The peaks at 1254 cm^{-1} and 769 cm^{-1} correspond to the bending vibration of the C sp²-N and C sp²-H bonds, respectively. The above features are observed in the spectra of the TPA-NH₂ ligand and synthesized materials. Specially, the characteristic peak at 554 cm^{-1} (FeO) appears in the MOFs patterns, which represents the coordination bond between Fe³⁺ and the ligand. As such, FT-IR spectroscopy contributes to confirming the formation of the bond between Fe(III) and the ligand *via* the oxygen atom in the synthesized MOFs.

3.1.3 BET analysis. The evaluated BET surface area of the synthesized MIL-88B(Fe)-NH₂(1.5) is $13.43\text{ m}^2\text{ g}^{-1}$. This value is consistent with previous studies (Table 1),⁴⁴⁻⁴⁶ and the BET area of MIL-88B(Fe)-NH₂(1.5) is still higher than that of other



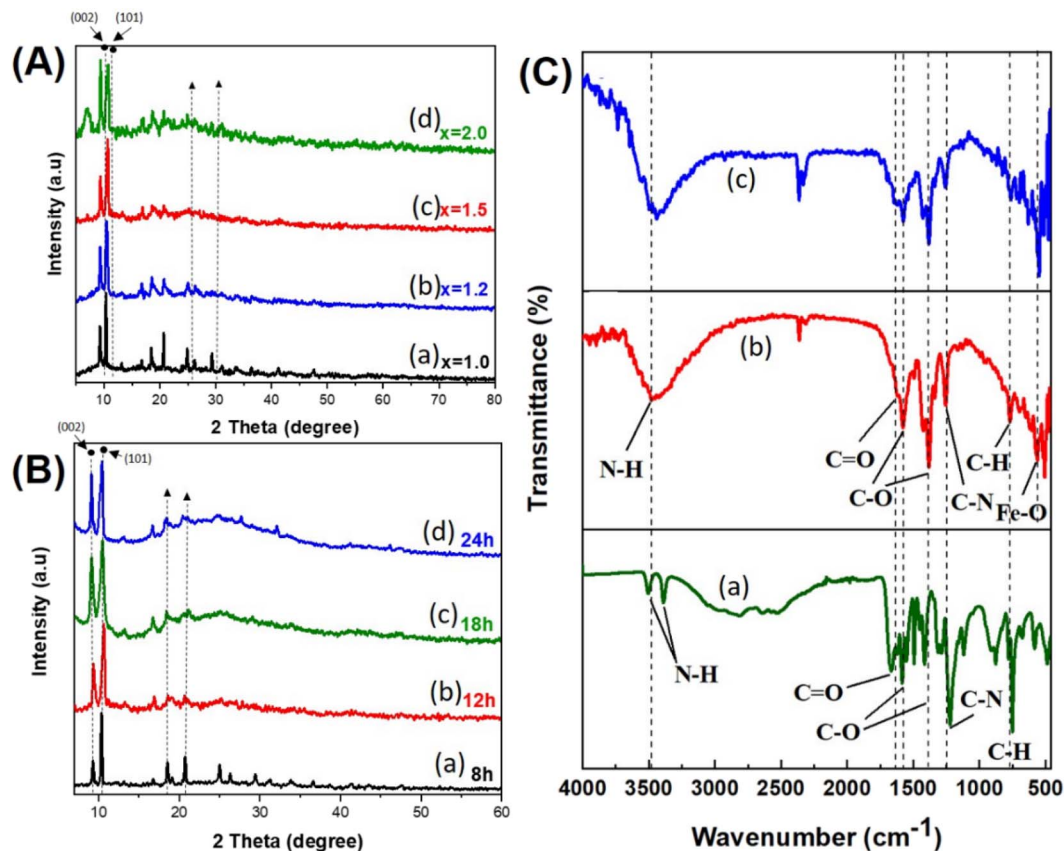


Fig. 2 (A and B) XRD patterns of the synthesized MIL-88B(Fe)-NH₂ materials (A) with different molar ratios of H₂N-C₆H₄-1,4-(COOH)₂/Fe^{III}; (B) at different hydrothermal temperatures; and (C) FT-IR spectra of (a) TPA-NH₂, (b) MIL-88B(Fe)-NH₂(1.5) and (c) MIL-88B(Fe)-NH₂(2.0).

Table 1 Specific surface area of some MIL-88BNH₂

Materials	S_{BET} (m ² g ⁻¹)	References
MIL-88B(Fe)-NH ₂	19.2	44
MIL-88B(Fe)-NH ₂	2.35	45
MIL-88B(Fe)-NH ₂	8.9	46
MIL-88B(Fe)-NH ₂	13.43	This study

reported MIL-88B(Fe)-NH₂ and Fe-MOFs materials.^{45–47} The causes can be attributed to the synthesis method and more importantly, to the closed microporous structures of MIL-88B(Fe)-NH₂. Furthermore, some Fe-MOFs are not sensitive to nitrogen gas because the nitrogen molecule's size and the pore's size of these MOFs materials are comparable.^{44–48}

3.1.4 SEM and TEM images. The MIL-88B(Fe)-NH₂ morphologies at the ratios of 1.5 and 2.0 were characterized by SEM and TEM, as shown in Fig. 3. The SEM images exhibit a uniform distribution of the material particles, whose size distribution and average size were calculated using ImageJ software. The mean widths of MIL-88B(Fe)-NH₂(1.5) and MIL-88B(Fe)-NH₂(2.0) are 414.3 and 377.5 nm, respectively; corresponding to the mean length/width ratio of 3.97 and 3.81 (inserted figures in Fig. 3D and H, respectively; and Table S1†). Although the size tends to decrease with increasing molar ratio, no morphological change is observed. This is also clearly shown

in the TEM images (Fig. 3C–F), where the particle sharpness at the two ratios is similar.

3.2. Electrochemical characteristics of the fabricated MIL-88B(Fe)-NH₂

Fig. 4 gives the CV (Fig. 4A) curves and the EIS spectra (Fig. 4B) recorded in a solution containing 0.005 M K₃Fe(CN)₆, 0.005 M K₄Fe(CN)₆, and 0.1 M KCl of the GCE (curve a) and the GCE/MIL-88B(Fe)-NH₂ (curve b), respectively. It can be seen in Fig. 4A that in the case of the GCE/MIL-88B(Fe)-NH₂ (curve b), the anodic and cathodic peak currents are higher than that of the GCE (curve a), indicating an increase in the electroactive area due to the modification of the GCE with MIL-88B(Fe)-NH₂. As shown in Fig. 4B, the EIS spectra of the two electrodes have a semicircle characterizing a charge transfer process and a linear region characterizing a diffusion process. An equivalent circuit (Fig. 4B, inset), which includes a solution resistance (R_s), a charge transfer resistance (R_{ct}), a constant phase element (Q_{CPE}), and a Warburg diffusion coefficient (W), can be used to simulate the EIS spectra, and the corresponding fitted plots are shown in Fig. 4B (curve (a') and curve (b')). The fitted R_{ct} results of the GCE and the GCE/MIL-88B(Fe)-NH₂ are 4377 Ω and 3440 Ω, respectively. Thus, the electrochemical performances demonstrate that the MIL-88B(Fe)-NH₂ layer drop-casted on GCE is able to remarkably enhance the electrochemical signal of GCE/MIL-88B(Fe)-NH₂.



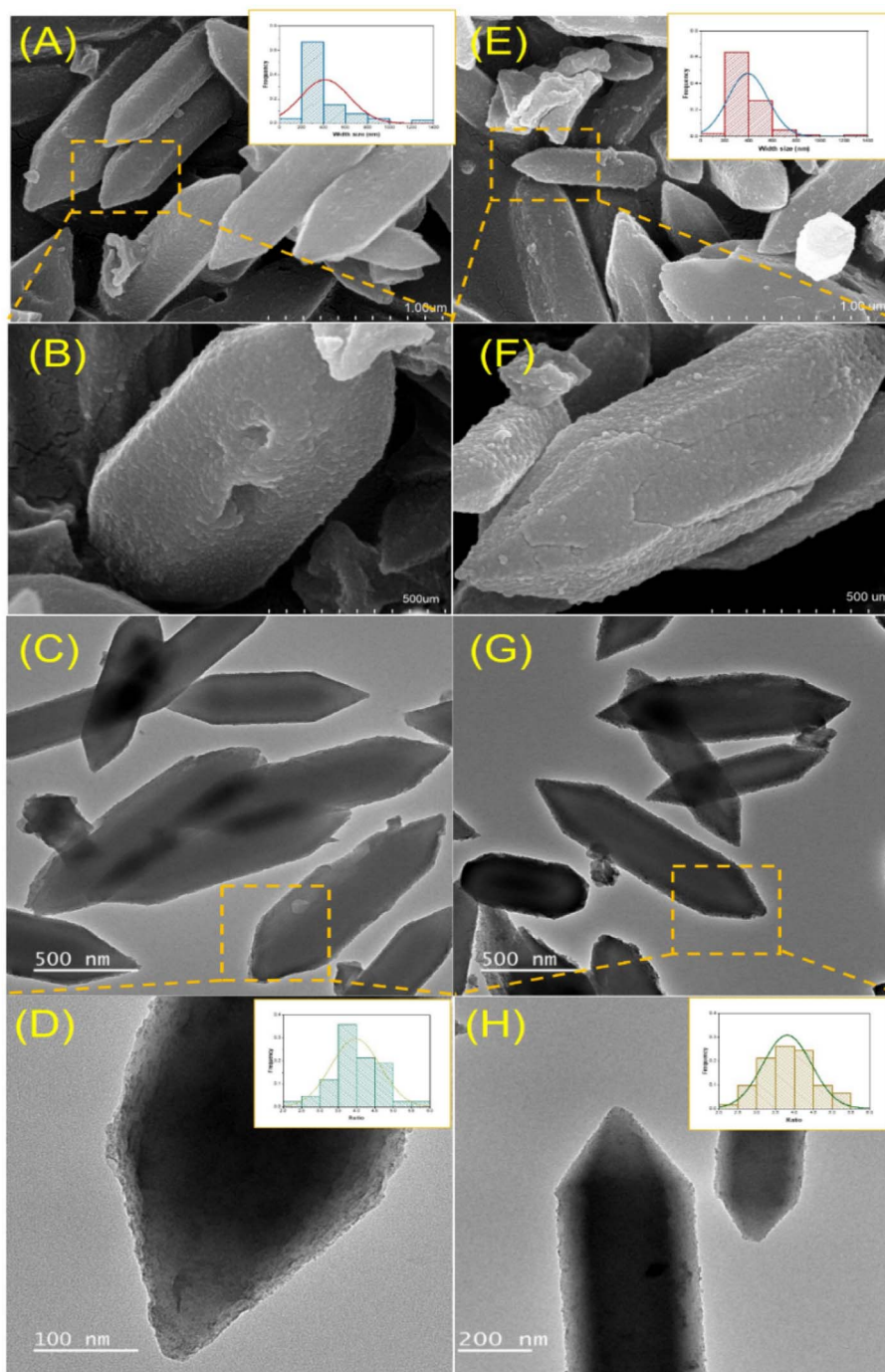


Fig. 3 (A–D) SEM and (E–H) TEM images of (A–D) MIL-88B(Fe)-NH₂(1.5), (E–H) MIL-88B(Fe)-NH₂(2.0). Inserted figures: (A and E) the width size distribution and (D and H) the ratio of the length to the width of (A and D) MIL-88B(Fe)-NH₂(1.5) and (E and H) MIL-88B(Fe)-NH₂(2.0).

3.3. Electrochemical detection of Cd²⁺, Pb²⁺, and Cu²⁺ ions using GCE/MIL-88B(Fe)-NH₂

DPV measurements of the GCE and the GCE/MIL-88B(Fe)-NH₂ were performed in a solution containing 20 μM Cd²⁺, 20 μM Pb²⁺, 20 μM Cu²⁺ and 0.1 M ABS (pH = 6.0), in order to investigate the ability of using the GCE/MIL-88B(Fe)-NH₂ as an electrochemical sensor for the detection of Cd²⁺, Pb²⁺, and Cu²⁺ ions in aqueous solutions, and the obtained results are

described in Fig. 5. It can be clearly seen in Fig. 5 (curve a) that with regards to GCE, there are no peaks. In contrast, in Fig. 5 (curve b), with regards to GCE/MIL-88B(Fe)-NH₂, there are three peaks at -0.79 V, -0.52 V, and -0.02 V, which are associated with the presence of Cd²⁺, Pb²⁺, and Cu²⁺ ions, respectively.⁴⁹ The results indicate that the GCE modified with MIL-88B(Fe)-NH₂ can be used as an electrochemical sensor for the determination of Cd²⁺, Pb²⁺, and Cu²⁺ ions in aqueous solutions.



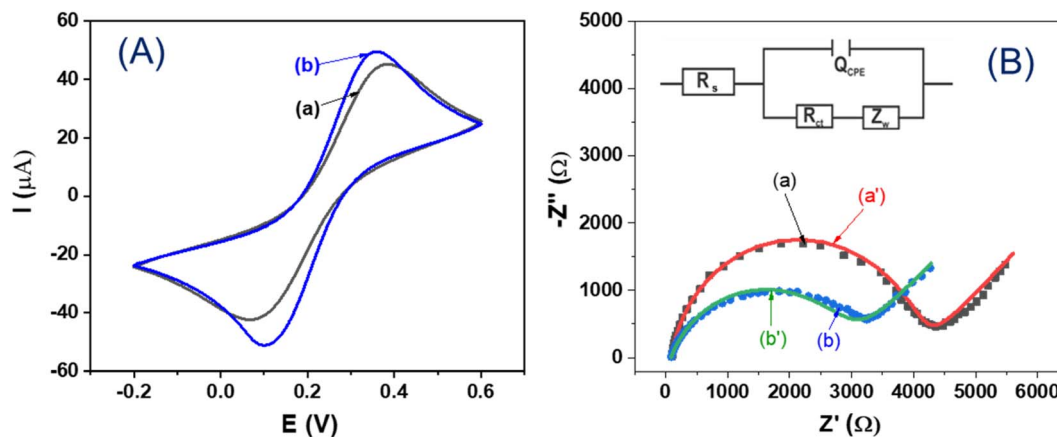


Fig. 4 (A) CV scans and (B) EIS spectra (Nyquist plots) of (a) GCE and (b) GCE/MIL-88B(Fe)-NH₂; (inserted figure in (B): Randles equivalent circuit; (a') and (b'): corresponding fitted plots). Experimental conditions: 0.1 M KCl solution containing K₃Fe(CN)₆/K₄Fe(CN)₆ (0.005 M) as the electrolyte. CVs were measured at a scan rate of 25 mV s⁻¹. EIS spectra were recorded with a frequency range from 100 kHz to 0.1 Hz, E_{AC} = 5 mV, and E_{DC} = 160 mV.

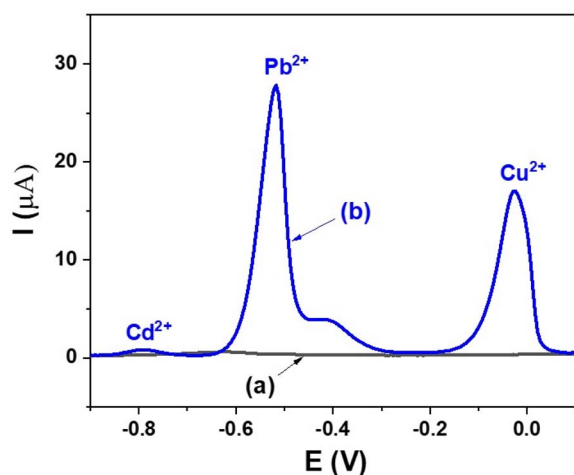


Fig. 5 DPV results of (a) GCE and (b) GCE/MIL-88B(Fe)-NH₂ measured in a solution containing 20 μM Cd²⁺, 20 μM Pb²⁺, 20 μM Cu²⁺ and 0.1 M ABS (pH = 6.0).

DPV measurements of the GCE/MIL-88B(Fe)-NH₂ electrodes were performed in 0.1 M ABS (pH = 6.0) solutions containing 10 μM Cd²⁺, 10 μM Pb²⁺, and 10 μM Cu²⁺ with differential measuring conditions, including potential step, pulse width, and pulse amplitude, in order to investigate the optimization studies for DPV, and the obtained results are described in Fig. 1S (A, B, and C, respectively).[†] As can be seen in Fig. 1S(A, B, and C),[†] when the potential step is 5 mV, the pulse width is 50 ms, and the pulse amplitude is 50 mV, the obtained DPV signal is the best for Cd²⁺, Pb²⁺, and Cu²⁺. Therefore, in this work, these measuring conditions were selected for DPV measurements.

Fig. 6A provides the DPV results of the GCE/MIL-88B(Fe)-NH₂ electrodes, which were measured in solutions with different Cd²⁺ concentrations ranging from 25 nM to 1 μM. It can be observed from Fig. 6A that the peak current of the sensor

increases when the Cd²⁺ concentration increases. Especially, the electrochemical signal is clearly observed even at a low Cd²⁺ concentration (25 nM). The increase in the Cd²⁺ concentration leads to an increase in the amount of Cd²⁺ ions accumulated on the electrode surface and an increase in the peak current. Fig. 6B gives a linear relationship between the peak current (*I*_{peak}) and the Cd²⁺ concentration (*C*_{Cd}²⁺) in the range from 25 nM to 1 μM, which is *I*_{peak} (μA) = 0.0492 + 0.4492 × *C*_{Cd}²⁺ (μM) with a correlation coefficient of *R*² = 0.9807. Similarly, Fig. 6C shows DPV results performed in solutions with different Pb²⁺ concentrations ranging from 0.3 μM to 10 μM of the GCE/MIL-88B(Fe)-NH₂ electrodes. Fig. 6D depicts a linear relationship between the peak current (*I*_{peak}) and the Pb²⁺ concentration (*C*_{Pb}²⁺) in the above range, which is *I*_{peak} (μA) = -0.0631 + 2.5642 × *C*_{Pb}²⁺ (μM) with a correlation coefficient of *R*² = 0.9917. Next, DPV results conducted in solutions with different Cu²⁺ concentrations ranging from 0.6 μM to 10 μM of the GCE/MIL-88B(Fe)-NH₂ electrodes are shown in Fig. 6E. A linear relationship between the peak current (*I*_{peak}) and the Cu²⁺ concentration (*C*_{Cu}²⁺) in the above range, which is *I*_{peak} (μA) = -0.3810 + 1.0005 × *C*_{Cu}²⁺ (μM) with a correlation coefficient of *R*² = 0.9871, is given in Fig. 6F. The detection limit (LoD) of the developed electrochemical sensor for the Cd²⁺, Pb²⁺ and Cu²⁺ ion detections were estimated at S/N > 3.^{58,59} The obtained results revealed that using the GCE/MIL-88B(Fe)-NH₂ electrochemical sensors, the LoD can be obtained at 2.0 × 10⁻¹⁰ M for Cd²⁺, 1.92 × 10⁻⁷ M for Pb²⁺ and 3.81 × 10⁻⁷ M for Cu²⁺, respectively.

DPV results of the GCE/MIL-88B(Fe)-NH₂ electrode in solutions with simultaneous increments in all three ion concentrations (Cd²⁺, Pb²⁺, Cu²⁺: from 2 μM to 10 μM) and their corresponding calibration plots are shown in Fig. 7A and B, respectively. These obtained results indicate that the fabricated sensor has a high reliability of developed chemical sensor. Moreover, the DPV results of the GCE/MIL-88B(Fe)-NH₂ electrodes in different solutions containing 5 μM Cd²⁺ + 5 μM Cu²⁺, and Pb²⁺ with concentrations increasing from 2 μM to 10 μM, and the corresponding calibration plot of Pb²⁺ are depicted in



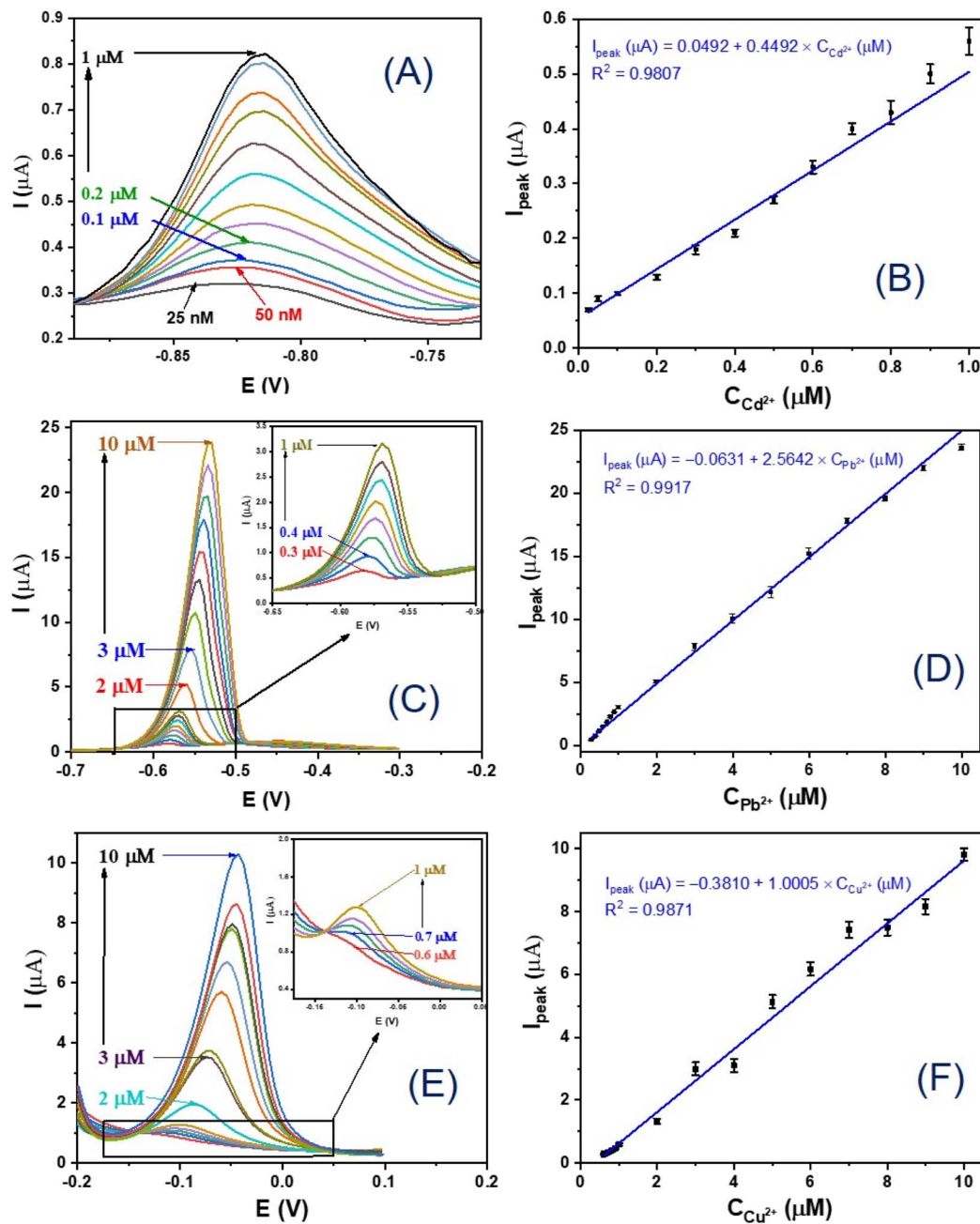


Fig. 6 (A, C and E) DPV results of GCE/MIL-88B(Fe)-NH₂ electrodes in 0.1 M ABS (pH = 6.0) solutions containing different concentrations of (A) Cd²⁺ (from 25 nM to 1 μM), (C) Pb²⁺ (from 0.3 μM to 10 μM) and (E) Cu²⁺ (from 0.6 μM to 10 μM); (B, D and F) The linear calibration curves exhibiting the relationship between the output signal of the electrochemical sensor and the concentration for (B) Cd²⁺, (D) Pb²⁺, and (F) Cu²⁺ ions, respectively.

Fig. 7C and D, in the order. Similarly, the DPV responses of the GCE/MIL-88B(Fe)-NH₂ electrodes in different solutions containing 5 μM Pb²⁺ + 5 μM Cu²⁺, and Cd²⁺ with concentrations increasing from 2 μM to 10 μM, and the corresponding calibration plot of Cd²⁺ are exhibited in Fig. 2SA and B,† respectively. The DPV signals shown in Fig. 7C, D, 2SA and B† clearly demonstrate the ability of the obtained sensor to detect the ions in the desired ranges of detection. However, a point which is different from the single metal ion detection (Fig. 6A, C and E) is that a satellite peak appears on the right side of Pb²⁺ when three

heavy metal ions are simultaneously detected (Fig. 7A and C). This satellite peak was demonstrated to be involved in the Pb–Cu interaction.^{60,61} Moreover, the DPV results of GCE/MIL-88B(Fe)-NH₂ electrodes in solutions containing 10 μM Cd²⁺, 10 μM Pb²⁺, 10 μM Cu²⁺, without and with other interfering ions, including Co²⁺, Ni²⁺, Zn²⁺, Cr₂O₇²⁻ (10 μM), and K⁺, Cl⁻ (20 μM), which are provided in Fig. 8 (curve a and curve b, respectively), show that our electrochemical sensor has good selectivity.

When the fabricated sensor is used to detect the three heavy metal ions using the DPV method, firstly, Cd²⁺, Pb²⁺ and Cu²⁺



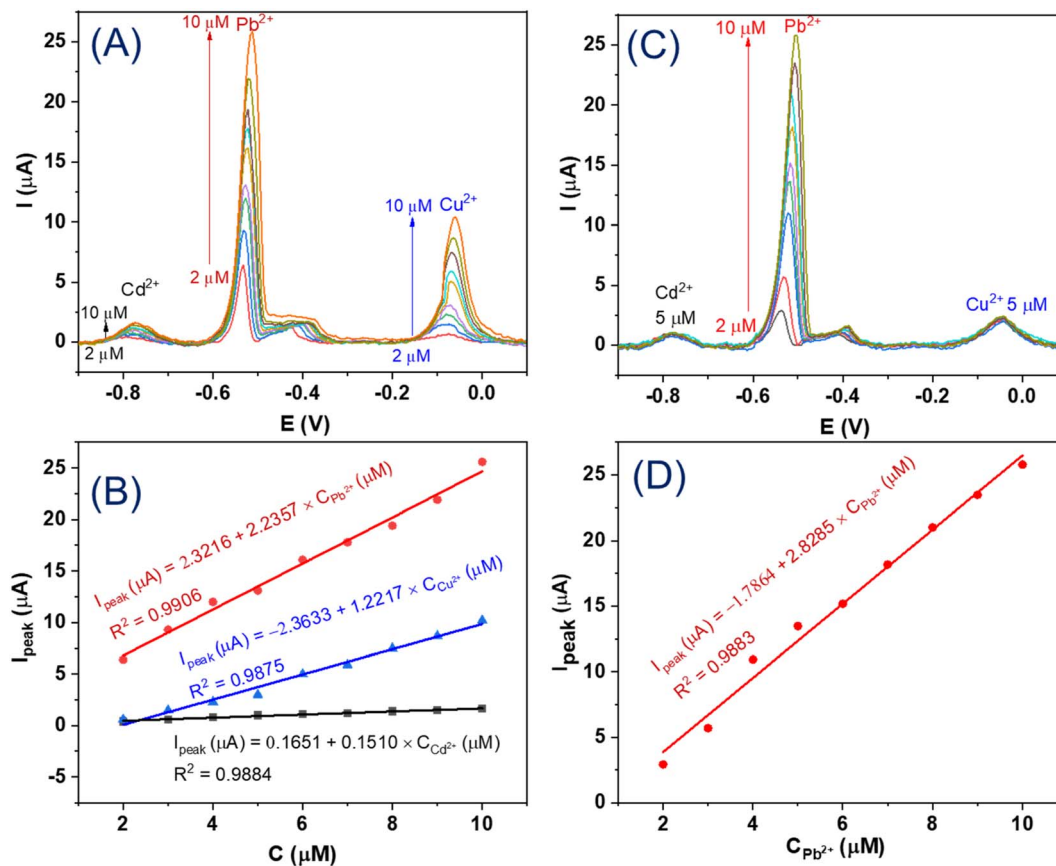


Fig. 7 (A) DPV response of the GCE/MIL-88B(Fe)-NH₂ electrode in 0.1 M ABS (pH = 6.0) solutions with simultaneous increments in all three ion concentrations (Cd²⁺, Pb²⁺, Cu²⁺: from 2 μM to 10 μM), and (B) their corresponding calibration plots; (C) DPV results of GCE/MIL-88B(Fe)-NH₂ electrodes in 0.1 M ABS (pH = 6.0) solutions containing 5 μM Cd²⁺, 5 μM Cu²⁺, and Pb²⁺ with concentrations increasing from 2 μM to 10 μM, and (D) the linear relationship between the output signal of the sensor and the concentration of Pb²⁺.

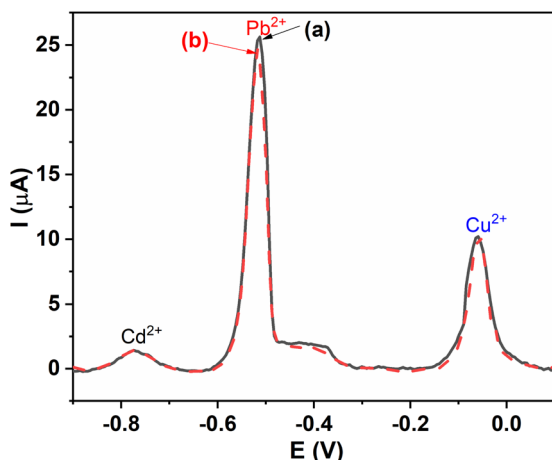


Fig. 8 DPV response of the GCE/MIL-88B(Fe)-NH₂ electrode in 0.1 M ABS (pH = 6.0) solutions containing 10 μM Cd²⁺, 10 μM Pb²⁺, 10 μM Cu²⁺, (a) without (a black, solid line), and (b) with other interfering ions, including Co²⁺, Ni²⁺, Zn²⁺, Cr₂O₇²⁻: 10 μM, and K⁺, Cl⁻: 20 μM (a red, dashed line, each 40 μL of 5 mM solutions: CoSO₄, NiSO₄, ZnCl₂, and K₂Cr₂O₇ is added to the measuring system containing 20 mL of 0.1 M ABS (pH = 6.0) + 10 μM Cd²⁺ + 10 μM Pb²⁺ + 10 μM Cu²⁺).

ions are adsorbed on the electrode surface and are reduced to form Cd, Pb, and Cu metals, respectively, during the deposition process with a constant negative potential applied (−1.2 V, 120 seconds, in this work); then, through the positive scan from a lower potential to a higher potential (from −0.9 to 0.1 V, in this study), these metals are oxidized, and the peak currents corresponding to their oxidation are recorded. The increase in the concentration of the heavy metal ions leads to the increase in the amount of the heavy metal ions adsorbed on the electrode surface, and the increase in the peak currents recorded after DPV measurements. The MIL-88B(Fe)-NH₂ layer with a large surface area has good adsorption capacity for Cd²⁺, Pb²⁺, and Cu²⁺ ions, so ion enrichments on the electrode surface are enhanced, and these ions can still be detected despite the low concentrations. Moreover, the electrocatalytic activity of the MIL-88B(Fe)-NH₂ material for the reduction of the metal ions is also an important reason for increasing the electrochemical signals. However, the adsorption capacity and electrocatalytic activity of MIL-88B(Fe)-NH₂ are different for different heavy metal ions, leading to the different limits of detection (2.0×10^{-10} M for Cd²⁺, 1.92×10^{-7} M for Pb²⁺ and 3.81×10^{-7} M for Cu²⁺, in this work). Moreover, an interesting characteristic is that Cd, Pb, and Cu metals are oxidized at the different



Table 2 Comparison of sensitivities and LODs of electrochemical sensors based on different materials for the detection of Cd²⁺, Pb²⁺, and Cu²⁺ ions

Electrode	Detection	Linear range (μM)	LOD (M)	Reference
GCE/NH ₂ -Fe ₃ O ₄ @C	Cd ²⁺	0.6–9.0	2.31 × 10 ⁻⁸	50
	Pb ²⁺	1.2–10.0	2.85 × 10 ⁻⁸	
	Cu ²⁺	0.4–4.0	3.84 × 10 ⁻⁸	
GCE/MIL-53(Fe)	Cd ²⁺	0.15–0.45	1.6 × 10 ⁻⁸	20
GCE/MIL-100(Cr)	Cd ²⁺	0–10	4.4 × 10 ⁻⁸	51
	Pb ²⁺	0–10	4.8 × 10 ⁻⁸	
	Cu ²⁺	0–10	1.1 × 10 ⁻⁸	
GCE/Fe-OSA	Cd ²⁺	0.02–10.71	1.92 × 10 ⁻⁸	52
	Pb ²⁺	0.04–13.40	3.6 × 10 ⁻⁸	
	Cu ²⁺	0.15–15.45	8.78 × 10 ⁻⁸	
GCE/BiONPs	Cd ²⁺	0.8–5.6	5 × 10 ⁻⁸	53
	Pb ²⁺	0.4–2.8	1.5 × 10 ⁻⁷	
GCE/Pd/PAC	Cd ²⁺	0.5–12.8	3.8 × 10 ⁻⁸	54
	Pb ²⁺	0.5–22.4	2.5 × 10 ⁻⁸	
	Cu ²⁺	0.5–11.8	1.3 × 10 ⁻⁷	
GCE/CuNPs/rGO	Cd ²⁺	0.05–2.00	2.03 × 10 ⁻⁷	55
	Pb ²⁺	0.05–3.00	1.86 × 10 ⁻⁷	
	Cu ²⁺	0.05–2.50	1.11 × 10 ⁻⁷	
GCE/Chitosan	Cd ²⁺	15.9–62.3	2.35 × 10 ⁻⁶	56
	Pb ²⁺	1.99–15.80	3.09 × 10 ⁻⁷	
	Cu ²⁺	3.99–39.10	8.99 × 10 ⁻⁷	
GCE/Ni-MOF	Pb ²⁺	0.5–6.0	5.08 × 10 ⁻⁷	57
GCE/MIL-88B(Fe)-NH ₂	Cd ²⁺	0.025–1.000	2.0 × 10 ⁻¹⁰	This study
	Pb ²⁺	0.3–10.0	1.92 × 10 ⁻⁷	
	Cu ²⁺	0.6–10.0	3.81 × 10 ⁻⁷	

potentials which characterize them (−0.79 V for Cd, −0.52 V for Pb, and −0.02 V for Cu, in our work). Therefore, the designed electrochemical sensor can be used to simultaneously detect the three heavy metal ions with high selectivity using DPV method.

As shown in Table 2, the fabricated GCE/MIL-88B(Fe)-NH₂ electrochemical sensor in this work is comparable to others summarized in previous works. In general, the MIL-88B(Fe)-NH₂-modified GCE possesses high sensitivity (especially in terms of Cd²⁺ detection), high reliability, and good selectivity. MIL-88B(Fe)-NH₂ is a promising MOF in the field of electrochemical sensors for detecting heavy metal ions, such as Cd²⁺, Pb²⁺, Cu²⁺, and others.

4. Conclusion

The metal–organic framework MIL-88B(Fe)-NH₂ was synthesized *via* solvothermal method, and characterized by XRD, SEM, TEM, and FT-IR measurements. The impact of parameters on the material formation, including the molar ratio of H₂NC₆H₃-1,4-(COOH)₂/Fe(III) and the time reaction, was investigated in detail. Under the optimized experimental conditions, the sharpness and uniformity of the MIL-88B(Fe)-NH₂ crystals were obtained. The electrochemical sensor relying on the as-synthesized MIL-88B(Fe)-NH₂ indicates the brilliant result for the determination of Cd²⁺, Pb²⁺ and Cu²⁺ with the low limit of detection, the wide linear detection range of concentrations, the high reliability, and the good selectivity. In addition, the fabrication method is simple and it can be extended for screen printing method for electrochemical sensor application in the disposal of heavy metal ions. Combining these above outcomes

imply that MIL-88B(Fe)-NH₂ is capable of becoming a potential candidate applied as an electrochemical sensor for the detection of heavy metal ions in practice.

Conflicts of interest

There are no conflicts to declare.

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