# Supporting Information

## $MnFe_2O_4$-loaded bamboo pulp carbon-based aerogel composite：synthesis, characterization and adsorption behavior study for heavy metals removal

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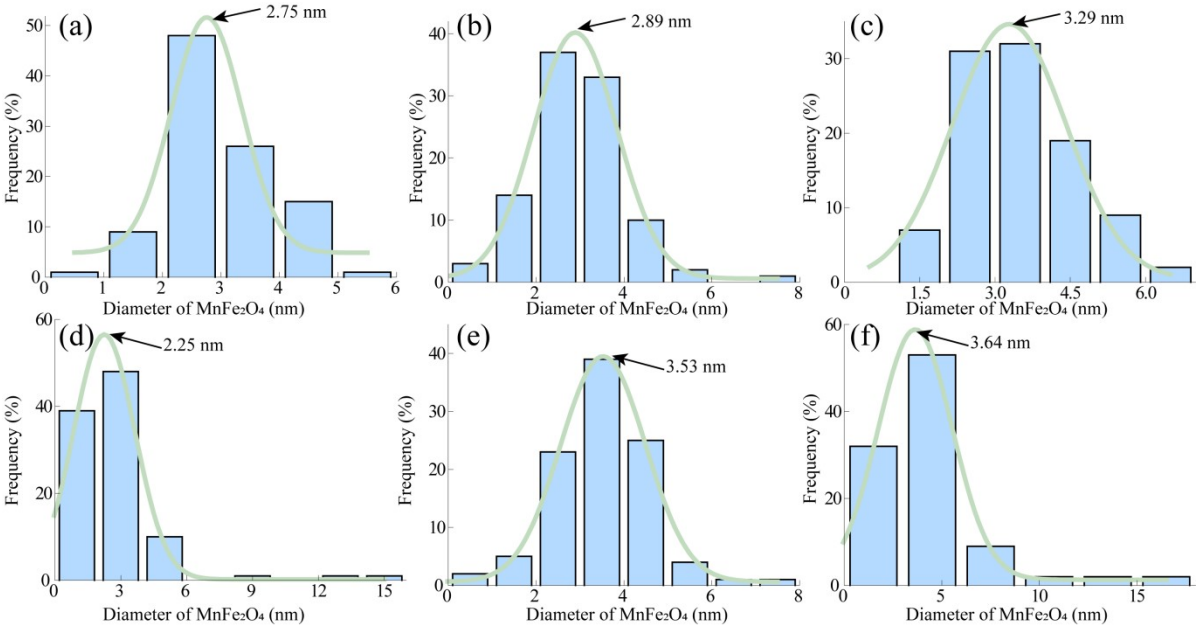


**Fig. S1** The particle size distribution of $MnFe_2O_4$ on the surface of MCA obtained by directional freezing：(a) MCA1-2; (b) MCA1-3; (c) MCA1-4; (d) MCA2-1; (e) MCA2-2; (f) MCA2-3

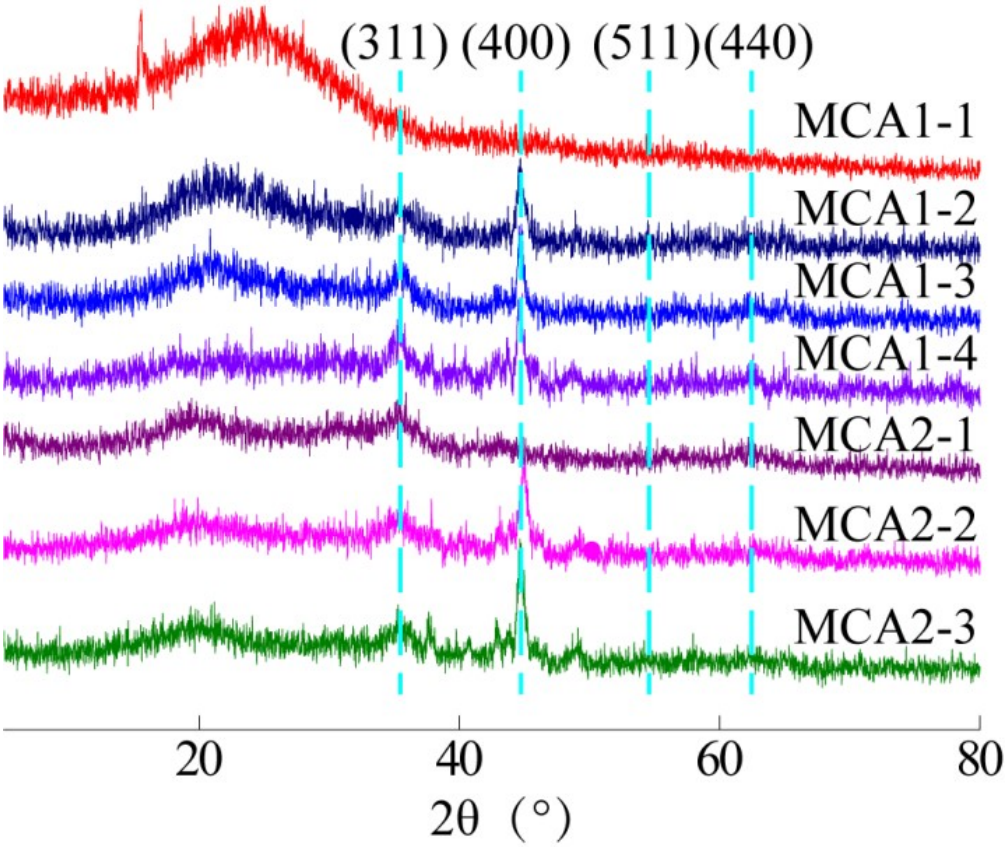


**Fig. S2** XRD characterization of MCA

**Table S1** Specific surface area, pore volume and porosity of MCA with different amounts of modifiers

| No. | $S_{BET}$ /$m^2 \cdot g^{-1}$ | $D_{pore}$ /nm | $V_{total\ pore}$ /$cm^3 \cdot g^{-1}$ | $V_{<50nm}$ /$cm^3 \cdot g^{-1}$ | $V_{<50\ nm}/V_{total\ pore}$ | ρ/% |
|---|---|---|---|---|---|---|
| MCA1-1 | 182.67 | 4.077 | 0.1772 | 0.1447 | 0.8166 | 95.33 |
| MCA1-2 | 128.79 | 5.890 | 0.1515 | 0.1025 | 0.6766 | 90.51 |
| MCA1-3 | 112.09 | 5.122 | 0.1358 | 0.1186 | 0.8733 | 80.88 |
| MCA1-4 | 109.72 | 4.897 | 0.1085 | 0.0838 | 0.7724 | 66.18 |

$\rho_0$ is the density of graphite，2.3 g/$cm^3$

Pseudo-first-order kinetic equation (Equation S1) and pseudo-second-order kinetic equation (Equation S2) are as follows：

$$q_t = q_e(1 - e^{-k_1 t}) \quad \text{（Equation S1）}$$

$$q_t = k_2 q_e^2 t / (1 + k_2 q_e t) \quad \text{（Equation S2）}$$

Where $q_e$ and $q_t$ are the amounts of $Pb^{2+}$, $Cu^{2+}$, or $Cd^{2+}$ adsorbed at equilibrium and t min, respectively, mg/g; $K_1$ is the rate constant of the pseudo-first-order kinetic model, $min^{-1}$; $K_2$ is the rate constant of the pseudo-second-order kinetic model, g/(mg·min); t is the adsorption time, min.

**Table S2** MCA adsorption kinetics fitting parameters for $Pb^{2+}$ in single, binary, and ternary systems

| adsorbates | concentration (mg/L) | Pseudo-first-order model | | | Pseudo-second-order model | | |
|---|---|---|---|---|---|---|---|
| | | $K_1$ ($min^{-1}$) | $q_e$ (mg/g) | $R^2$ | $K_2$ (g/mg·min) | $q_e$ (mg/g) | $R^2$ |
| $Pb^{2+}$ | 20 | 0.0253 | 16.74 | 0.985 | 0.0014 | 19.91 | 0.974 |
| | 40 | 0.0346 | 29.24 | 0.997 | 0.0013 | 33.34 | 0.994 |
| | 60 | 0.0319 | 38.88 | 0.957 | 0.0010 | 43.83 | 0.971 |
| $Pb^{2+}/Cu^{2+}$ | 20 | 0.0261 | 9.55 | 0.981 | 0.0027 | 11.24 | 0.966 |
| | 40 | 0.0301 | 16.87 | 0.988 | 0.0020 | 19.41 | 0.992 |
| | 60 | 0.0383 | 18.93 | 0.994 | 0.0022 | 21.55 | 0.974 |
| $Pb^{2+}/Cd^{2+}$ | 20 | 0.0381 | 12.10 | 0.950 | 0.0035 | 13.73 | 0.916 |
| | 40 | 0.0474 | 19.88 | 0.981 | 0.0029 | 22.20 | 0.997 |
| | 60 | 0.0249 | 25.59 | 0.987 | 0.0010 | 30.15 | 0.983 |
| $Pb^{2+}/Cu^{2+}/Cd^{2+}$ | 20 | 0.0266 | 7.12 | 0.972 | 0.0039 | 8.35 | 0.986 |
| | 40 | 0.0188 | 13.74 | 0.979 | 0.0011 | 17.27 | 0.966 |
| | 60 | 0.0268 | 16.53 | 0.993 | 0.0015 | 19.73 | 0.979 |

**Table S3** MCA adsorption kinetics fitting parameters for $Cu^{2+}$ in single, binary, and ternary systems

| adsorbates | concentration (mg/L) | Pseudo-first-order model | | | Pseudo-second-order model | | |
|---|---|---|---|---|---|---|---|
| | | $K_1$ ($min^{-1}$) | $q_e$ (mg/g) | $R^2$ | $K_2$ (g/mg·min) | $q_e$ (mg/g) | $R^2$ |
| $Cu^{2+}$ | 20 | 0.0196 | 22.29 | 0.981 | 0.0007 | 28.09 | 0.963 |
| | 40 | 0.0304 | 32.97 | 0.969 | 0.0009 | 38.89 | 0.937 |
| | 60 | 0.0438 | 37.46 | 0.985 | 0.0016 | 41.40 | 0.973 |
| $Cu^{2+}/Pb^{2+}$ | 20 | 0.0363 | 11.70 | 0.935 | 0.0035 | 13.32 | 0.903 |
| | 40 | 0.0574 | 16.53 | 0.995 | 0.0048 | 18.05 | 0.988 |
| | 60 | 0.0402 | 20.44 | 0.950 | 0.0023 | 23.05 | 0.983 |
| $Cu^{2+}/Cd^{2+}$ | 20 | 0.0421 | 16.13 | 0.962 | 0.0032 | 18.03 | 0.927 |
| | 40 | 0.0170 | 24.38 | 0.975 | 0.0005 | 31.16 | 0.961 |
| | 60 | 0.0250 | 30.47 | 0.971 | 0.0007 | 36.67 | 0.945 |
| $Cu^{2+}/Pb^{2+}/Cd^{2+}$ | 20 | 0.0398 | 8.31 | 0.963 | 0.0059 | 9.31 | 0.986 |
| | 40 | 0.0247 | 14.70 | 0.989 | 0.0017 | 17.41 | 0.986 |
| | 60 | 0.0201 | 20.02 | 0.997 | 0.0009 | 24.60 | 0.994 |

**Table S4** MCA adsorption kinetics fitting parameters for $Cd^{2+}$ in single, binary, and ternary systems

| adsorbates | concentration (mg/L) | Pseudo-first-order model | | | Pseudo-second-order model | | |
|---|---|---|---|---|---|---|---|
| | | $K_1$ ($min^{-1}$) | $q_e$ (mg/g) | $R^2$ | $K_2$ (g/mg·min) | $q_e$ (mg/g) | $R^2$ |
| $Cd^{2+}$ | 20 | 0.0167 | 15.28 | 0.920 | 0.0007 | 20.11 | 0.892 |
| | 40 | 0.0127 | 29.46 | 0.972 | 0.0003 | 40.68 | 0.961 |
| | 60 | 0.0199 | 36.52 | 0.983 | 0.0004 | 45.61 | 0.969 |
| $Cd^{2+}/Pb^{2+}$ | 20 | 0.0214 | 11.95 | 0.966 | 0.0015 | 14.74 | 0.943 |
| | 40 | 0.0234 | 18.03 | 0.998 | 0.0012 | 21.77 | 0.987 |
| | 60 | 0.0384 | 18.73 | 0.964 | 0.0021 | 21.58 | 0.938 |
| $Cd^{2+}/Cu^{2+}$ | 20 | 0.0284 | 7.63 | 0.913 | 0.0045 | 8.69 | 0.955 |
| | 40 | 0.0228 | 12.69 | 0.990 | 0.0016 | 15.30 | 0.977 |
| | 60 | 0.0188 | 17.03 | 0.974 | 0.0010 | 20.82 | 0.983 |
| $Cd^{2+}/Pb^{2+}/Cu^{2+}$ | 20 | 0.0137 | 6.09 | 0.930 | 0.0017 | 7.82 | 0.941 |
| | 40 | 0.0195 | 9.63 | 0.988 | 0.0016 | 12.06 | 0.983 |
| | 60 | 0.0295 | 12.83 | 0.989 | 0.0024 | 14.93 | 0.992 |

Langmuir isotherm model (Equation S3) and Freundlich isotherm model (Equation S4) are as follows：

$$q_e = q_m K_L C_e/(1 + bC_e) \quad \text{（Equation S3）}$$

$$q_e = K_F C_e^{\,1/n} \quad \text{（Equation S4）}$$

Where $q_e$ is the amount of $Pb^{2+}$, $Cu^{2+}$, or $Cd^{2+}$ adsorbed by MCA at equilibrium and $q_m$ is saturation capacity of MCA for$Pb^{2+}$, $Cu^{2+}$, or $Cd^{2+}$， mg/g; $C_e$ is the concentration of $Pb^{2+}$, $Cu^{2+}$ and $Cd^{2+}$ in the solution at equilibrium, μg/mL; $K_L$ is the adsorption equilibrium constant of Langmuir isothermal model, L/mg; $K_F$ is the adsorption equilibrium constant of Freundlich isothermal model, $mg \cdot g^{-1} \cdot (L \cdot mg^{-1})^{1/n}$; 1/n is the adsorption intensity.

**Table S5** MCA adsorption isotherm curve fitting parameters for $Pb^{2+}$ in single, binary, and ternary systems

| adsorbates | temperature (°C) | Langmuir isotherm model | | | Freundlich isotherm model | | |
|---|---|---|---|---|---|---|---|
| | | $q_m$ (mg/g) | $K_L$ | $R^2$ | n | $K_F$ | $R^2$ |
| $Pb^{2+}$ | 25 | 53.18 | 0.0568 | 0.997 | 2.037 | 6.02 | 0.983 |
| | 35 | 61.70 | 0.0771 | 0.999 | 2.034 | 8.07 | 0.970 |
| | 45 | 74.38 | 0.0982 | 0.993 | 1.971 | 10.55 | 0.947 |
| $Pb^{2+}/Cu^{2+}$ | 25 | 30.47 | 0.0444 | 0.946 | 2.064 | 3.20 | 0.990 |
| | 35 | 34.31 | 0.0055 | 0.975 | 2.167 | 4.26 | 0.991 |
| | 45 | 37.01 | 0.0751 | 0.963 | 2.384 | 5.98 | 0.942 |
| $Pb^{2+}/Cd^{2+}$ | 25 | 38.91 | 0.0352 | 0.984 | 1.805 | 2.90 | 0.951 |
| | 35 | 44.37 | 0.0434 | 0.982 | 1.916 | 4.07 | 0.947 |
| | 45 | 55.26 | 0.0466 | 0.995 | 1.887 | 5.31 | 0.968 |
| $Pb^{2+}/Cu^{2+}/Cd^{2+}$ | 25 | 24.68 | 0.0353 | 0.886 | 1.930 | 2.08 | 0.943 |
| | 35 | 32.30 | 0.0340 | 0.922 | 1.837 | 2.45 | 0.973 |
| | 45 | 37.49 | 0.0372 | 0.995 | 1.788 | 2.83 | 0.966 |

**Table S6** MCA adsorption isotherm curve fitting parameters for $Cu^{2+}$ in single, binary, and ternary systems

| adsorbates | temperature (°C) | Langmuir isotherm model | | | Freundlich isotherm model | | |
|---|---|---|---|---|---|---|---|
| | | $q_m$ (mg/g) | $K_L$ | $R^2$ | n | $K_F$ | $R^2$ |
| $Cu^{2+}$ | 25 | 44.54 | 0.1402 | 0.978 | 2.668 | 9.95 | 0.990 |
| | 35 | 63.86 | 0.1103 | 0.957 | 2.291 | 11.21 | 0.999 |
| | 45 | 84.21 | 0.1014 | 0.933 | 2.160 | 13.47 | 0.996 |
| $Cu^{2+}/Pb^{2+}$ | 25 | 34.54 | 0.0249 | 0.910 | 1.651 | 1.80 | 0.853 |
| | 35 | 53.18 | 0.0206 | 0.957 | 1.484 | 1.98 | 0.926 |
| | 45 | 67.07 | 0.0226 | 0.963 | 1.489 | 2.67 | 0.940 |
| $Cu^{2+}/Cd^{2+}$ | 25 | 44.57 | 0.0550 | 0.985 | 1.950 | 4.73 | 0.942 |
| | 35 | 49.26 | 0.0834 | 0.992 | 2.071 | 6.95 | 0.948 |
| | 45 | 52.63 | 0.1317 | 0.971 | 2.239 | 9.97 | 0.898 |
| $Cu^{2+}/Pb^{2+}/Cd^{2+}$ | 25 | 28.56 | 0.0390 | 0.988 | 2.005 | 2.67 | 0.956 |
| | 35 | 32.50 | 0.0447 | 0.978 | 2.008 | 3.26 | 0.928 |
| | 45 | 36.14 | 0.0574 | 0.949 | 2.128 | 4.43 | 0.875 |

**Table S7** MCA adsorption isotherm curve fitting parameters for $Cd^{2+}$ in single, binary, and ternary systems

| adsorbates | temperature (°C) | Langmuir isotherm model | | | Freundlich isotherm model | | |
|---|---|---|---|---|---|---|---|
| | | $q_m$ (mg/g) | $K_L$ | $R^2$ | n | $K_F$ | $R^2$ |
| $Cd^{2+}$ | 25 | 61.05 | 0.0338 | 0.953 | 1.692 | 4.00 | 0.977 |
| | 35 | 64.01 | 0.0450 | 0.959 | 1.788 | 5.39 | 0.971 |
| | 45 | 73.63 | 0.0509 | 0.941 | 1.753 | 6.47 | 0.956 |
| $Cd^{2+}/Pb^{2+}$ | 25 | 20.20 | 0.3478 | 0.878 | 4.421 | 8.21 | 0.977 |
| | 35 | 24.12 | 0.4406 | 0.923 | 4.328 | 10.22 | 0.988 |
| | 45 | 26.47 | 0.6602 | 0.926 | 4.707 | 12.77 | 0.982 |
| $Cd^{2+}/Cu^{2+}$ | 25 | 31.02 | 0.0187 | 0.993 | 1.496 | 1.10 | 0.981 |
| | 35 | 37.46 | 0.0212 | 0.991 | 1.458 | 1.37 | 0.980 |
| | 45 | 55.35 | 0.0158 | 0.989 | 1.307 | 1.31 | 0.980 |
| $Cd^{2+}/Pb^{2+}/Cu^{2+}$ | 25 | 30.71 | 0.0252 | 0.984 | 1.417 | 0.84 | 0.977 |
| | 35 | 31.00 | 0.1049 | 0.991 | 1.509 | 1.37 | 0.965 |
| | 45 | 36.29 | 0.0331 | 0.974 | 1.501 | 1.92 | 0.947 |

The thermodynamic parameters of the adsorption process are calculated by Equations (S5)-(S8).

$$\ln K = \frac{\Delta S^{\theta}}{R} - \frac{\Delta H^{\theta}}{RT} \quad \textbf{(Equation S5)}$$

$$\Delta G^{\theta} = -RT\ln K \quad \textbf{(Equation S6)}$$

$$\Delta G^{\theta} = \Delta H^{\theta} - \mathrm{T}\Delta S^{\theta} \quad \textbf{(Equation S7)}$$

$$K_{\mathrm{d}} = \frac{q_e}{C_e} \quad \textbf{(Equation S8)}$$

Where R is the ideal gas constant, 8.314 J/(mol • K); T is the absolute temperature, K; $\Delta G^{\theta}$ is the change of Gibbs free energy, J/K; $\Delta H^{\theta}$ is the change of enthalpy, J/K; $\Delta S^{\theta}$ is change of entropy, J/(mol • K); K is the equilibrium constant, (L/mol); $q_e$ is the amount of $Pb^{2+}$, $Cu^{2+}$ or $Cd^{2+}$ in the MCA at equilibrium; $C_e$ is the concentration of $Pb^{2+}$, $Cu^{2+}$ or $Cd^{2+}$ in the solution at equilibrium, mg/L.

**Table S8** Thermodynamic parameters of $Pb^{2+}$adsorption by MCA in single, binary, and ternary systems

| adsorbates | $\Delta G^{\theta}$ （kJ/mol） | | | $\Delta H^{\theta}$ （kJ/mol） | $\Delta S^{\theta}$ （kJ/mol·K） |
|---|---|---|---|---|---|
| | 25℃ | 35 ℃ | 45 ℃ | | |
| $Pb^{2+}$ | -1.152 | -2.324 | -3.589 | 35.162 | 0.122 |
| $Pb^{2+}/Cu^{2+}$ | -0.311 | -0.354 | -1.001 | 20.551 | 0.066 |
| $Pb^{2+}/Cd^{2+}$ | -0.072 | -0.656 | -0.879 | 23.517 | 0.077 |
| $Pb^{2+}/Cu^{2+}/Cd^{2+}$ | -0.631 | -1.093 | -1.770 | 18.782 | 0.057 |

**Table S9** Thermodynamic parameters of $Cu^{2+}$adsorption by MCA in single, binary, and ternary systems

| adsorbates | $\Delta G^{\theta}$ （kJ/mol） | | | $\Delta H^{\theta}$ （kJ/mol） | $\Delta S^{\theta}$ （kJ/mol·K） |
|---|---|---|---|---|---|
| | 25℃ | 35 ℃ | 45 ℃ | | |
| $Cu^{2+}$ | -1.958 | -2.906 | -3.829 | 25.933 | 0.094 |
| $Cu^{2+}/Pb^{2+}$ | -0.040 | -0.819 | -1.656 | 26.941 | 0.085 |
| $Cu^{2+}/Cd^{2+}$ | -0.189 | -1.573 | -3.004 | 41.776 | 0.141 |
| $Cu^{2+}/Pb^{2+}/Cd^{2+}$ | -0.236 | -0.987 | -1.704 | 23.581 | 0.073 |

**Table S10** Thermodynamic parameters of $Cd^{2+}$adsorption by MCA in single, binary, and ternary systems

| adsorbates | $\Delta G^{\theta}$ （kJ/mol） | | | $\Delta H^{\theta}$ （kJ/mol） | $\Delta S^{\theta}$ （kJ/mol·K） |
|---|---|---|---|---|---|
| | 25℃ | 35 ℃ | 45 ℃ | | |
| $Cd^{2+}$ | -0.804 | -1.519 | -2.327 | 21.878 | 0.076 |
| $Cd^{2+}/Pb^{2+}$ | -0.531 | -1.719 | -2.832 | 33.784 | 0.115 |
| $Cd^{2+}/Cu^{2+}$ | -1.130 | -1.600 | -2.387 | 21.167 | 0.063 |
| $Cd^{2+}/Pb^{2+}/Cu^{2+}$ | -0.628 | -1.752 | -2.803 | 35.207 | 0.109 |

Distribution coefficient ($K_d$) and adsorption selectivity factor $\alpha_M^A$ are calculated by Equations (S9)-(S10). $K_d$ represents the strength of the affinity of the adsorbent to the adsorbate, L/g. $\alpha_M^A$ represents the adsorption selectivity factor of the adsorbent on the target ion (A) in the solution with interfering ions (M).

$$K_d = (C_0 - C_e) / C_e \times V / m \quad \textbf{(Equation S9)}$$

$$\alpha_M^A = \frac{q_A C_M}{q_M C_A} \quad \textbf{(Equation S10)}$$

Where $C_0$ is the concentration of heavy metals in the solution before adsorption, mg/mL, $C_e$ is the concentration of heavy metals in solution at adsorption equilibrium, g/ml, V is the volume of sample solution, mL; m is the weight of sample, g; $q_A$ is the adsorption amount of A at adsorption equilibrium, mg/g; $q_M$ is the adsorption amount of M at adsorption equilibrium, mg/g; $C_A$ is the concentration of A in solution at adsorption equilibrium, mg/L; $C_M$ is the concentration of M in solution at adsorption equilibrium, mg/L.

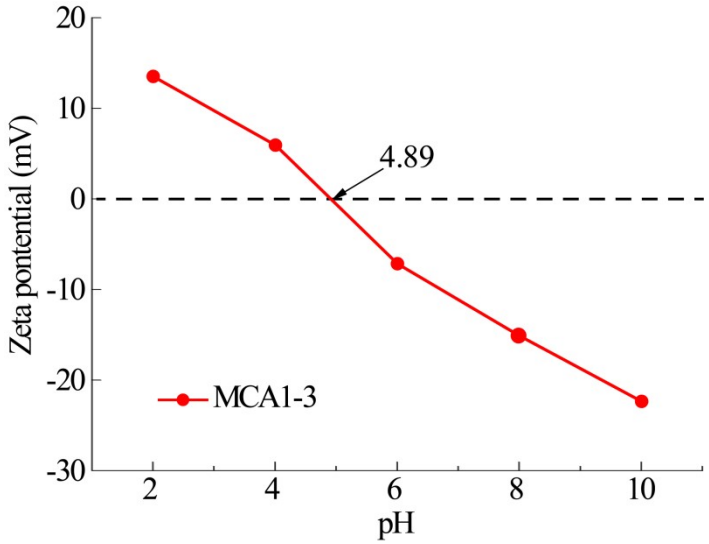


**Fig. S3** The zeta potentials of MCA1-3 at different pH in the presence of $KNO_3$ ($10^{-3}$mol·$L^{-1}$).

**Table S11** Comparison of MCA with other biomass based materials.

| Adsorbent | Initial concentration (μg/mL) | | | Adsorption capacity (mg/g) | | | Ref. |
|---|---|---|---|---|---|---|---|
| | $Pb^{2+}$ | $Cu^{2+}$ | $Cd^{2+}$ | $Pb^{2+}$ | $Cu^{2+}$ | $Cd^{2+}$ | |
| Magnetic carbon quantum dots from Pomegranate peel ($Fe_3O_4$-PPCQDs) | 150 | / | 150 | 17.92 | / | 23.75 | [1] |
| magnetic multi-functional biochar adsorbents (MMF-BC) | 25 | / | 25 | 61.25 | / | 53.72 | [2] |
| Wood ash amended biochar | 150 | 150 | 150 | 61.5 | 38.9 | 10.2 | [3] |
| Garden waste biochar | 300 | 300 | / | 45.9 | 25.2 | / | [4] |
| MCA | 60 | 60 | 60 | 74.38 | 84.21 | 73.63 | This work |