Supplementary information

Effective removal of Sr^{2+} ions by K_2SbPO_6/polyacrylonitrile composite microspheres

Shuangjiang Li [1,2,3], Jianghai He [1,2,3], Yanling Guo [2], Lu Yang [2], Haiyan Sun [2], Meiling Feng [1,2,3,*] and Xiaoying Huang [2,3]

[1] **College of Chemistry, Fuzhou University, Fuzhou 350116, P. R. China; lishuangjiang@fjirsm.ac.cn (S.L.); hejianghai@fjirsm.ac.cn (J.H.)**

[2] **State Key Laboratory of Structural Chemistry, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou, Fujian 350002, P. R. China; guoyanling97@163.com (Y.G.); yanglu@fjirsm.ac.cn (L.Y.); shy@fjirsm.ac.cn (H.S.); xyhuang@fjirsm.ac.cn (X.H.)**

[3] **Fujian College, University of Chinese Academy of Sciences, Fuzhou 350002, P. R. China**

[*] **Correspondence: fml@fjirsm.ac.cn (M.F.); Tel.: +86-591-63173146 (M.F.)**

1. Batch adsorption experiments.

For isothermal adsorption experiments, solutions with different initial Sr^{2+} ions concentrations (C_0 = 10.62–520.60 mg L^{-1}) were prepared. The ratio of the adsorbed sample to the solution (m/V) was 1 g L^{-1} (m = 10 mg, V = 10 mL). The solid–liquid mixtures were stirred for about 12 h at room temperature. After filtration, the solution was diluted with 2% HNO_3 solution and finally tested by inductively coupled plasma–mass spectrometry (ICP-MS) or inductively coupled plasma–optical emission spectrometry (ICP-OES).

In the kinetic experiments, 50 mg of K_2SbPO_6/PAN microspheres were added to 50 mL of Sr^{2+} ions solution (C_0 = 19.11 mg L^{-1}) and stirred at room temperature. At different moments, a certain amount of supernatant was aspirated. It was filtered and diluted with a 2% HNO_3 solution for testing by ICP-OES.

In the pH-dependent study, the pH values of the solutions containing Sr^{2+} ions (C_0 = 9.46–10.06 mg L^{-1}) were first adjusted from 3 to 12 with HNO_3 or NaOH solution. The adsorption was carried out at room temperature at an input ratio of m/V of 1 g L^{-1} (m = 10 mg, V = 10 mL) with a stirring time of about 12 h. After filtration, the solution was diluted with 2% HNO_3 solution and finally tested by ICP-OES.

Competitive ion adsorption experiments were carried out at room temperature. The removal of Sr^{2+} ions by K_2SbPO_6/PAN microspheres was studied in the presence of different concentrations of K^+, Na^+, Cs^+, Ca^{2+}, and Mg^{2+} ions. At the end, filtration was performed, then diluted with 2% HNO_3 solution and finally detected by ICP-OES or ICP-MS.

K_2SbPO_6/PAN microspheres irradiated by 100 kGy β rays and 100 kGy γ rays were used to test their performance for the Sr^{2+} adsorption. Then, 10 mg of the pristine K_2SbPO_6/PAN microspheres and irradiated samples were added to 10 mL of Sr^{2+} ion aqueous solutions. The experiments lasted for about 12 h contact time at room temperature. The filtered solution was analyzed by ICP-OES.

2. Equations.

The equations for the analysis of adsorption experiments are summarized as follows:

(3) The adsorption capacity q (mg g^{-1}) can be calculated according to Eq. S1.

$$q = \frac{(C_0 - C_e)V}{m} \qquad \text{(Eq. S1)}$$

C_0 (mg L^{-1}) and C_e (mg L^{-1}) are the initial and equilibrium concentration of target ions, respectively. m (g) and V (mL) are the mass of the adsorbent and the volume of the solution used in the adsorption experiment, respectively.

(2) Eq. S2, S3, and S4 represent the classical isotherm models, namely the Langmuir, Freundlich, and Langmuir–Freundlich models, which are used to evaluate the maximum adsorption capacity (q_m) of the adsorbent for a target ion.

$$q = q_m \frac{K_L C_e}{1 + bC_e} \qquad \text{(Eq. S2)}$$

$$q = K_F C_e^{\frac{1}{n}} \qquad \text{(Eq. S3)}$$

$$q = q_m \frac{(K_L C_e)^{\frac{1}{n}}}{1 + (K_L C_e)^{\frac{1}{n}}} \qquad \text{(Eq. S4)}$$

q_m is the maximum adsorption capacity (mg g^{-1}); K_L is the Langmuir constant related to the affinity of the ion for the adsorbent (L mg^{-1}), and n is the density constant at the adsorption site. K_F ($mg^{1-1/n} \cdot L^{1/n}/g$) is the fitting parameter related to the adsorption capacity.

(3) The removal rate R (%) can be calculated according to Eq. S5.

$$R = \frac{(C_0 - C_e)}{C_0} \times 100\% \qquad \text{(Eq. S5)}$$

(4) Kinetics models are shown in Eq. S6 and S7.

$$ln\frac{(q_e - q)}{q_e} = -k_1 t \qquad \text{(Eq. S6)}$$

$$\frac{t}{q} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t \qquad \text{(Eq. S7)}$$

k_1 and k_2 are pseudo-first-order and pseudo-second-order rate constants of the kinetics models, respectively. The pseudo-second-order rate expression has been widely applied to the adsorption of pollutants from aqueous solutions.

(5) The distribution coefficient K_d (mL g^{-1}) can be calculated according to Eq. S8.

$$K_d = \frac{V}{m}\frac{(C_0 - C_e)}{C_0} \qquad \text{(Eq. S8)}$$

3. Figure S1–Figure S7.

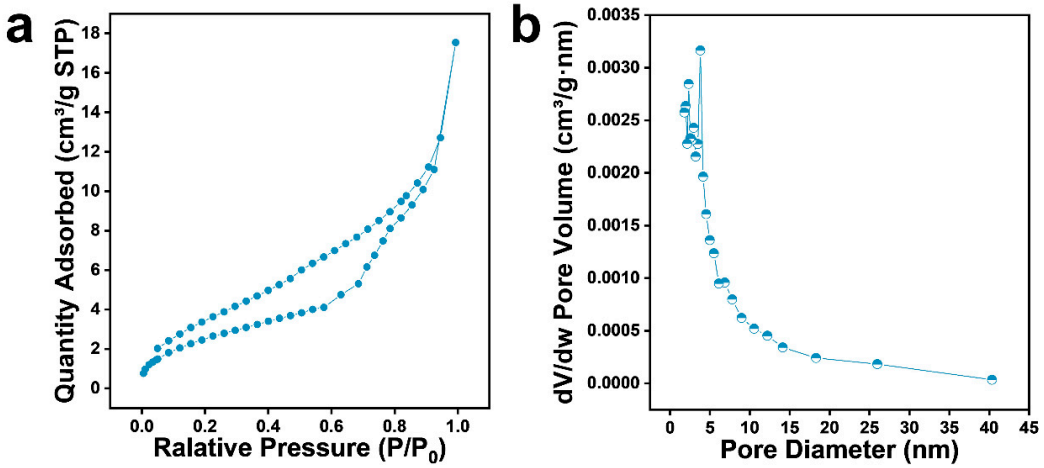

Figure S1. Adsorption and desorption isotherms (**a**) and pore size distributions (**b**) of the K_2SbPO_6/PAN microspheres under N_2 atmosphere.

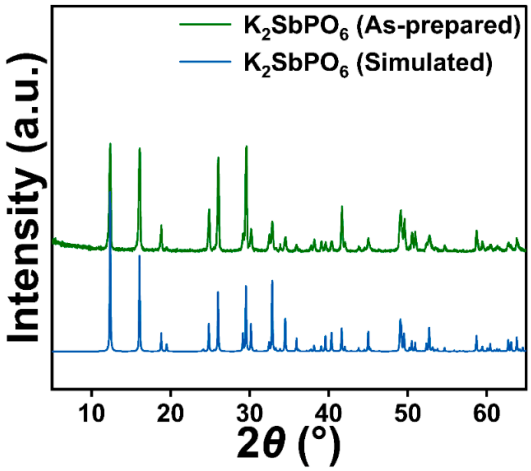

Figure S2. Simulated and as-prepared PXRD patterns of K_2SbPO_6.

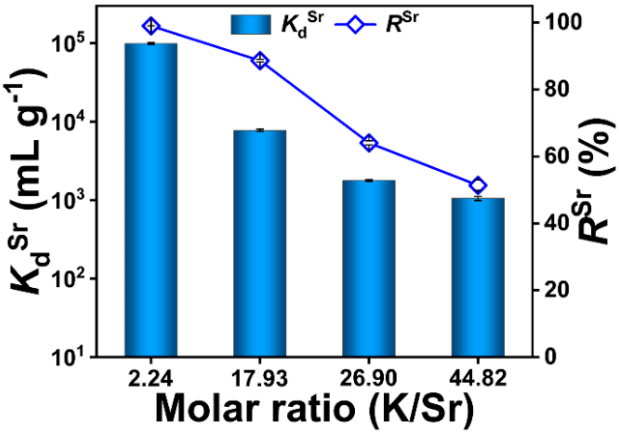

Figure S3. K_d^{Sr} and R^{Sr} of K_2SbPO_6/PAN microsphere at different K/Sr molar ratios.

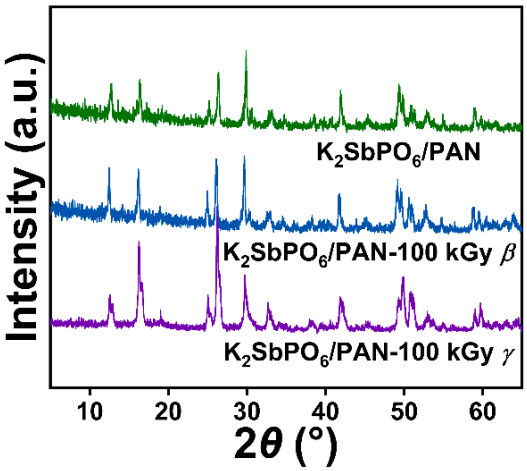

Figure S4. PXRD patterns of K_2SbPO_6/PAN microspheres before and after irradiation.

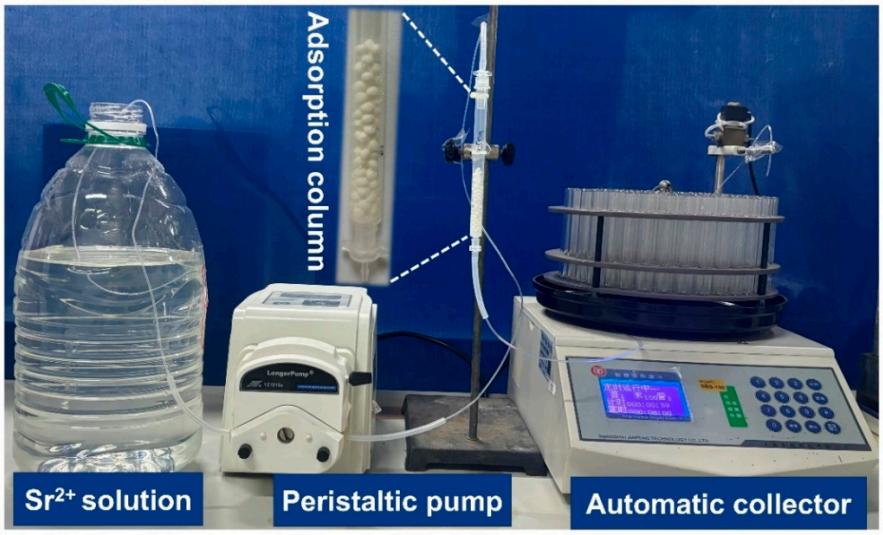

Figure S5. Device diagram of column adsorption of K_2SbPO_6/PAN microspheres for removal of Sr^{2+} ions.

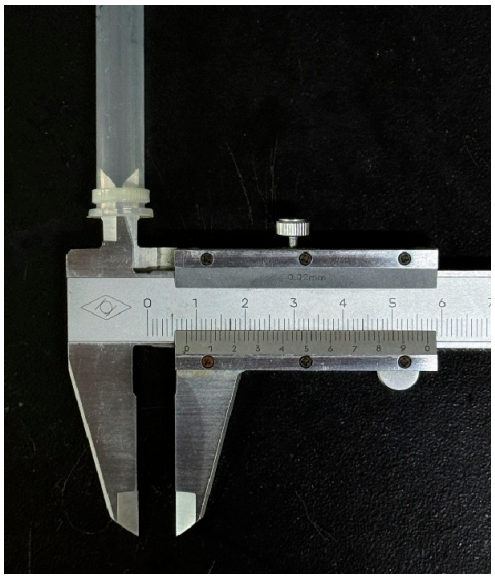

Figure S6. The diameter of the polyacetylene column used in the column experiments.

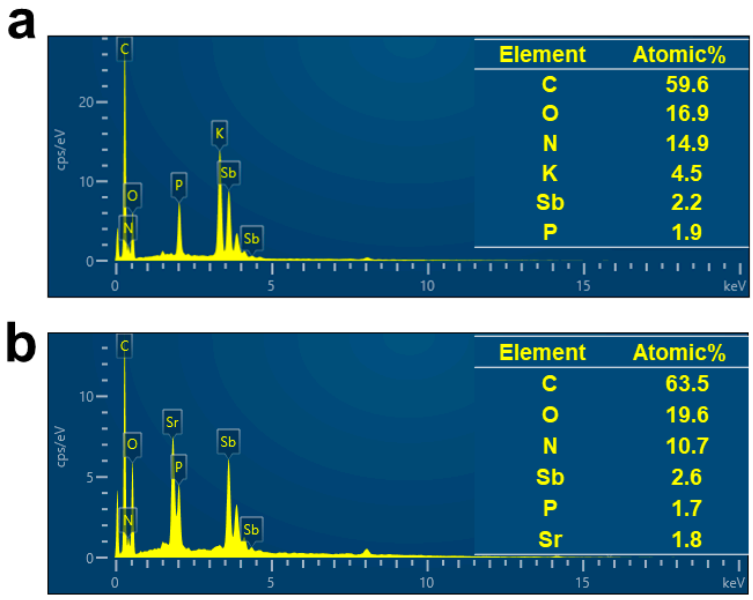

Figure S7. EDS analysis results of K_2SbPO_6 (**a**) and K_2SbPO_6-Sr (**b**).

3. Table S1–Table S14.

Table S1. BET analysis of K_2SbPO_6/PAN microspheres.

Sample	BET surface area ($m^2\ g^{-1}$)	Langmuir surface area ($m^2\ g^{-1}$)
K_2SbPO_6/PAN	9.7929	47.1488

Table S2. Experimental results of the adsorption capacity study of K_2SbPO_6/PAN microsphere (m/V = 1 g L^{-1}, at room temperature and 24 h contact time).

C_0^{Sr} (mg L^{-1})	C_e^{Sr} (mg L^{-1})	q_e^{Sr} (mg g^{-1})
10.62	0.064	10.55
51.42	0.19	51.24
103.83	6.72	97.10
159.35	37.01	122.35
604.29	478.12	126.16
1022.69	891.10	131.60

Table S3. Adsorption constants were obtained by fitting isotherm data to K_2SbPO_6/PAN microspheres using Langmuir, Freundlich, and Langmuir–Freundlich models.

Adsorption isotherm model	Langmuir model	Langmuir–Freundlich model	Freundlich model
R^2	0.909	0.959	0.862
q_m^{Sr} (mg g^{-1})	130.25	131.15	
b (L mg^{-1})	1.53	1.25	
n		1.66	6.52
k_F			62.10

Table S4. Comparison of the Sr^{2+} adsorption abilities of K_2SbPO_6/PAN microspheres and other reported adsorbents.

Sample	q_m^{Sr} (mg/g)	pH range	t_e^{Sr} (min)	Ref.
K_2SbPO_6/PAN	131.15	3-12	900	This work
2P-TiO_2	94.1	3-9	60	[1]
$(Me_2NH_2)_{4/3}(Me_3NH)_{2/3}Sn_3S_7$·1.25$H_2O$/PAN	62.88	2-10	360	[2]
NaTS	80.00	2-13	5	[3]
SnO_2-Sb_2O_5	30.2	0-12	* NC	[4]
KTS-3	102	2-12	＜10	[5]

* NC: not clear.

Table S5. Sr^{2+} adsorption kinetics results of K_2SbPO_6/PAN microsphere (m/V = 1 g L^{-1}, at room temperature).

t (min)	C_t^{Sr} (mg L^{-1})	R^{Sr} (%)
0	19.11 ± 0.31	0.00 ± 0.00
2	18.38 ± 0.075	3.85 ± 1.16
3	18.27 ± 0.28	4.40 ± 3.00
5	17.64 ± 0.26	7.71 ± 2.84
10	16.74 ± 0.26	12.42 ± 2.79
30	15.11 ± 0.41	20.91 ± 3.44
60	12.69 ± 0.17	33.59 ± 1.94
120	6.83 ± 0.049	64.29 ± 0.32
210	1.09 ± 0.00014	94.30 ± 0.092
300	0.067 ± 0.00028	99.65 ± 0.0071
600	0.069 ± 0.0011	99.64 ± 0.00014
720	0.068 ± 0.00057	99.64 ± 0.0087
900	0.074 ± 0.0013	99.62 ± 0.00047

Table S6. Kinetic fitting parameters of K_2SbPO_6/PAN microsphere for Sr^{2+} removal.

	k_1 (min^{-1})	k_2 ($g \cdot mg^{-1} \cdot min^{-1}$)	q_e^{Sr} (mg L^{-1})	R^2
Pseudo-first-order model	0.00875		19.53	0.990
Pseudo-second-order model		0.0471	3.75	0.999

Table S7. The pH-dependent adsorption results of K_2SbPO_6/PAN microsphere for Sr^{2+} removal (m/V = 1 g L^{-1}, at room temperature and 24 h contact time).

pH	C_0^{Sr} (mg L^{-1})	C_e^{Sr} (mg L^{-1})	K_d^{Sr} (mL g^{-1})	R^{Sr} (%)
3	9.47 ± 0.089	0.097 ± 0.00038	9.68×10^4 ± 1300.86	98.98 ± 0.014
4	9.57 ± 0.14	0.045 ± 0.00063	2.13×10^5 ± 161.37	99.53 ± 0.00035
5	9.46 ± 0.016	0.10 ± 0.00087	9.18×10^4 ± 943.43	98.92 ± 0.011
6	9.57 ± 0.13	0.13 ± 0.0043	7.21×10^4 ± 2967.43	98.63 ± 0.063
7	9.81 ± 0.090	0.046 ± 0.0011	2.11×10^5 ± 1844.76	99.53 ± 0.0066
8	9.87 ± 0.16	0.069 ± 0.00020	1.42×10^5 ± 1260.60	99.30 ± 0.0091
9	9.90 ± 0.084	0.070 ± 0.0012	1.41×10^5 ± 1566.50	99.29 ± 0.0063
10	9.94 ± 0.020	0.096 ± 0.0013	1.02×10^5 ± 2267.80	99.03 ± 0.015
11	10.06 ± 0.063	0.27 ± 0.00049	3.61×10^4 ± 166.75	97.30 ± 0.012
12	9.98 ± 0.083	0.88 ± 0.020	1.03×10^4 ± 352.24	91.13 ± 0.28

Table S8. The adsorption results of K_2SbPO_6/PAN microsphere under different Na^+/Sr^{2+} molar ratios (m/V = 1 g L^{-1}, at room temperature and 24 h contact time).

Molar ratio (Na^+/Sr^{2+})	C_0^{Na} (mg L^{-1})	C_0^{Sr} (mg L^{-1})	C_e^{Sr} (mg L^{-1})	K_d^{Sr} (mL g^{-1})	R^{Sr} (%)
19.06	48.67 ± 0.39	9.13 ± 0.13	0.050 ± 0.00014	$1.82 \times 10^5 \pm 3068.07$	99.45 ± 0.0091
38.11	96.64 ± 0.33	9.20 ± 0.035	0.048 ± 0.00064	$1.92 \times 10^5 \pm 1858.84$	99.48 ± 0.0050
76.22	189.12 ± 1.09	9.02 ± 0.048	0.070 ± 0.0013	$1.28 \times 10^5 \pm 1672.69$	99.23 ± 0.010
152.44	375.97 ± 1.90	9.09 ± 0.068	0.083 ± 0.00085	$1.08 \times 10^5 \pm 299.67$	99.08 ± 0.0025

Table S9. The adsorption results of K_2SbPO_6/PAN microsphere under different Cs^+/Sr^{2+} molar ratios (m/V = 1 g L^{-1}, at room temperature and 24 h contact time).

Molar ratio (Cs^+/Sr^{2+})	C_0^{Cs} (mg L^{-1})	C_0^{Sr} (mg L^{-1})	C_e^{Sr} (mg L^{-1})	K_d^{Sr} (mL g^{-1})	R^{Sr} (%)
0.66	9.35 ± 0.12	8.95 ± 0.019	0.052 ± 0.000071	$1.72 \times 10^5 \pm 132.81$	99.42 ± 0.00045
2.64	37.13 ± 0.042	9.17 ± 0.038	0.068 ± 0.00028	$1.34 \times 10^5 \pm 9.47$	99.26 ± 0.000052
13.18	185.46 ± 1.56	9.09 ± 0.099	2.19 ± 0.0018	$3.14 \times 10^3 \pm 41.98$	75.86 ± 0.24
65.90	956.85 ± 2.90	8.89 ± 0.092	2.56 ± 0.020	$2.48 \times 10^3 \pm 62.83$	71.23 ± 0.52

Table S10. The adsorption results of K_2SbPO_6/PAN microsphere under different K^+/Sr^{2+} molar ratios (m/V = 1 g L^{-1}, at room temperature and 24 h contact time).

Molar ratio (K^+/Sr^{2+})	C_0^{K} (mg L^{-1})	C_0^{Sr} (mg L^{-1})	C_e^{Sr} (mg L^{-1})	K_d^{Sr} (mL g^{-1})	R^{Sr} (%)
2.24	4.93 ± 0.079	5.11 ± 0.0066	0.051 ± 0.0014	$9.91 \times 10^4 \pm 2663.94$	99.00 ± 0.027
17.93	38.28 ± 0.083	5.12 ± 0.084	0.58 ± 0.0096	$7.78 \times 10^3 \pm 288.56$	88.60 ± 0.37
26.90	57.70 ± 0.16	5.13 ± 0.056	1.84 ± 0.011	$1.78 \times 10^3 \pm 47.13$	64.05 ± 0.61
44.82	96.15 ± 0.13	5.18 ± 0.055	2.52 ± 0.052	$1.06 \times 10^3 \pm 64.56$	51.37 ± 1.53

Table S11. The adsorption results of K_2SbPO_6/PAN microsphere under different Mg^{2+}/Sr^{2+} molar ratios (m/V = 1 g L^{-1}, at room temperature and 24 h contact time).

Molar ratio (Mg^{2+}/Sr^{2+})	C_0^{Mg} (mg L^{-1})	C_0^{Sr} (mg L^{-1})	C_e^{Sr} (mg L^{-1})	K_d^{Sr} (mL g^{-1})	R^{Sr} (%)
2.86	4.41 ± 0.0070	4.58 ± 0.041	0.63 ± 0.0083	$6.28 \times 10^3 \pm 30.79$	86.26 ± 0.058
9.35	14.42 ± 0.061	4.45 ± 0.072	1.38 ± 0.0090	$2.22 \times 10^3 \pm 72.97$	68.99 ± 0.70
27.86	42.97 ± 0.23	4.44 ± 0.026	1.70 ± 0.019	$1.61 \times 10^3 \pm 44.47$	61.72 ± 0.65
64.29	99.10 ± 0.17	4.50 ± 0.0029	1.79 ± 0.011	$1.52 \times 10^3 \pm 13.50$	60.26 ± 0.21

Table S12. The adsorption results of K_2SbPO_6/PAN microsphere under different Ca^{2+}/Sr^{2+} molar ratios (m/V = 1 g L^{-1}, at room temperature and 24 h contact time).

Molar ratio (Ca^{2+}/Sr^{2+})	C_0^{Ca} (mg L^{-1})	C_0^{Sr} (mg L^{-1})	C_e^{Sr} (mg L^{-1})	K_d^{Sr} (mL g^{-1})	R^{Sr} (%)
2.30	5.84 ± 0.0045	4.50 ± 0.040	0.045 ± 0.00070	$9.87 \times 10^4 \pm 831.51$	98.99 ± 0.0084
10.72	27.25 ± 0.038	4.48 ± 0.028	0.033 ± 0.00028	$1.37 \times 10^5 \pm 325.22$	99.27 ± 0.0017
17.07	43.38 ± 0.11	4.45 ± 0.017	0.68 ± 0.0033	$5.59 \times 10^3 \pm 6.80$	84.82 ± 0.016
33.54	85.24 ± 0.23	4.49 ± 0.051	1.62 ± 0.0020	$1.78 \times 10^3 \pm 27.98$	64.05 ± 0.36

Table S13. Results of Sr^{2+} removal by K_2SbPO_6/PAN microsphere before and after irradiation (m/V = 1 g L^{-1}, at room temperature and 24 h contact time).

Samples	C_0^{Sr} (mg L^{-1})	C_e^{Sr} (mg L^{-1})	K_d^{Sr} (mL g^{-1})	R^{Sr} (%)
Pristine	9.52 ± 0.068	0.12 ± 0.0029	7.98×10^4 ± 2601.60	98.76 ± 0.040
100 kGy γ	9.52 ± 0.068	0.14 ± 0.00014	6.87×10^4 ± 583.35	98.56 ± 0.012
100 kGy β	9.52 ± 0.068	0.12 ± 0.00035	7.73×10^4 ± 323.43	98.72 ± 0.0053

Table S14. Results of adsorption column experiments of K_2SbPO_6/PAN microsphere (C_0^{Sr} = 10.04 mg L^{-1}, room temperature).

t (min)	C_f^{Sr} (mg L^{-1})	R^{Sr} (%)
0	10.04 ± 0.25	0.00
20	1.29 ± 0.0057	87.15 ± 0.38
1940	1.31 ± 0.0085	86.93 ± 0.25
3700	1.36 ± 0.0099	86.44 ± 0.44
7180	1.42 ± 0.013	85.84 ± 0.49
7980	1.45 ± 0.0028	85.59 ± 0.34
8620	1.59 ± 0.038	84.21 ± 0.02
9180	1.62 ± 0.047	83.90 ± 0.057
10300	1.67 ± 0.061	83.36 ± 0.18
11180	1.71 ± 0.0028	82.96 ± 0.40
11700	1.79 ± 0.0099	82.14 ± 0.35

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