Table S1. Breakthrough curve data for Zn and Pb on AMP-p and calculation of dynamic capacities**.**

Part A: calculation of DBC and TDC by trapezoidal integration of the breakthrough curve

The breakthrough curve for Zn and Pb on AMP-p is presented in Figure 6 of the main text. The integral $\int(1-C/C_0)dV$ was calculated by the trapezoidal rule over the measured points of the curve up to the end of the run (5.2 L). The integration gives:

$$\int_0^{5.2} (1 - C/C_0)dV = 5.09 \text{ L}$$

The total dynamic capacity was calculated as:

$$\text{TDC} = \frac{C_0 \cdot \int(1 - C/C_0)dV}{m} = \frac{7.494 \cdot 5.09}{67} = 0.570 \text{ mmol/g}$$

consistent with the value reported in Table 6 (0.571 mmol/g).

The dynamic breakthrough capacity was calculated from Equation (1) using the breakthrough volumes read from Figure 6:

$$DBC = \frac{(C_0 - C_{bt}) \cdot (V_{br} - V_{free})}{m}$$

Where $C_{bt} = 0.1C_0$, $V_{free} = 0.038$ L (free volume of the column, $\varepsilon \approx 0.38$), and m = 67 g.

Part B: breakthrough curve points (V, C/C0) for Zn and Pb.

Parameter	Zn	Pb
C_0, mmol/L	7.494	$5.31 \cdot 10^{-3}$
$V_{breakthrough}$ (exp.), L	3.64	1.1
V_{free}, L	0.038	0.038
$V_{breakthrough}$ (corr), L	3.602	1.062
DBC = $(C_0 - 0.1C_0 \cdot V_{bt}$ / m, mmol/g	0.363	$7.57 \cdot 10^{-5}$
$\int(1-C/C_0)dV$ (to $C/C_0 \approx 1.0$), L	5.09	n/d
TDC = $C_0 \cdot \int$ / m, mmol/g	0.570	n/d
Total sorbed metal (TDC · m), mmol	38.26	0.0047*

* For Pb, the retained amount was not obtained by integration-based capacity calculation (the Pb loading is close to the analytical detection limit). The integrated breakthrough curve gives ≈0.020 mmol, and the feed−effluent difference gives ≈0.027 mmol (Supplementary Table S2); these values are used for the desorption efficiency in Table S2, Part D. Note that DBC(Pb) × m = 0.005 mmol represents the amount retained at the breakthrough point (V = 1.1 L) and is consistent with both estimates.

Table S2. Material balance for Zn and Pb in the dynamic column test on AMP-p

Conditions: m_{sorb} = 67 g; V_{bed} = 100 mL; T = 70 °C; feed rate 5 mL/min; C_0(Zn) = 490 mg/L; C_0(Pb) = 1.1 mg/L; $V_{feed\ passed\ to\ saturation}$ ≈ 5.2 L.

Part A: Feed and effluent

Stream	V, L	C (Zn), mg/L	m(Zn), mg	C(Pb), mg/L	m(Pb), mg
Feed (to saturation)	5.2	490	2548	1.1	5.72
Effluent (to saturation)	5.2	~8.5	~44	~0.02 (average)	~0.1
Retained on sorbent (feed − effluent)	-	–	2504 (38.3 mmol)	–	≈0.027 mmol

Note: Note: For Zn, the retained amount (38.3 mmol) is consistent with TDC(Zn) = 0.571 mmol/g. For Pb, the feed−effluent difference (≈0.027 mmol) agrees within the analytical uncertainty with the integral of the breakthrough curve (≈0.020 mmol, Supplementary Table S1); both estimates are used for the desorption efficiency in Part D.

Part B: Washing

Stream	V, L	C (Zn), mg/L	m(Zn), mg	C(Pb), mg/L	m(Pb), mg
Washing (distilled water, 70 °C)	0.25	<0.1	<0.025	<0.01	<0.0025

Part C: Desorption

Stream	V, L	C (Zn), mg/L	m(Zn), mg	C(Pb), mg/L	m(Pb), mmol
Desorption (10% H_2SO_4)	0.55	~4500 (average)	37.88	~1.22 (average)	0.00325 measured in the eluate
Max concentration in 75 mL fraction	–	6020	–	2.4	–
Concentration factor	–	12.3	–	2.2	–

Part D: Closure of the balance

Component	Retained on sorbent, mmol	Desorbed, mmol	Irreversibly retained, mmol	Desorption, %	Washing loss, %
Zn	38.26 (TDC × m)	37.88 (measured)	0.38	99.0	<0.001
Pb	0.020 (curve) 0.027 (feed−effluent)	0.00325 (measured)	0.017-0.024	12-16	<0.05

* The Pb retained value was not measured directly. Two independent estimates are given: integration of the breakthrough curve (≈0.020 mmol) and the feed−effluent difference (≈0.027 mmol). The desorption efficiency is calculated for both, giving 12–16%. The unrecovered Pb (≈0.017–0.024 mmol) was not detected in any analyzed solution; plausible explanations (incomplete elution, analytical uncertainty near the detection limit, possible precipitation of sparingly soluble PbSO4 during elution with 10% H2SO4) are discussed in Section 3.6 as hypotheses.