

Electronic Supplementary Information

Covalent Organic Framework Membranes for Ion Separations and Ion-Driven Energy Conversion

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Table S1. Summary of the separation performance of COF membranes in monovalent/multivalent cation separation.

Membrane	Feed concentration (mol L ⁻¹)	Driving force	K ⁺ permeation rate (mol m ⁻² h ⁻¹)	K ⁺ /Mg ⁺ selectivity	Na ⁺ /Mg ²⁺ selectivity	Li ⁺ /Mg ²⁺ selectivity	K ⁺ /Li ⁺ selectivity	K ⁺ /Al ³⁺ selectivity
COF-300 ¹	0.1 M	ΔC				0.07	31.5	
COF-DhaTg ²	0.1 M	ΔC		590	506	230		
COF-TpTg/SPPSU-Cl ³	0.05 M	ΔE	1.8	20.27	10.57	5.89		
COFTpPa-SO ₃ Na/PAN ⁴	0.1 M	ΔC	0.5	400	480	192		
COF-B18C6Tapa/PAN ⁵	0.05 M	ΔE	0.589	40	16	12		
COF-TfbDab-Azo ⁶	0.2 M	ΔC	0.74					6000

ΔC : dialysis conditions

ΔE : electro-driven conditions

Table S2. Summary of the separation performance of COF membranes in Li⁺/Mg²⁺ separation.

Membrane	Feed concentration (mol L ⁻¹)	Driving force	Li ⁺ permeation rate (mol m ⁻² h ⁻¹)	Li ⁺ /Mg ²⁺ selectivity	Na ⁺ /Mg ²⁺ selectivity	K ⁺ /Mg ²⁺ selectivity
COF-TpEb ⁷	0.2 M	ΔC	0.13	48.0	99.8	130.4
COF-Eb ₁ Bd ₁ /PAN ⁸	0.5 M	ΔC		353	360	35
COF-TamDta-CH _{0.6} ⁹	0.1 M	ΔC	0.2	203	425	625
COF-TpTg-PA ¹⁰	0.5 g L ⁻¹ LiCl 30:1 (MgCl ₂ :LiCl)	ΔP	1.0	21.3		
COF-TpMpd-PA ¹¹	2000 ppm 20:1 (MgCl ₂ :LiCl)	ΔP	0.08	73.0		
COF-TpMpd-PA/PES ¹²	2 g L ⁻¹ 20:1 (MgCl ₂ :LiCl)	ΔP		40.6		
COF-TpPa-SO ₃ H-PA ¹³	2 g L ⁻¹	ΔP		120		
COF-TpEb/PEI ¹⁴	1000 ppm	ΔP	0.39	30.7		
COF-Qa-PA-2 ¹⁵	2000 ppm	ΔP		82.6		
COF-TfbTg-PA-3 ¹⁶	1000 ppm	ΔP	0.3	61.8		
COF-TpPa-SO ₃ H ¹⁷	0.1 M	ΔC	0.0025	1000		
COF-TpTat-P ¹⁸	0.1 M	ΔC	0.224	474		
ZIF-8/COF-TpPa-SO ₃ H/nylon ¹⁹	0.5 M	ΔC	23.2	116		
COF-TpPa-SO ₃ H-PDDA ²⁰	2000 ppm 50:1 (MgCl ₂ :LiCl)	ΔP	0.013	61.6		
COF-TpDy ²¹	0.1 M	ΔC	0.1	217	680	765
COF-EO ₄ /PAN ²²	0.1 M	ΔC	0.23	64		

COF-EO ₃ /PAN ²³	0.1 M	ΔE	0.2	1352		
COF-BtzTp ²⁴	0.1 M	ΔC	0.16	210		
COF-EO ₂ ²⁵	2000 ppm 150:1 (MgCl ₂ :LiCl)	ΔP	0.03	30.2		

ΔC : dialysis conditions

ΔE : electro-driven conditions

ΔP : pressure-driven conditions

Table S3 Summary of the separation performance of COF membranes in lithium recovery from spent batteries.

Membrane	Feed concentration (mol L⁻¹)	Driving force	Li⁺ permeation rate (mol m⁻² h⁻¹)	Li⁺/Cu²⁺ selectivity	K⁺/Al³⁺ selectivity	Li⁺/Ni²⁺ selectivity	Li⁺/Co²⁺ selectivity	Li⁺/Mn²⁺ selectivity
COF-TfpmBd-COOH ²⁶	0.1 M	ΔC	0.5	490				
COF-TfpmPa ²⁷	0.1 M	ΔC			823.5			
COF-TpPy ²⁸	0.1 M	ΔC	0.13			107.7	106.8	67
COF-DmaTg ²⁹	0.1 M	ΔC	0.059			1491	996	243

ΔC : dialysis conditions

Table S4. Summary of the separation performance of COF membranes in monovalent cations separation.

Membrane	Feed concentration (mol L ⁻¹)	Driving force	Li ⁺ permeation rate (mol m ⁻² h ⁻¹)	Na ⁺ permeation rate (mol m ⁻² h ⁻¹)	K ⁺ permeation rate (mol m ⁻² h ⁻¹)	Na ⁺ /K ⁺ selectivity	K ⁺ /Li ⁺ selectivity	Na ⁺ /Li ⁺ selectivity
COF-Cys-60% ³⁰	0.1 M	ΔC		0.0613	0.0245	2.5		
COF-TpPa-SO ₃ H ³¹	0.1 M	ΔC			0.33		16.4	
COF-TpHz-D ³²	0.1 M	ΔC	0.14			5.4	0.026	0.14
COF-TpPa-COOH-3 ³³	0.1 M	ΔC			0.269		18.7	
COF-TpPa-SO ₃ H-(r) ³⁴	0.1 M	ΔC		0.15	0.3		∞	∞
COF-DhHz-15C ³⁵	1.0 M	ΔC		0.00933		58.31		

ΔC : dialysis conditions

Table S5. Summary of the separation performance of COF membranes in proton and metal cation separation.

Membrane	Feed concentration (mol L ⁻¹)	Driving force	H ⁺ permeation rate (mol m ⁻² h ⁻¹)	H ⁺ /Fe ²⁺ selectivity	H ⁺ /Li ⁺ selectivity	H ⁺ /Na ⁺ selectivity	H ⁺ /K ⁺ selectivity	H ⁺ /Mg ²⁺ selectivity	H ⁺ /Ca ²⁺ selectivity	H ⁺ /Al ³⁺ selectivity
COF-TfbTg/HPAN ³⁶	1 M H ⁺ + 0.26 M Fe ²⁺	ΔC		1266						
COF-DhaTg/HPAN ³⁷	1 M H ⁺ + 0.26 M Fe ²⁺	ΔC		4589						
COF-DmaTg/HPAN ³⁸	1 M H ⁺ + 0.2 M Fe ²⁺	ΔC		1248.9						
COF-TamTp ³⁹	0.5 M H ⁺ + 0.12 M Fe ²⁺	ΔC		5617		354			1913	8247
COF-Eb ₁ Bd ₁ /HPAN ⁴⁰	0.5 M H ⁺ + 0.13 M Fe ²⁺	ΔC		5186.9						
COF-TpTapa ⁴¹	0.1 M	ΔC		1499	145	143	136	608		
COF-DmaTg/PES ⁴²	0.1 M	ΔC			334	269	253		388	1173
COF-TpTg ⁴³	0.25 M	ΔC	0.9	3545	346	259	253	1116	886	4334
COF-Eb _{0.33} (Pa-SO ₃ H) ₃ /PAN ⁴⁴	0.5 M	ΔC				5.7	3.8	18.6	12.3	
COF-TpPa-SO ₃ H ⁴⁵	1 M	ΔC			∞	∞	∞			

ΔC: dialysis conditions

Table S6. Summary of the separation performance of COF membranes in Cl⁻/SO₄²⁻ separation.

Membrane	Feed concentration (mol L ⁻¹)	Driving force	Cl ⁻ permeation rate (mol m ⁻² h ⁻¹)	Cl ⁻ /SO ₄ ²⁻ selectivity
COF-TpPa-SO ₃ H ⁴⁶	0.35 mM	ΔC	0.009	3.6
COF-DmaTb-PA ⁴⁷		ΔP		84
COF-TpPa-SO ₃ H/aAEM3 ⁴⁸	0.05 M	ΔC		18.92
COF-TpPa-SO ₃ Na-PA ⁴⁹	500 ppm	ΔP		310
COF-TpPa-PA ⁵⁰	200 ppm	ΔP		137
COF-TpaPip-0.0625 ⁵¹	2 g L ⁻¹	ΔP		96.5
COF-DhaTb-PA-4 ⁵²	1000 ppm	ΔP		105.1
COF-DtaTb-170 ⁵³	0.1 M	ΔC		64

ΔC: dialysis conditions

ΔP: pressure-driven conditions

Table S7. Summary of the separation performance of COF membranes for radioactive and rare metal ion separation.

Membrane	Feed concentration (mol L⁻¹)	Driving force	Cr⁺ permeation rate (mol m⁻² h⁻¹)	Cr⁺/La³⁺ selectivity	Cr⁺/Sr²⁺ selectivity	Sr²⁺/La³⁺ selectivity	U⁶⁺/Th⁴⁺ selectivity	Sr²⁺/Y³⁺ selectivity
COF-HbabTat ⁵⁴	0.1 M	ΔC	0.33	69.8	13.3	2.1		
COF-TfbDbd-(S) ⁵⁵	20 ppm	ΔC					9.8	
COF-TbDha- <i>o</i> ⁵⁶	20 ppm	ΔC						49

ΔC: dialysis conditions

Table S8. Summary of the energy conversion performance of COF membranes integrated into RED devices.

Materials	System (NaCl Aqueous)	Power density (W m ⁻²)	Energy conversion efficiency (%)	External stimuli	Testing area (m ²)
COF-TpPa-SO ₃ H ⁵⁷	0.5 M 0.01 M	5.9	25.9	--	3×10 ⁻⁸
COF-TamDp-SO ₃ H ⁵⁸	0.5 M 0.01 M	21.2	45.3	--	3×10 ⁻⁸
COF-TpV-CF ₃ SO ₃ ⁵⁹	0.5 M 0.01 M	55	--	--	1.2×10 ⁻¹²
COF-TpDa-PVA-4.1% ⁶⁰	0.5 M 0.01 M (KCl)	12.5	--	--	3.14×10 ⁻⁸
COF-TpTg/PAN ⁶¹	0.5 M 0.01 M (H ₂ SO ₄)	97.1	--	--	7.85×10 ⁻⁹
COF-TfpPa-SO ₃ H/SANF ⁶²	0.5 M 0.01 M	8.7	--	--	3×10 ⁻⁸
Ca-COF ⁶³	0.5 M 0.01 M	180.5	37.1	--	1×10 ⁻¹⁰
COF-ZnTPP ⁶⁴	0.5 M 0.01 M	135.8	--	--	3.14×10 ⁻¹²
COF-ZnTPPTpa ⁶⁵	0.001 M (LiCl) 1 M (MeOH)	84.5	--	--	--
COF-ZnTPPVg ⁶⁶	0.5 M 0.01 M	102	--	--	3.14×10 ⁻¹²
COF-CuTPP ⁶⁷	0.5 M 0.01 M	22.08	5.63		2.5×10 ⁻⁷
COF-DhaDt ⁶⁸	0.5 M 0.01 M	51.4 (pH=3.5)	--	--	--
COF-TfppEb ⁶⁹	0.5 M 0.01 M	7,174	11.52		7.9×10 ⁻¹⁵
COF-Bta ₁ Bth ₁ /PAN ⁷⁰	0.01 M 0.5 M 0.01 M	51.9	33	--	7.85×10 ⁻⁹
COF-Bta/PAN ⁷¹	0.01 M 0.5 M 0.01 M	60 (247 ^[a])		ΔT=30 K	7.85×10 ⁻⁹
COF-Eb ₁ Bd ₂ /PAN ⁷²	0.5 M 0.01 M	113 (215 ^[a])	--	ΔT=40 K	7.85×10 ⁻⁹
COF-TpPa-(SO ₃ Na) ₁ /PAN ⁷³	0.5 M 0.01 M	97 (231 ^[a])	--	ΔT=60 K	7.85×10 ⁻⁹
COF-TpEb@TpPa-SO ₃ Na-300 ⁷⁴	0.5 M 0.01 M	19.2	26.9	--	3×10 ⁻⁸
COF-SO ₃ H-24 and COF-Qa-24 ⁷⁵	0.5 M 0.01 M	43.2	--	--	3×10 ⁻⁸
COF-Dma ₃ Dha ₁ -Qa ⁷⁶	0.5 M 0.01 M	53.2 (69.6 ^[a])	--	200 mW cm ⁻²	8×10 ⁻⁹
COF-PtaDha-SO ₃ K ⁷⁷	0.5 M 0.01 M	10.8 (18.0 ^[a])	21.2	100 mW cm ⁻²	4×10 ⁻⁸
COF-COOH-6h and COF-Qa-6h ⁷⁸	0.01 M 0.5 M 0.01 M	104 (195 ^[a])	--	ΔT=35 K	7.85×10 ⁻⁹

COF-TpPa-Tmc/PES ⁷⁹	2 M 0.04 M (H ₂ SO ₄)	135.65	--	--	3×10 ⁻⁸
HB _{67.7} @COF/PAN and JG _{80.1} @COF/PAN ⁸⁰	0.01 M 0.5 M 0.01 M	51.4	36.8	--	7.85×10 ⁻⁹
HB _{0.84} /JG _{0.55} @COF and JG _{0.86} /HB _{0.54} @COF ⁸¹	0.5 M 0.01 M	63.7	23	--	--
HB _{5.7} @COF-TamDha/PAN ⁸²	0.5 M 0.01 M	75.4 (129 ^[a])	--	120 mW cm ⁻²	1.5×10 ⁻¹⁰
COF-TpDa/ANF ⁸³	0.5 M (H ₂ SO ₄)+1 mM (NaCl) 0.01 M (H ₂ SO ₄)	550.5	--	--	5.03×10 ⁻⁵
COF-TftTmt ⁸⁴	0.5 M 0.01 M	14.1 (pH=14)	--	--	7.85×10 ⁻⁹
COF-TbBdt ⁸⁵	0.5 M 0.01 M	96 (155 ^[a])	27.1 (46.1)	0.5 M 0.05 M Na ₃ PO ₄	7.85×10 ⁻⁹
COF-TamDha ⁸⁶	0.5 M 0.01 M	217.7	--	--	2.25×10 ⁻¹⁰
COF-TafDb ⁸⁷	0.5 M 0.1 mM	0.17 mW m ⁻²	--	--	--
COF-300 ⁸⁸	0.5 M 0.01 M (KCl)	5.31	10.38	--	2×10 ⁻⁸
COF-LZU1/CNT-CNF ⁸⁹	0.5 M 0.01 M	3.91	--	--	3×10 ⁻⁸
COF-TpPa-COOH/HPAN ⁹⁰	0.5 M 0.01 M (KCl)	4.90	32.6	--	3×10 ⁻⁸
COF-TpPa/PAN ⁹¹	3 M 3 M (KCl)	20.22	--	PO ₄ ³⁻ , ΔT=50 K	7.85×10 ⁻⁹
COF-DhHz ⁹²	2.5 M 0.05 M	16.9	36	--	3×10 ⁻¹⁰
DG _{6.2} @COF/PAN ⁹³	0.5 M (NaCl) 5 mM (CaCl ₂)	42.2	48	--	1.5×10 ⁻¹⁰
COF-TfbTb/AAO ⁹⁴	5 M 0.01 M	17.95	4.5	--	3×10 ⁻⁸
COF-TpTapa/ANM ⁹⁵	5 M 0.01 M	27.8 (pH=6.2)	9.58	--	3×10 ⁻⁸

[a] The values in parentheses represent the output power density when an additional power difference is present.

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