Supplementary information

Advances in Preparing Metal–Organic Framework-Based Air Filters for the Removal of Particulate Matter, Volatile Organic Compounds, and Toxic Gases

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Comprehensive comparisons of various MOF-based composite filters for particulate, VOCs and gaseous pollutant removal

Sequence	Ref No	MOF type	MOF synthesis method	MOF-based filter / material	Substrates	How MOF was attached	MOF loading rate	MOF particle size / morphology	Crystallinity or particle size characterization	Filter thickness / size / basis weight for PM tests	PM concentration and test condition	PM removal efficiency	Pressure drop after PM test	Face velocity	Temperature / RH	PM test duration	PM removal test type	Concentration of VOC or toxic gases before adsorption	VOC or toxic agas adsorption capacity	VOC or toxic gases adsorption test	VOC or toxic gases adsorption test temperature	Filter thickness / size for VOC or toxic gas adsorption tests	Relative humidity for the VOC or toxic gas adsorption test	Test area	VOC or toxic gases adsorption test duration	Pressure drop after VOC or toxic gas adsorption	No of replicates / uncertainty	Activation / regeneration	VOC or toxic gas test type	Breakthrough / hotlights	Key limitations / comparability
1	25	UiO-66-NH2	Solvothermal method	MOF-PAN/MOF-fibers MOF-PS/MOF-fibers MOF-PVP/MOF-fibers	Aluminum foil, nonwoven fabric or stainless steel mesh	MOF-PAN, MOF-PS or MOF-PVP solutions firstly prepared, then electrospun on substrates.	20–60 wt%	UiO-66-NH2 irregular, ~ 150 nm	PXRD, FT-IRM, TEM, BET	Thickness: to roughly fit particular filter.	PM2.5~500 μg/m3, PM10~720μg/m3	About 85% for PM2.5, 86.8% for PM10. 3rd place in the tests.	NA	Not available. SGZ5102 (cotton) spread at 30mL/min at 115 l/cotton (diameter	25°C, 60% RH	Every 4 hours for 48 hours	Dynamic	100 ppm	UiO-66-NH2/PAN achieved the highest in the tests, reaching 0.019 g/g for the SO2.	95 mL/min	25°C	Eight layers of the filter with a diameter of 2 cm were cut in the filter cell and exposed to the stream.	60% RH	3.14cm² (2cm diameter filter)	20 min	20.0 Pa	N/A	Not mentioned	Dynamic	UiO-66-NH2/PAN achieved the highest in the tests in this paper, reaching 0.019 g/g for the SO2.	Lower PM removal efficiency. No data on VOC adsorption capability.
1	25	ZIF-8	Solvothermal method	MOF-PAN/MOF-fibers MOF-PS/MOF-fibers MOF-PVP/MOF-fibers	Aluminum foil, nonwoven fabric or stainless steel mesh	MOF-PAN, MOF-PS or MOF-PVP solutions firstly prepared, then electrospun on substrates.	20–60 wt%	ZIF-8 round particle ~125 nm	PXRD, FT-IRM, TEM, BET	The thickness of each layer of ZIF-8/PAN/MOF-fiber with nonwoven support is 10 μm. A piece of fiber with a diameter of 2 cm was cut as one tests	PM2.5~500 μg/m3, PM10~720μg/m3	ZIF-8/PAN/MOF-fiber shows the highest PM removal efficiency of 86.3% (~2.20% for PM2.5, 89.8% for PM10).	NA	Not available. SGZ5102 (cotton) spread at 30mL/min	25°C, 60% RH	Every 4 hours for 48 hours	Dynamic	100 ppm	The lowest capacity, 0.004 g/g for SO2.	95 mL/min	25°C	Eight layers of the filter with a diameter of 2 cm were cut in the filter cell and exposed to the stream.	60% RH	3.14cm² (2cm diameter filter)	20 min	20.0 Pa	N/A	Not mentioned	Dynamic	Very low SO2 capacity (0.004 g/g). No data on VOC adsorption capability.	Lower PM removal efficiency. No data on VOC adsorption capability.
1	25	Mg-MOF-74	Solvothermal method	MOF-PAN/MOF-fibers MOF-PS/MOF-fibers MOF-PVP/MOF-fibers	Aluminum foil, nonwoven fabric or stainless steel mesh	MOF-PAN, MOF-PS or MOF-PVP solutions firstly prepared, then electrospun on substrates.	20–60 wt%	Mg-MOF-74, irregular, 500–1000 nm	PXRD, FT-IRM, TEM, BET	Thickness: to roughly fit particular filter.	PM2.5~500 μg/m3, PM10~720μg/m3	About 85.9% for PM2.5, 85% for PM10. 2nd place in the tests.	NA	Not available. SGZ5102 (cotton) spread at 30mL/min	25°C, 60% RH	Every 4 hours for 48 hours	Dynamic	100 ppm	The 3rd in the test, 0.043 g/g for SO2.	95 mL/min	25°C	Eight layers of the filter with a diameter of 2 cm were cut in the filter cell and exposed to the stream.	60% RH	3.14cm² (2cm diameter filter)	20 min	20.0 Pa	N/A	Not mentioned	Dynamic	\	Lower PM removal efficiency. No data on VOC adsorption capability.
1	25	MOF-199	Solvothermal method	MOF-PAN/MOF-fibers MOF-PS/MOF-fibers MOF-PVP/MOF-fibers	Aluminum foil, nonwoven fabric or stainless steel mesh	MOF-PAN, MOF-PS or MOF-PVP solutions firstly prepared, then electrospun on substrates.	20–60 wt%	MOF-199 round, ~ 120 nm	PXRD, FT-IRM, TEM, BET	Thickness: to roughly fit particular filter.	PM2.5~500 μg/m3, PM10~720μg/m3	About 70% for PM2.5, 85% for PM10. 4th place in the tests.	NA	Not available. SGZ5102 (cotton) spread at 30mL/min	25°C, 60% RH	Every 4 hours for 48 hours	Dynamic	100 ppm	The 2nd in the test, 0.043 g/g for SO2.	95 mL/min	25°C	Eight layers of the filter with a diameter of 2 cm were cut in the filter cell and exposed to the stream.	60% RH	3.14cm² (2cm diameter filter)	20 min	20.0 Pa	N/A	Not mentioned	Dynamic	\	Lower PM removal efficiency. No data on VOC adsorption capability.
2	80	ZIF-67	In situ synthesis	ZIF-67@PAN	Electrospun PAN nanofiber	MOF grown homogeneously in-situ on PAN by immersion treatment	40% ~ 200% mass ratio	Irregular, size not measured, roughly 150 ~ 300 nm from SEM images	XRD, SEM, TEM, BET	4cm × 4 cm × 30 mL. Thickness was not provided.	NA	97.2% ~ 63.8% for PM2.5.	49 Pa for ZIF-67@PAN, 79 Pa for PAN fiber	5 m/s	30 °C, 80% RH	Not reported. Likely at 0.5 h	Dynamic	100 ppb formaldehyde	84.9% formaldehyde by after 15 min, 75% after 120 min	N/A	Not reported, likely 25°C	N/A	N/A	N/A	120 min	N/A	N/A	N/A	84.9% formaldehyde after 15 min, 75% after 120 min	No data on the pressure drop after formaldehyde. VOC: no data on regeneration
3	52	ZIF-8	In situ synthesis. Electrospun fibers were immersed in methanol for recrystallization by steam diffusion	ZIF-8@SiO2 nanofiber membrane	SiO2-containing nanofiber membrane	ZIF-8 nanocrystals grown on SiO2 nanofiber membrane surfaces by solvothermal by steam diffusion.	20-60%	ZIF-8 round particle ~120 nm	XRD, FESEM, FTIR, BET	A piece of membrane with its size area of 7.07 cm² (φ = 3 cm).	Isooctane smoke, inlet 382 mg/m3	99.96% removal for isooctane smoke	1.4kPa	2 cm/s	PM test: not reported. Likely at ambient.	10 min	Dynamic	Initial concentration of formaldehyde in 1.42 mg/m3	79.35% formaldehyde adsorption capacity (1.42 mg/m3 × 1 m3/h × 0.5 h = 0.7 mg) for formaldehyde.	0.9 cm/s	25 °C	Three specimens stacked in a 50 mm diameter column	50% RH	1963 cm² (in 3cm diameter column)	120 min	N/A	PM: n=5, SD error bars. Gas: not stated	by purging N_2 overnight at 80 °C	N/A	N/A	N/A	N/A	No data on the pressure drop after 7 cycles of formaldehyde adsorption.
4	53	Zr-MOF (UiO-66)-grafted cotton fabric (UiO-66-NH2, UiO-66-(OH)2, MIL-101(Cr)-NH2, MIL-101(Cr)-(OH)2)	Solvothermal method	Zr-MOF/cotton with different functional groups	Cotton	Covalent bonding of cyno-polysiloxane(CPTMS) on MOF crystals to cotton using CPTMS as a linker between the MOF and cotton.	MIL-7: 1062.2 mg/g; UiO-66: 1 cotton (26.2610 MOF: 1054.6	Irregular, size not measured	XRD, SEM, FTIR, BET	Square-shape fibre, 5cm × 5 cm	PM2.5 concentration: 500 ± 125 ppm, PM10 concentration: 700 ± 85 ppm.	Best results: Zr-MOF-NH2 cotton: 89.5% PM2.5 / 91.0% PM10. Other Zr-MOF-functional cotton: 85.0% PM2.5 and 87.0% PM10.	31 Pa	20 cm/s (0.2 m/s)	N/A	12 h	Dynamic	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	No data on VOC adsorption capacity.
5	54	ZIF-67	Hydrothermal method at RT	ZIF-67/PS/HPMF6/polystyrene hierarchical porous nanofiber membrane)	Polystyrene nanofiber membrane	Electrospinning, ZIF-67 engaged in Polystyrene nanofiber membrane	0.8%, 10.23%, 16.8%, 22.3%, 19.3%	ZIF-67 crystallites immersed cube shape, ~ 22 nm	PXRDM, TEM, FTIR, XRD, XPS, TGA, BET	Thickness: 0.15 ± 0.002 mm; PM load area: 25 cm²	Ncl/3 ~2.5 μm, 5.35 cm/s, ~25 cm² 200 mg of PM2.5, 2.66 cm² 10h 0% RH	99.92% PM2.5 (Ncl/3), all membranes: >98.7% above 0.3 μm. Incense smoke test: 99% PM2.5	91 Pa	0.35 cm/s	10%RH, room temperature	NA	Dynamic	SO2, NO and HCHO/N2 concentration was 45 ppm, 50 ppm and 100 ppm. 0.2 g of MIF-100 was added in the membrane module for the time-adsorption dependent tests	1.582 mg/g at equilibrium for SO2, NO and HCHO removal efficiency was 91.3%, 100% and 68%, respectively	50 mL/min for SO2, NO and HCHO	room temperature	0.15 ± 0.002 mm	10% RH (capacity peaks at 10%, falls either side)	2.84 cm²	>5 h to reach equilibrium; 1.5 h according to Fig.2.	N/A	N/A	N/A	N/A	Dynamic	1.582 mg/g at equilibrium for SO2, NO and HCHO removal efficiency was 91.3%, 100% and 68%, respectively	Both controls possess [MOF fiber and base substrate] and [MOF fiber and base substrate] exhibit similar trends. But the UiO ergy is an equilibrium endpoint in a closed module and must not be ranked against any dynamic breakthrough capacity.
6	55	ZIF-8	In situ growth method	ZIF-8 grown PLA fiber web	Polylactic acid (PLA) fibers	In situ ZIF-8 growth on PLA web, cotton changing	NA	NA	XRD, SEM, TEM, contact angle	NA	NaCl aerosols, with particle size of 75 nm and concentration of 32 ± 20 mg/m³	89.4% (from theory-designed ZIF@PLA; #3 for NaCl)	20 Pa	5.8 cm/s	N/A		Dynamic	0.02 % para	100 × 10⁻⁶ mmol g-1(t=min) from mean ZIF@PLA; #3	5 cm/s	25 °C	diameter of 7.13 cm	50%	40 cm²	N/A	N/A	N/A	N/A	Dynamic		Lack of PM2.5 and PM10 tests, hard to judge the PM removal performance. No data on VOC adsorption. No regeneration data.
7	56	MIL-125-NH2	Solvothermal method	ILS&OH&in-MIL-125-NH2-MIMO-13	MIMO-13 solvent	Liquid-filtration deposition	5, 10, 25 wt%	MIL-125-NH2 octagonal plate, length = 700 nm, thickness ~ 300 nm	XRD, SEM, FTIR, BET	0.47 ± 0.05 mm; 75 ± 2 g/m² two cases 200 cm²	Monodisperse NaCl particles with a size of 261-700 nm	20%Efficiency was close to clean MIMO-13 at low loading; 100%Efficiency was close to clean MIMO-13 at high coating level (250wt%).	<1.5% (5 wt%), <1.7% (10 wt%), <12.2% (25 wt%) at v = 0.1 ~ 0.5 m/s base	5 cm/s *	~30% RH	NA	Dynamic	5 ppm toluene	5 cm/s	Not reported, likely 25°C	47 mm diameter flat sheet	Not reported, likely ~30% RH	17.35 cm²	N/A	N/A	N/A	N/A	Dynamic	1.Efficiency was close to clean MIMO-13 at low loading; 2.The initial toluene removal efficiency of the MIMO-13 ILS&OH&in-MIL-125-NH2 reaches 75% and 89% for the uncoated and coated MIL-125-NH2 powders, respectively	Our NaCl nanoparticles are a coarser of PM2.5. No data on PM10. The cyclone smoke and/or DFU BIG but may not be representative of PM2.5 in real-world usage. Anyway, the overall performance is good!
7	56	UiO-66-NH2	Solvothermal method	ILS&OH&in-UiO-66-NH2-MIMO-13	MIMO-13 solvent	Liquid-filtration deposition. *this study was not trying to be coated onto MIMO-13 and a longer coating time is needed*	5, 10, 25 wt%	~ 200 nm	XRD, SEM, FTIR, BET	0.47 ± 0.05 mm; 75 ± 2 g/m²	Monodisperse NaCl particles with a size of 261-700 nm	Close to clean MIMO-13 at low loading	NA	5 cm/s *	~30% RH	NA	Dynamic	5 ppm toluene	Toluene: 40% (25 wt%, MIMO-13)	5 cm/s	Not reported, likely 25°C	47 mm diameter flat sheet	Not reported, likely ~30% RH	17.35 cm²	N/A	N/A	N/A	N/A	Dynamic	\	Lower VOC performance than MIL-125-NH2. demonstrates importance of MOF chemistry
7	56	ZIF-67	Solvothermal method	ILS&OH&in-ZIF-67&MIMO-13	MIMO-13 solvent	Liquid-filtration deposition	5, 10, 25 wt%	*no average size is close to that of MIL-125-NH2 particles*, no data found.	XRD, SEM, FTIR, BET	0.47 ± 0.05 mm; 75 ± 2 g/m²	Monodisperse NaCl particles with sizes of 261-700 nm	Close to MIMO-13 at low loading	NA	5 cm/s *	~30% RH	NA	Dynamic	5 ppm toluene	Toluene: 20% (25 wt%, MIMO-13)	5 cm/s	Not reported, likely 25°C	47 mm diameter flat sheet	Not reported, likely ~30% RH	17.35 cm²	N/A	N/A	N/A	N/A	Dynamic	\	Demonstrates that PM fraction alone does not predict VOC performance
7	56	MIL-125-NH2, UiO-66-NH2, ZIF-67	Solvothermal method	ILS&OH&in-MIMO-13/MIPA	MIPA (or MIMO-13) cluster	Liquid-filtration deposition. MOFs were less uniformly coated onto MIPA, thicker than MIMO-13	5, 10, 25 wt%	NA	XRD, SEM, FTIR, BET	0.5 ± 0.05 mm; 72 ± 2 g/m²	Monodisperse NaCl particles with sizes of 261-700 nm	High initial PM efficiency	NA	5 cm/s *	~30% RH	NA	Dynamic	NA	NA	NA	NA	47 mm diameter flat sheet	Not reported, likely ~30% RH	17.35 cm²	N/A	N/A	N/A	N/A	Dynamic	\	High baseline pressure drop and smaller pores make MOF-coated MIPA less practical than MIMO-13 for multifunctional applications
8	57	UiO-66	Solvothermal method	UiO-66@bacterial cellulose aerogel	Bacterial cellulose	Pre-made MOF powder blended into BC suspension, ethanol-assisted, then physically entrapped in the cellulose network by freeze-drying	0.1–0.4 g MOF per 0.5 g BC powder	NA	XRD, SEM, BET, FTIR, Zeta potential	Thickness: 0.8 cm, diameter ca. 4.0 cm	800 μg/m³ PM2.5	96.9–97.7% for PM2.5	57 Pa	2 cm/s (200 cm/s)	80%RH	30h	Dynamic	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	Segmentation: Back with 300-mL water ethanol (1:1 mix), 9 cycles, efficiency stayed >96%.	NA	\	Only incense smoke as PM2.5 source. No VOC or toxic gas adsorption tests.
8	57	UiO-66-NH2	Solvothermal method	UiO-66-NH2@bacterial cellulose aerogel	Bacterial cellulose	Pre-made MOF powder blended into BC suspension, ethanol-assisted, then physically entrapped in the cellulose network by freeze-drying	0.1–0.4 g MOF per 0.5 g BC powder	Regular octahedral morphology, particle size around 500 nm	XRD, SEM, BET, FTIR, Zeta potential	Thickness: 0.8 cm, diameter ca. 4.0 cm	800 μg/m³ PM2.5	91.1–91.3% for PM2.5	24.1 ± 0.7 Pa	2 cm/s (200 cm/s)	80%RH	30h	Dynamic	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	\	Only incense smoke as PM2.5 source. No VOC or toxic gas adsorption tests.
9	58	ZIF-8	Electrocompressive solution synthesis method*	MOF-coated CA/SF cotton fabric membrane	Cotton acetate nanofiber (CA/SF) membrane	MOF incorporated with electrospun nanofibers/cotton architecture	2.6 mV/s	Hexagonal (2D) and Cuboctahedral (3D) shaped	Zeta potential, SEM, BET	9.2 (2), 0.242, 0.253, 0.279, and 0.363 mm for NPNA, NP1.8, NP3.6, NP4.8, and NP7.2 mm, Cotton-based 30 g/m² effective area 38 cm²	NA	95.48%	14.2 Pa	32 L/min	N/A	N/A	Dynamic	100 ppm	N/A	Filter is chamber with air out flow)	Not reported, likely room temperature	10 mm 15 cm	N/A	380 cm² (20 mm × 19 cm Gas inlet/filter)	120 min	N/A	≈ 9.2 (for measurements, take average)	N/A	static	\	PM free due particle size of NaCl in nuclear. The toxic gas adsorption test is a sealed chamber concentration decay, so the ~99% gas figures are based on static conditions. No VOC tests.
10	59	ZIF-8	Electrocompressive solution synthesis method*	ZIF-8/Polystyrene nanofiber membrane	Polystyrene nanofiber membrane	ZIF-8 was incorporated into electrospun PS fibers during electrospinning process.	4.0 wt%, 7.4 wt%, 13.1 wt%, 17.2 wt%, and 21.4 wt%	Spherical shape, average particle size 50 nm	XRD, TEM, ZETA, BET	Thickness: 75μm; filtration area 12.5cm²	Ncl/3aerosol particles with a mean diameter of 260 nm at a mass PM. incorrect smoke with PM2.5 concentration of 500mg/m³	99.75% PM2.5 / 99.96% PM10	63 Pa (PM2.5) and 47 Pa (PM2.5), respectively	2.66 cm/s	N/A	30 min	Dynamic	100 ppm SO2/N2 gas	1570 mg/g SO2	0.5cm/s	25°C	75μm thickness membrane	10±5% RH	N/A	10h	N/A	N/A	N/A	Dynamic	1.Diameter of efficiency: 99.75% PM2.5 / 99.96% PM10 / 0.137/99 mg/g SO2.	Lack of regeneration data.