Supporting Information for:

Impact of Wildfire Smoke Events on Indoor Air Quality and Evaluation of a Low-Cost Filtration Method

Nathaniel W. May[1*], Clara Dixon[1], and Daniel A. Jaffe[1,2]

[1]*University of Washington Bothell, Bothell, WA 98011, USA*
[2]*University of Washington, Seattle, WA 98195, USA*

*Corresponding author: natemay@uw.edu

S1 EXPERIMENTAL

S1.1 MERV-13 Fan Filter Unit Design

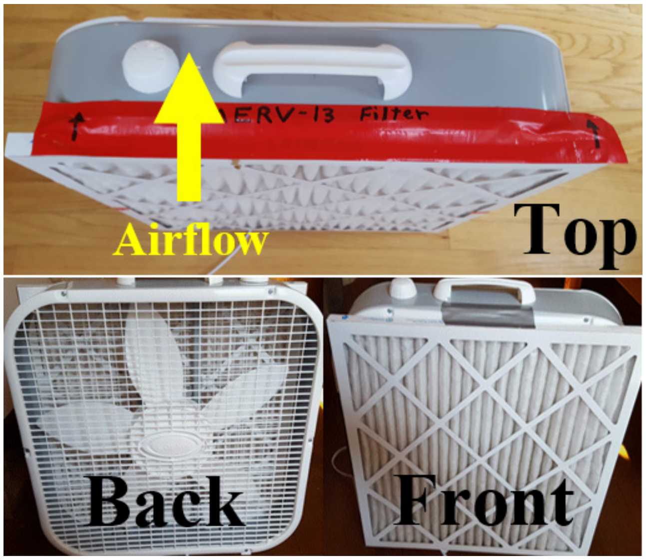

Figure S1. Photographs of the top, back, and front of the MERV-13 filter fan unit (FFU).

S1.2 Size-Resolved Measurements of PM

A Grainger 23V750 handheld particle counter was used to measure size resolved particle number concentrations in six size bins (0.3, 0.5, 1.0, 2.5, 5.0, and 10 μm), with the two submicron size bins the focus of analysis herein. This particle counter has been used to measure particle number concentration in at least one prior study (Reiman et al., 2018), but no performance evaluations are found in the literature. PAS are known to lack particle sizing specificity (Levy Zamora et al., 2019), which is a product of the lack of sheath air to separate individual particles in the sensing region and the wide laser beam that scatters an ensemble of particles rather than individual particles. The Grainger 23V750, which employs a similar sensing method to the PAS, may have the same limitations in particle sizing specificity.

The EDM-180 is a US EPA equivalence monitor for 24-hour averaged $PM_{2.5}$ mass concentrations that operates at a flow rate of 1.2 L min^{-1} with a nafion dryer inlet and a 660 nm laser to optically measure number concentrations in 31 size bins (0.23−32 μm) (Grimm and Eatough, 2009). The following linear regression equation of 5-minute averaged number concentrations measured by Grainger and Grimm under laboratory smoke conditions **(Figure S2)** was used to correct experimental Grainger data. The 0.3 μm Grainger size bin correction factor was calculated by comparison to the sum of 0.30, 0.35, 0.40, and 0.45 μm Grimm size bins, and the 0.5 μm Grainger size bin correction factor calculated from the sum of 0.50, 0.58, 0.65, 0.70, and 0.80 μm Grimm size bins. The divergent slopes and large y-intercepts of the 0.3 and 0.5 μm size bin linear regressions indicate the lack of particle sizing specificity results in an undercount of smaller particles and an overcount of larger particles by the Grainger **(Figure S2)**. We also tested the filtration of wildland fire smoke by a MERV-13 FFU in a single pass through by placing the apparatus in an open window, with Grainger measurements on alternating sides used to estimate reductions in particle number concentrations **(Figure S5)**.

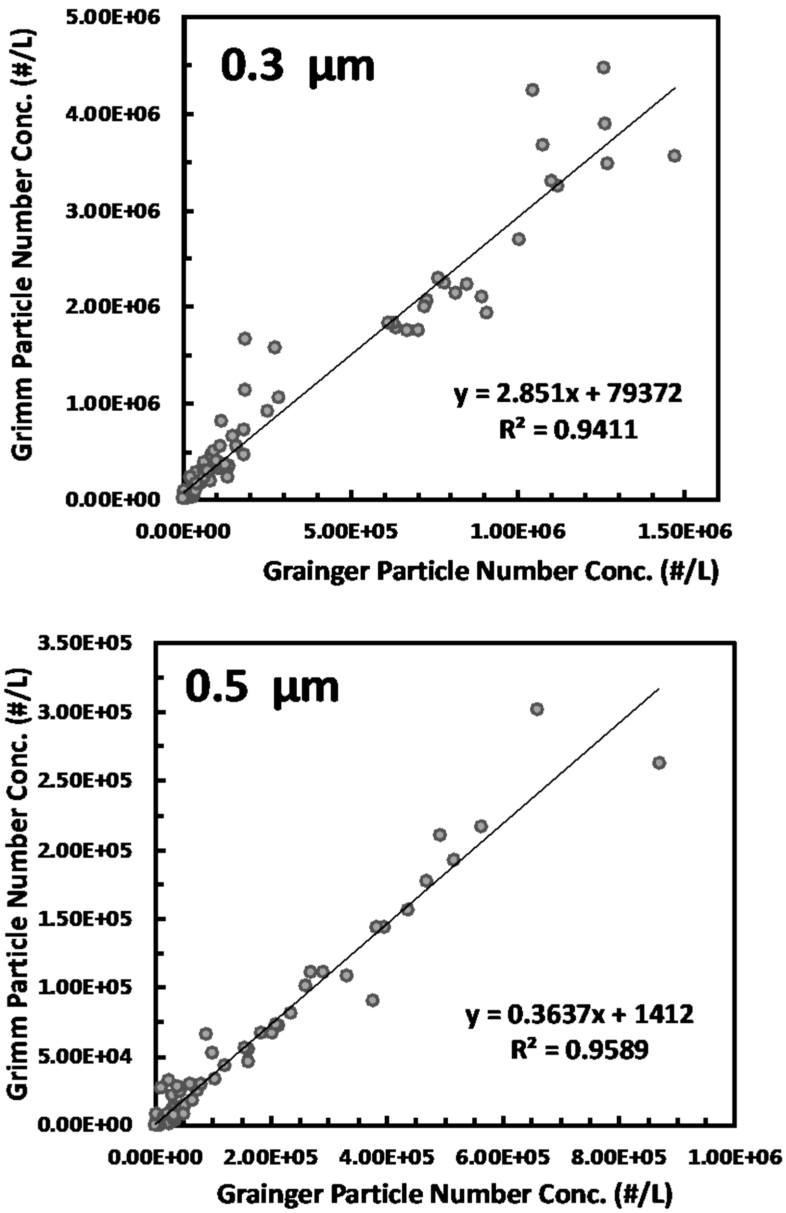

Figure S2. Scatter plots and linear regression of 5-minute averaged Grainger and Grimm EDM-180 particle number measurements, for the Grainger 0.3 and 0.5 µm size bins, of laboratory-generated smoke. The Grainger 0.3 µm size bin was compared to the sum of the 0.30, 0.35, 0.40, and 0.45 µm Grimm size bins, and the 0.5 µm Grainger size bin was compared to the sum of the 0.50, 0.58, 0.65, 0.70, and 0.80 µm Grimm size bins.

S1.3 PurpleAir Sensors & $PM_{2.5}$ Measurements

Table S1. PurpleAir sensor (PAS) indoor (I) and outdoor (O) locations and the results of linear regression analysis of indoor and outdoor $PM_{2.5}$ measurements, including slope (F_{in}), y-intercept (C_s), linear correlation coefficient (R^2), I/O ratios, as well as maximum and minimum I and O $PM_{2.5}$ concentrations. PAS data is from the wildfire smoke−impacted period of 9/5/2020 00:00–9/15/2020 23:00 UTC. Building types are school (S), commercial (C), and residential (R).

Indoor (I) & Outdoor (O) Sensor Names & Locations	Build Type	F_{in}	C_s	R^2	I/O	Indoor $PM_{2.5}$ (μg m^{-3}) Max	Indoor $PM_{2.5}$ (μg m^{-3}) Min	Outdoor $PM_{2.5}$ (μg m^{-3}) Max	Outdoor $PM_{2.5}$ (μg m^{-3}) Min
O: "Tonasket School District – Outdoor" I: "Tonasket HS/MS Indoor" (Tonasket, WA)	S	0.771	-2.25	0.968	0.745	262	3	294	2
O: "Gateway School" I: "Gateway School: Indoors" (Santa Cruz, CA)	S	0.719	-0.33	0.923	0.712	129	6	145	5
I: "UC Berkeley Stanley Hall Indoor Air" O: "UC Berkeley Stanley Hall Outside Air" (Berkeley, CA)	S	0.797	-0.62	0.996	0.785	137	2	172	2
I: "PPPM - Hendricks Hall" O: "PPPM - EMU Oregon Plaza" (Eugene, OR)	S	0.468	3.42	0.827	0.484	254	3	526	6
O: "CCA Del Rey" I: "CCA Del Rey Community Center" (Del Rey, CA)	S	0.632	6.82	0.755	0.817	92	13	135	12
I: "FRC MPB Indoor" O: "FRC MPB Outdoor" (Quincy, CA)	S	0.408	22.6	0.797	0.496	407	5	850	6
O: "Yolo County Office of Education Monitor" I: "Yolo County Office of Education Monitor" (Woodland, CA)	C	0.432	8.43	0.791	0.557	98	6	243	3
I: "AgreeYa Solutions" O: "AgreeYa Solutions HQ" (Folsom, CA)	C	0.549	3.55	0.939	0.599	156	7	270	8
O: "DP Lab PM1" I: DP Lab Inside PM1" (Sacramento, CA)	C	0.624	5.29	0.914	0.698	207	5	338	4
O: "ECOC – ROOF" I: "ECOC Warehouse" (Sacramento, CA)	C	0.436	16.6	0.613	0.721	145	7	298	4
O: "LRAPA-Cottage Grove" I: "LRAPA-Cottage Grove Library Indoor" (Cottage Grove, OR)	C	0.623	2.21	0.864	0.633	355	5	494	5
O: "LRAPA-Oakridge City Hall Outside" I: "LRAPA-Oakridge City Hall Inside" (Oakridge, OR)	C	0.288	11.9	0.485	0.331	252	5	547	5
O: "LRAPA-Office Outside" I: "LRAPA-Office Inside" (Springfield, OR)	C	0.304	-0.17	0.841	0.303	278	3	685	6
O: "402 Otterson Dr Outside" I: "402 Otterson Drive" (Chico, CA)	C	0.336	6.27	0.714	0.401	180	5	459	6

Indoor (I) & Outdoor (O) Sensor Names & Locations	Build Type	F_{in}	C_s	R^2	I/O	Indoor $PM_{2.5}$ (µg m^{-3})		Outdoor $PM_{2.5}$ (µg m^{-3})	
						Max	Min	Max	Min
I: "100 Oceangate" O: "SCSB_20" (Long Beach, CA)	C	0.709	1.06	0.861	0.746	66	3	114	3
I: "Canby Air Station 1B" O: "Canby Air Station 1C" (Canby, OR)	C	0.454	18.3	0.423	0.528	98	6	243	3
I: "360-Indoor" O: "360-Outdoor" (Mankas Corner, CA)	R	0.547	5.38	0.755	0.659	93	5	200	8
I: "KS Inside" O: "KS Outside" (Berkeley, CA)	R	0.601	5.67	0.939	0.705	131	4	204	2
I: "Mortar Rock" O: "Outside Mortar Rock" (Berkeley, CA)	R	0.252	7.09	0.438	0.367	100	2	221	2
I: "Chez Smuseby" O: "Hors De Chez Smuseby" (Kensington, CA)	R	0.687	2.04	0.935	0.725	143	3	192	2
O: "Chestnut Ave – Outside I: "Chestnut Ave Indoors" (Long Beach, CA)	R	0.010	7.77	0.001	0.279	46	3	96	8
O: "580farm" I: "580farm Inside" (San Leandro, CA)	R	0.028	8.81	0.025	0.181	68	2	217	3
O: "Castro Valley 37-122" I: "Castro Valley 37-122a" (Castro Valley, CA)	R	0.357	2.04	0.837	0.391	101	5	200	3
I: "Via Harriet (Inside)" O: "Via Harriet (Outside)" (Hayward, CA)	R	0.099	6.91	0.162	0.216	109	3	197	2
I: "Summit Adventure" O: "Summit Adventure" (Bass Lake, CA)	R	0.831	12.2	0.931	0.882	582	5	711	6
O: "Montara" I: "Montara" (Montara, CA)	R	0.744	5	0.800	0.865	118	2	159	1
I: "Hailey, ID" O: "Hailey, ID" (Hailey, ID)	R	0.309	8.93	0.355	0.571	115	3	172	4
O: "MesaVista" I: "MVcasa" (Boise, ID)	R	0.423	3.96	0.788	0.561	65	4	95	4
O: "Glenbrook House Rd" I: "GHR Inside" (Glenbrook, NV)	R	0.082	8.21	0.051	0.232	165	4	279	3
I: "Eagle Indoor Sensor" O: "Alpine View" (Incline Village, NV)	R	0.040	11.6	0.117	0.297	53	7	254	4
I: "Tyrolian Village" O: "Tyrolian Village" (Incline Village, NV)	R	0.409	10.5	0.746	0.622	99	5	306	4
O: "Nambe" I: "Nambe" (Reno, NV)	R	0.079	5.16	0.638	0.168	27	4	225	5

Indoor (I) & Outdoor (O) Sensor Names & Locations	Build Type	F_{in}	C_s	R^2	I/O	Indoor $PM_{2.5}$ (µg m^{-3})		Outdoor $PM_{2.5}$ (µg m^{-3})	
						Max	Min	Max	Min
O: "GH Tillamook Row" I: "GH Tillamook Row 48a" (Portland, OR)	R	0.189	17.8	0.222	0.306	262	3	576	5
I: "#1" O: "#2" (Bonney Lake, WA)	R	0.088	1.19	0.338	0.101	81	2	352	4
O: "Crestview-Outdoor" I: "Crestview-Indoor" (SeaTac, WA)	R	0.151	10.7	0.246	0.345	63	4	352	4
O: "Spokane South Hill #1" I: "Spokane South Hill #1" (Spokane, WA)	R	0.152	4.25	0.804	0.212	86	4	284	3
O: "Rockwood" I: "Rockwood Retirement" (Spokane, WA)	R	0.532	2.00	0.970	0.558	172	4	288	3
I: "Bryant Air – Indoor Wally!!!" O: "Bryant Air – Wally!!!" (Seattle, WA)	R	0.119	4.11	0.559	0.163	43	2	196	3
O: "Hopfer Road" I: "Hopfer 2" (Omak, WA)	R	0.150	12.9	0.280	0.284	99	3	386	3
O: "Fpk2d" I: "Fpk2e" (SeaTac, WA)	R	0.868	3.48	0.676	0.942	197	5	338	9
I: "GRIDBASE" O: "GRIDBASE" (Glide, OR)	R	0.222	-2.84	0.936	0.214	216	3	854	5
I: "Indoor Sandee Palisades, Troutdale" O: "Sandee Palisades, Troutdale" (Troutdale, OR)	R	0.102	8.24	0.457	0.151	111	3	464	4

S2 RESULTS & DISCUSSION

S2.1 Residential Case Study

An additional residential case study, with particle infiltration examined with and without interventions to improve IAQ, is presented in **Figure S3**. In August 2018, an unoccupied home in OR ran a weekly AC cycle with standard HVAC filters installed. A F_{in} of 0.38 was observed during this month-long wildfire smoke−influenced period. The same OR home was occupied in July and August 2019, with MERV-13 air filters installed in the HVAC system and two automated HEPA filter units. During a 10-day period of wildfire smoke influence, the continuous use of multiple filtration methods contributed to a 50% lower F_{in} (0.18) than observed with weekly HVAC filtration in 2018. Windows and doors were closed at all times in the residence. The results of the residential case studies **(Figures 2 & S4)** together demonstrate that the type, number, and frequency of interventions to improve IAQ is highly influential in $PM_{2.5}$ infiltration during wildland fire smoke events.

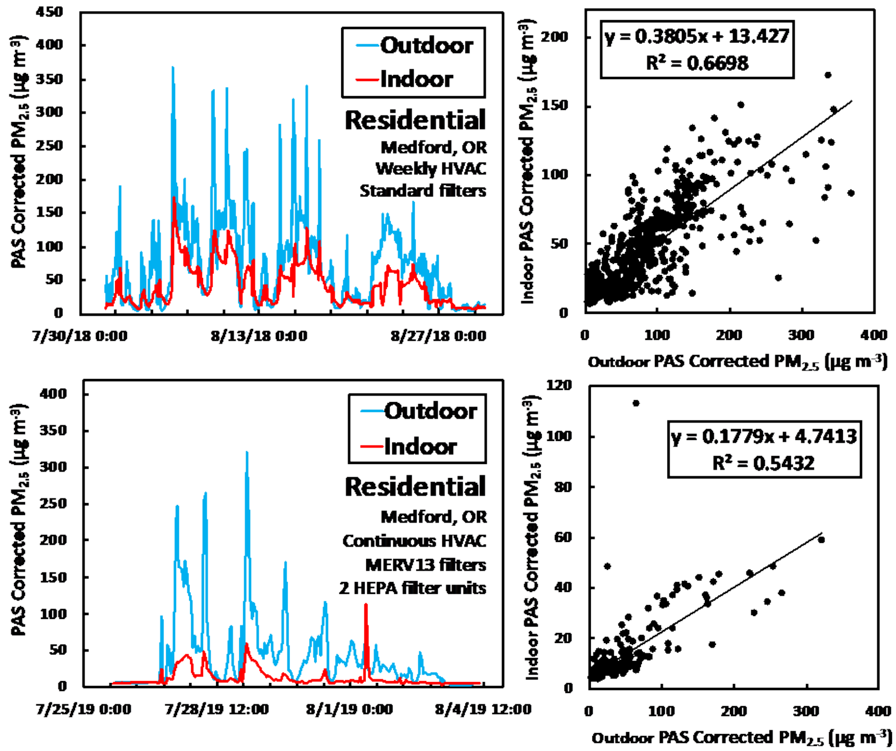

Figure S3. Outdoor and indoor $PM_{2.5}$ mass concentrations measured by Purple Air sensors (PAS) with EPA correction applied for a Medford, OR, residential location during summer wildfire smoke-impacted periods in 2018 and 2019. Location name and information on indoor air quality interventions is presented in the time series (left), with corresponding F_{in} (slope), C_S (y-intercept), and correlation coefficients (R^2) presented in correlation plots (right).

S2.2 Commercial & School Case Studies

The two commercial case studies **(Figure S4)**, which were both occupied to some degree, kept windows and doors closed but did not report indoor air quality interventions beyond standard HVAC filtration. Despite similar reported air handling, the Cottage Grove, OR, library (F_{in} = 0.62) exhibited twice the $PM_{2.5}$ infiltration of the Springfield office (F_{in}=0.30) and the Oakridge city hall (F_{in} = 0.31) **(Table S1)**. The $PM_{2.5}$ I/O ratio at the Cottage Grove library is consistent with observed higher black carbon I/O ratio in commercial buildings with an HVAC system supplied by outdoor air, lower rated filters, and/or permanently open doors or windows (Wu et al., 2012). In contrast, the Springfield office is consistent with observed lower black carbon I/O ratios in commercial buildings with all windows and doors closed, higher rated filters, and/or recirculating air HVAC system (Wu et al., 2012). However, recirculated air and decreased outdoor air exchange is associated with increased airborne viral transmission (Jarvis, 2020; Morawska et al., 2020). The school case study (Tonasket, WA) reported the use of standard HVAC filtration similar to the commercial case studies, but with some windows opened to increase outdoor air exchange in response the COVID-19 pandemic (Schoen, 2020) **(Figure S4)**. The Tonasket school, which was occupied by staff to some degree but not students, exhibited higher $PM_{2.5}$ infiltration (F_{in} = 0.77) than either commercial case study.

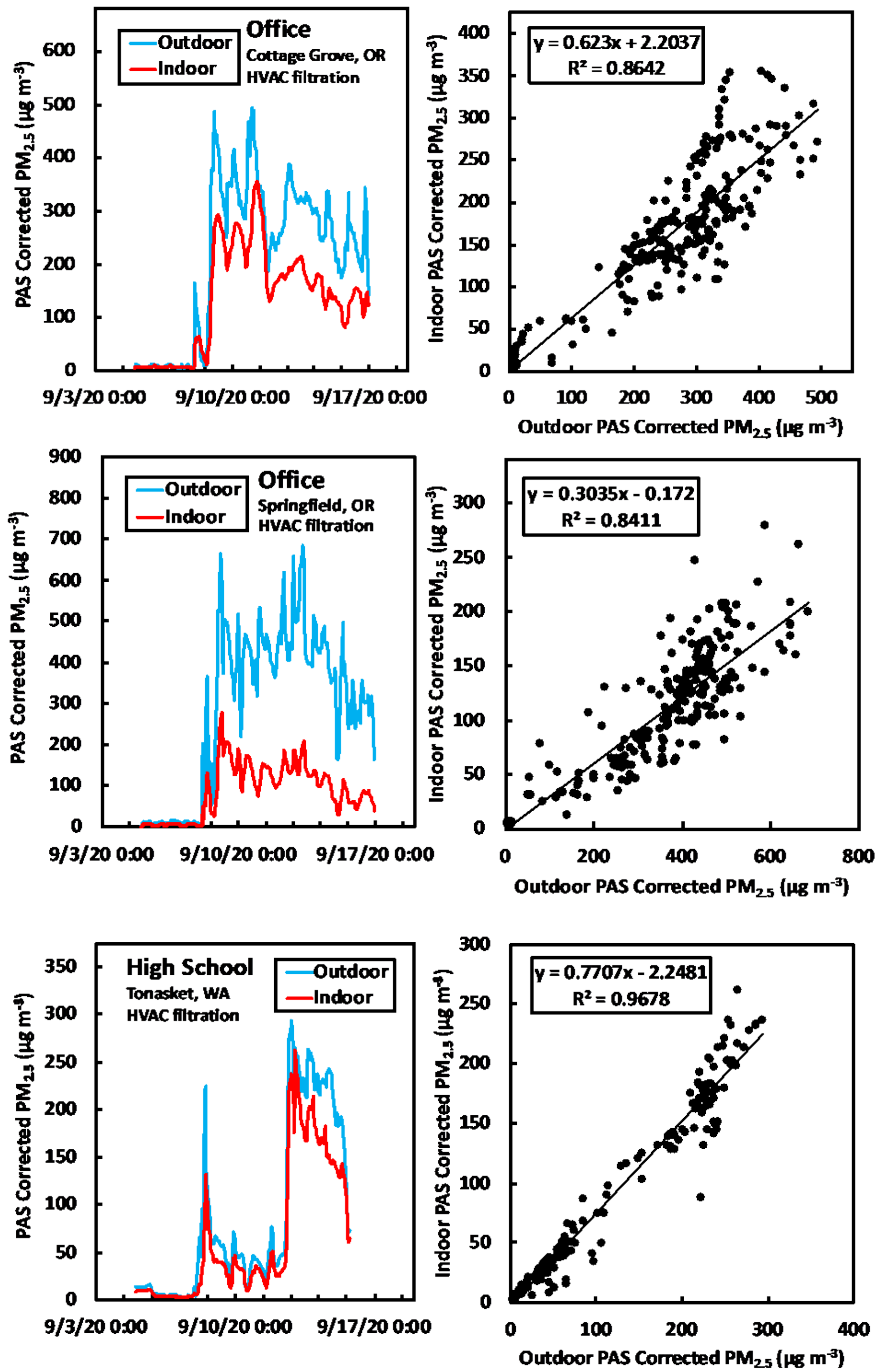

Figure S4. Outdoor and indoor $PM_{2.5}$ mass concentrations measured by Purple Air sensors (PAS) with EPA correction applied during wildfire smoke–impacted time periods during a September 5–15, 2020 period of wildfire smoke for two commercial and one school case study locations. Location name and information on indoor air quality interventions is presented in the time series (left), with corresponding F_{in} (slope), C_S (y-intercept), and correlation coefficients (R^2) presented in correlation plots (right).

S2.3 MERV-13 Fan Filter Unit Submicron Filtration

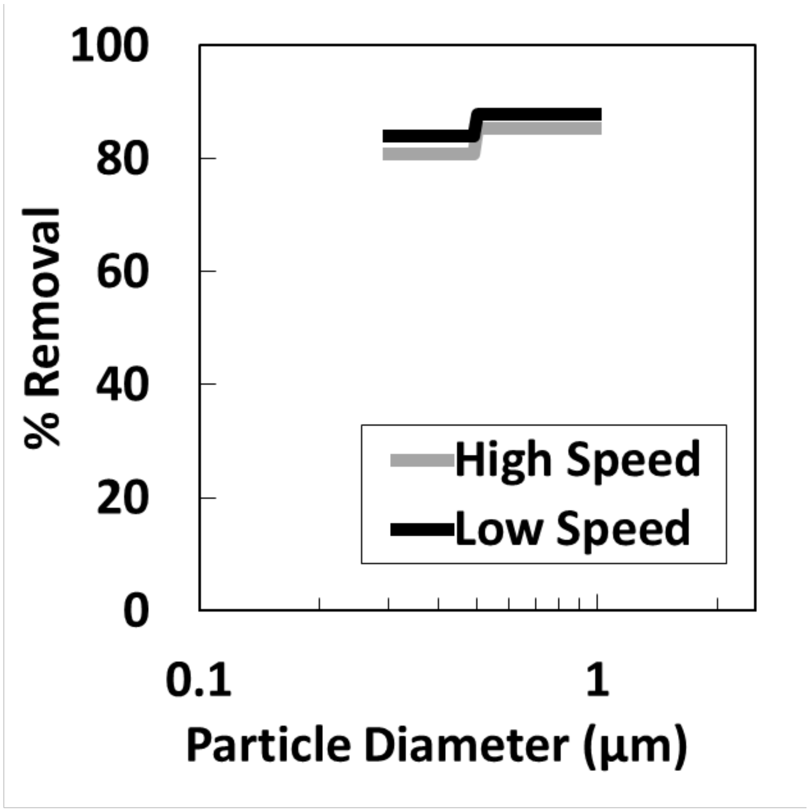

Figure S5. Percent reduction of submicron particle number concentration, measured by the Grainger particle counter, after a single pass through the MERV-13 filter in a Seattle, WA, home impacted by wildfire smoke on September 14, 2020.

References

Grimm, H., Eatough, D.J. (2009). Aerosol Measurement: The Use of Optical Light Scattering for the Determination of Particulate Size Distribution, and Particulate Mass, Including the Semi-Volatile Fraction. J. Air Waste Manage. Assoc. 59, 101–107. https://doi.org/10.3155/1047-3289.59.1.101

Jarvis, M.C. (2020). Aerosol Transmission of SARS-CoV-2: Physical Principles and Implications . Frontiers in Public Health. https://doi.org/10.3389/fpubh.2020.590041

Levy Zamora, M., Xiong, F., Gentner, D., Kerkez, B., Kohrman-Glaser, J., Koehler, K. (2019). Field and Laboratory Evaluations of the Low-Cost Plantower Particulate Matter Sensor. Environ. Sci. Technol. 53, 838–849. https://doi.org/10.1021/acs.est.8b05174

Morawska, L., Tang, J.W., Bahnfleth, W., Bluyssen, P.M., Boerstra, A., Buonanno, G., Cao, J., Dancer, S., Floto, A., Franchimon, F., Haworth, C., Hogeling, J., Isaxon, C., Jimenez, J.L., Kurnitski, J., Li, Y., Loomans, M., Marks, G., Marr, L.C., Mazzarella, L., et al. (2020). How can airborne transmission of COVID-19 indoors be minimised? Environ. Int. 142, 105832. https://doi.org/10.1016/j.envint.2020.105832

Reiman, J.M., Das, B., Sindberg, G.M., Urban, M.D., Hammerlund, M.E.M., Lee, H.B., Spring, K.M., Lyman-Gingerich, J., Generous, A.R., Koep, T.H., Ewing, K., Lilja, P., Enders, F.T., Ekker, S.C., Huskins, W.C., Fadel, H.J., Pierret, C. (2018). Humidity as a non-pharmaceutical intervention for influenza A. PLoS One 13, e0204337. https://doi.org/10.1371/journal.pone.0204337

Schoen, L.J. (2020). EQ Applications: Guidance for Building Operations During the COVID-19 Pandemic. ASHRAE J. 62, 3.

Wu, X. (May), Apte, M.G., Bennett, D.H. (2012). Indoor Particle Levels in Small- and Medium-Sized Commercial Buildings in California. Environ. Sci. Technol. 46, 12355–12363. https://doi.org/10.1021/es302140h