

ORIGINAL ARTICLE

Fine and ultrafine particle removal efficiency of new residential HVAC filters

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Abstract

Particle air filters used in central residential forced-air systems are most commonly evaluated for their size-resolved removal efficiency for particles 0.3–10 μm using laboratory tests. Little information exists on the removal efficiency of commercially available residential filters for particles smaller than 0.3 μm or for integral measures of mass-based aerosol concentrations (eg, $\text{PM}_{2.5}$) or total number concentrations (eg, ultrafine particles, or UFPs) that are commonly used in regulatory monitoring and building measurements. Here, we measure the size-resolved removal efficiency of 50 new commercially available residential HVAC filters installed in a recirculating central air-handling unit in an unoccupied apartment unit using alternating upstream/downstream measurements with incense and NaCl as particle sources. Size-resolved removal efficiencies are then used to estimate integral measures of $\text{PM}_{2.5}$ and total UFP removal efficiency for the filters assuming they are challenged by 201 residential indoor particle size distributions (PSDs) gathered from the literature. Total UFP and $\text{PM}_{2.5}$ removal efficiencies generally increased with manufacturer-reported filter ratings and with filter thickness, albeit with numerous exceptions. $\text{PM}_{2.5}$ removal efficiencies were more influenced by the assumption for indoor PSD than total UFP removal efficiencies. Filters with the same ratings but from different manufacturers often had different removal efficiencies for $\text{PM}_{2.5}$ and total UFPs.

KEYWORDS

air filtration, filter performance rating, microparticle performance rating, minimum efficiency reporting value, particulate matter, pollutant control

1 | INTRODUCTION

Central heating, ventilating, and air-conditioning (HVAC) filters are increasingly being recommended to reduce exposure to airborne particulate matter in buildings,^{1–15} including in residences where the majority of exposure to particulate matter of both indoor and outdoor origin often occurs.¹⁶ In the United States, the three most common rating systems that manufacturers use to characterize and market their residential particulate air filters include the following: MERV (Minimum Efficiency Reporting Value) from ASHRAE Standard 52.2¹⁷; MPR (Microparticle Performance Rating) from 3M;

and FPR (Filter Performance Rating), which is exclusively used for filters sold by the retail store, The Home Depot. The test methods for each rating system generally involve challenging filters with a test aerosol in a laboratory test duct and measuring the single-pass size-resolved removal efficiency for particles 0.3 to 10 μm in diameter.

The most widely used metric, MERV, classifies the particle removal efficiency of HVAC filters based on the minimum removal efficiency across three particle size bins (0.3–1, 1–3, and 3–10 μm) under various dust loading conditions. 3M developed the proprietary MPR system to demonstrate the ability of a filter to capture the smallest particles in this 0.3–10 μm size range (ie, 0.3–1 μm).

MPR values range from 300 (Basic) to 2800 (Premium). The proprietary FPR metric utilizes a color and number scale from 4 to 10 that somewhat resembles the MERV metric. Both MPR and FPR are proprietary standards with little public information available on how they are tested or rated.

There are several shortcomings apparent in these existing test methods and rating systems that can limit their utility for many stakeholders. First, each metric uses the size-resolved removal efficiency of particles 0.3 μm and larger; they do not provide information on the removal efficiency for smaller particles, even though: (a) the majority of indoor sources generate particles in the submicron and ultrafine particle (UFP: particles <0.1 μm) size ranges,¹⁸⁻²⁵ (b) the vast majority of outdoor particles (on a number basis) are in the UFP size range,²⁶ and (c) UFPs and submicron aerosols are increasingly understood to adversely impact human health.²⁷⁻³³ Second, these test standards do not evaluate the removal efficiency for mass-based aerosol metrics (eg, PM_{10} , $\text{PM}_{2.5}$, or PM_{10}), even though the vast majority of regulatory monitors (and thus the majority of epidemiology studies) utilize mass-based aerosol concentrations.³⁴ Of particular importance, fine particulate matter (ie, $\text{PM}_{2.5}$) is widely considered to be the most relevant mass-based particulate matter metric from a health and regulatory standpoint.³⁴⁻⁴¹

The International Standards Organization (ISO) recently published a new series of filter test standards (ISO 16890) that use size-resolved removal efficiency data from laboratory testing (although only for 0.3 to 10- μm particles) to approximate mass-based particle removal efficiencies for PM_{10} , $\text{PM}_{2.5}$, and PM_{10} .⁴² However, ISO 16890 is still not widely adopted in the US market, and the aerosol distributions used in the standard to estimate mass-based removal efficiencies come from historical ambient data, which do not necessarily reflect modern indoor environments.⁴³ Last, data from laboratory tests may not yield results that are directly relevant to in situ field performance, which could differ substantially based on filter face velocity, aerosol source, and other factors that influence particle removal efficiency.⁴⁴

To address some of these limitations, the objectives of this study are to: (a) measure the size-resolved particle removal efficiency for particle sizes ranging from 10 nm to 2.5 μm of a sample of 50 new commercially available residential HVAC filters from 10 different manufacturers; and (b) combine the measured efficiency data with a large number of indoor particle size distribution (PSDs), collected from a literature review, to estimate integral measures of total UFP and $\text{PM}_{2.5}$ removal efficiency for these filters in a range of indoor residential environments. The 50 filters, which had manufacturer-reported performance ratings from three rating systems (including MERV, MPR, and FPR) and a range of depths (from 2.5 to 12.7 cm [1 to 5 inches]), were collected through a sample of convenience, including some donated by manufacturers and retailers and others purchased new. All filters were tested new; dust loading is not investigated here, although dust loading and aging are well known to affect particle removal efficiency, most commonly by increasing efficiency for uncharged mechanical media and decreasing efficiency for charged media.⁴⁵⁻⁴⁷

Practical Implications

- We provide novel data on the removal efficiency for size-resolved particles and for integral measures of total $\text{PM}_{2.5}$ and ultrafine particles (UFPs) for 50 new commercially available residential air filters, assuming they are used to filter residential indoor air under a variety of assumptions for particle size distributions.
- These data can be useful for informing filter selection in real indoor environments.
- The use of these two metrics (total UFPs and $\text{PM}_{2.5}$) allows for characterizing filter removal efficiency for a range of indoor sources on a basis that is more closely aligned with metrics commonly obtained from handheld and stationary aerosol instruments used in buildings and ambient regulatory monitoring.
- Results reveal that manufacturer-reported efficiency metrics based on laboratory tests alone cannot always be used to distinguish filters in their indoor total UFP or $\text{PM}_{2.5}$ removal efficiency, particularly for lower efficiency filters.
- Results also provide novel insights into how the characteristics of the particle size distributions that challenge HVAC filters in real environments can drive variability in removal efficiency for integral measures of total UFPs and $\text{PM}_{2.5}$.

2 | METHODS

2.1 | Size-resolved HVAC filter removal efficiency test procedures

Experiments were conducted between June 2015 and February 2018 in an unoccupied apartment on the third floor of Carman Hall for graduate student housing on the main campus of Illinois Institute of Technology in Chicago, IL (refer to the SI, Appendix A, for more details).^{48,49} The instrumented apartment has a floor area and volume of approximately 60 m^2 and 150 m^3 , respectively. A 100% recirculating central air-handling unit is installed in the living room and connected to interior rigid sheet metal ductwork. The unit is intended to mimic a typical central residential air handler and duct distribution system, but it is not connected to heating or cooling equipment. All tested filters were the same width and height as the filter slot (40.6 cm \times 63.5 cm) and ranged from 2.5 cm (1-inch) to 12.7 cm (5-inch) in depth. There was no measurable filter bypass. The air handler fan has a permanent split capacitor (PSC) motor, which operates at constant fan speed and generally responds to higher system pressures by delivering reduced airflow rates (unlike variable speed electronically commutated or brushless permanent magnet motors).^{50,51} PSC motors are still widely used in US residential systems, although market

share has decreased in recent years.^{52–54} Airflow rates were initially measured using an Energy Conservatory TrueFlow plate and estimated during each filter test by measuring the static pressure in the supply plenum and following a procedure described in the instrument manual.⁵⁵ The nominal airflow rate of the air-handling unit without a filter installed was measured to be 1180 m³/hour ($\pm 7\%$ uncertainty of reading). Filter pressure drop was measured using an Energy Conservatory DG-700 differential pressure gauge ($\pm 1\%$ uncertainty of reading) connected to a pressure tap in the return plenum just a few cm downstream of the filter.

Particle removal efficiencies were measured for each filter using an alternating upstream-downstream method. A TSI NanoScan Scanning Mobility Particle Sizer (SMPS) and a TSI Optical Particle Sizer (OPS) were used to alternately measure size-resolved particle concentrations upstream and downstream of each filter (Figure 2). TSI conductive tubing was used to connect the particle monitors to the upstream and downstream monitoring locations. An electronic switching valve (Swagelok SS-43GXS4-42DCX), controlled by a three-channel electronic timer (Sestos B3S-2R-24), was used to automatically alternate sampling between upstream and downstream.⁵⁶ To elevate upstream concentrations of a wide range of particle sizes, particles were generated by burning incense^{13,44} and by operating a TSI particle generator (Model 8026) loaded with NaCl tablets mixed into tap water. Typical upstream PSDs resulting from these two generation methods are shown in the SI (Appendix A). To prevent rapid particle dilution in the large volume of the apartment, a small flow chamber (100 × 40 × 60 cm) was installed in front of the return plenum. Each test was conducted for 8 complete upstream/downstream cycles, lasting approximately 1 hour for each full test. Each sampling interval included 4 minutes of upstream measurements followed by 4 minutes of downstream measurements. For both upstream and downstream sampling periods, the first minute of data collected was excluded to ensure that the sampling lines were cleared from the previous measurement. The tests were conducted at room temperature, and the temperature and relative humidity inside the duct did not deviate significantly from the room conditions, as the NaCl aerosol generator had minimal water vapor output.

ASHRAE Guideline 26 for in situ particle removal efficiency testing was followed as closely as possible.⁵⁷ The inlet nozzles of the upstream and downstream sampling probes were aligned parallel to the airstream, and isokinetic sampling was confirmed to be reasonably maintained because the sampling air velocity was always within $\pm 20\%$ of the free-stream air velocity. The calculated average velocity through the sampling probe (ie, the sample flow rate divided by the cross-sectional interior area of the sampling tubing) was 3.5 m/s. Initial free-stream air velocity measurements made with a Fluke air velocity meter (Model #975) without a filter installed averaged 3.3 m/s in the location of both sampling probes (ie, within 6% of the calculated sampling velocity). The lowest airflow rate, measured with the most restrictive filter, was 1030 m³/hour, with an estimated free-stream air velocity of 2.9 m/s (which was within 17% of the calculated sampling velocity).

The removal efficiency of the combination of the filter and ductwork for each particle size bin i ($\eta_{\text{ducts+filter},i}$), including 20 bins in total across both instruments, with geometric mean particle diameter from 11.5 nm to 2.57 μm , was calculated from the resulting data using Equation 1.

$$\eta_{\text{ducts+filter},i} = \left(1 - \frac{C_{\text{downstream},i}}{C_{\text{upstream},i}} \right) \quad (1)$$

where $C_{\text{upstream},i}$ and $C_{\text{downstream},i}$ are the upstream and downstream particle concentrations in a given size bin, respectively. The size-resolved removal efficiency of the filter alone ($\eta_{\text{filter},i}$) was calculated using Equation 2, assuming removal by the ductwork and filter act in series.⁴⁴

$$\eta_{\text{filter},i} = \left(1 - \frac{1 - \eta_{\text{ducts+filter},i}}{1 - \eta_{\text{ducts},i}} \right) \quad (2)$$

where $\eta_{\text{ducts},i}$ is the average size-resolved removal efficiency for size bin i measured with the HVAC system operating and no filter installed. The size-resolved removal efficiency for each test condition is reported as an average of the eight combined upstream/downstream sample periods. Uncertainty is estimated as the standard deviation of the calculated removal efficiency over the eight sample periods with a given filter added in quadrature with the standard deviation of the calculated removal efficiency over the eight sample periods without a filter (ie, background removal by ductwork).

Subsequently, empirical equations were fit to the measured size-resolved removal efficiency data for each filter to generate continuous functions of removal efficiency versus particle diameter. This procedure allowed for estimating removal efficiency for all particle sizes, including those that were not explicitly measured by the SMPS + OPS system, which was useful for matching to continuous PSDs (explained in the next section). A polynomial regression was conducted between the logarithm of the percent penetration and the logarithm of particle diameter⁵⁸ using SPSS, beginning with a

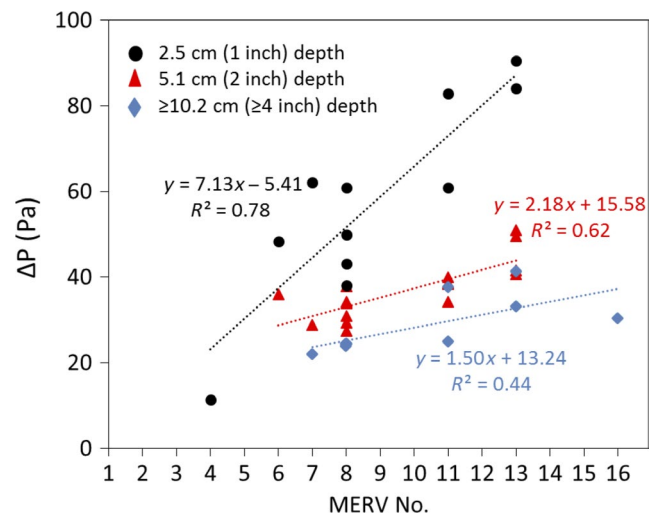


FIGURE 1 Initial pressure drops for new filters versus manufacturer-reported MERV

third-order polynomial and increasing in order (up to sixth order in a few cases) until the correlation coefficient (R^2) exceeded 0.9.

2.2 | Mapping to indoor particle size distributions

A literature review was conducted to identify previous studies that reported measurements of indoor PSDs in a variety of (mostly residential) indoor environments, including those with indoor sources present, such as cooking, burning incense, and others. The purpose of the review was to gather a wide enough variety of PSDs to explore how variations in indoor PSDs might influence estimates of integral measures of $PM_{2.5}$ and UFP removal efficiency.^{26,43} Google Scholar was used to search for the following terms: indoor concentration, particle size distribution, particle size characterization, SMPS, ultrafine particle emissions, and fine particle emissions. Sixteen studies reporting a total of 201 PSDs were selected for analysis through this procedure.⁵⁹⁻⁷⁴ Most of these studies (a) occurred in various European cities (with a few in the United States and Asia), (b) measured size-resolved particle number concentrations in the range of 10 nm to 1000 nm, and (c) reported their results graphically in terms of $dN/d\log D_p$ versus the log of particle size, D_p .

Tri-modal (and in some cases bi-modal, if appropriate) lognormal distributions were fit to each of the 201 indoor PSDs by adjusting geometric means (GMs), geometric standard deviations (GSDs), and total number concentrations for nucleation, accumulation, and coarse modes. These fits were made either (a) manually, using a semi-transparent graphical method in which fitted distributions were overlaid on the reported measured distributions and distribution statistics were adjusted until an adequate visual fit was achieved,²⁶ or (b) automatically, using the software package Distfit.⁷⁵ This yielded 201 smooth indoor PSDs from 0.001 μm to 2.5 μm , which were then used to map to the continuous functions of removal efficiency of each filter generated previously by polynomial regression on the measured removal efficiency data for particle sizes 0.01–2.5 μm .

The resulting 201 PSDs were then used to estimate integral measures of indoor UFP number concentrations and $PM_{2.5}$ mass concentrations that a filter would be challenged with when used inside a building with a recirculating HVAC system (eg, a typical US residence). Total UFP removal efficiency was calculated using Equation 3, and $PM_{2.5}$ mass-based removal efficiency was calculated using Equation 4.

$$\eta_{UFP} = 1 - \frac{\sum_{i=0.01 \mu m}^{0.1 \mu m} N_i \times (1 - \eta_{filter,i})}{\sum_{i=0.01 \mu m}^{0.1 \mu m} N_i} \quad (3)$$

$$\eta_{PM_{2.5}} = 1 - \frac{\sum_{i=0.01 \mu m}^{2.5 \mu m} N_i \times \rho_i \times \frac{\pi d_i^3}{6} \times (1 - \eta_{filter,i})}{\sum_{i=0.01 \mu m}^{2.5 \mu m} N_i \times \rho_i \times \frac{\pi d_i^3}{6}} \quad (4)$$

where η_{UFP} = estimated “total UFP” removal efficiency of a filter for particle sizes in the range from 0.01 to 0.1 μm ; $\eta_{PM_{2.5}}$ = estimated $PM_{2.5}$ removal efficiency of a filter; d_i = particle diameter of size i (cm);

N_i = upstream number concentration of particles with diameter d_i (#/cm³); $\eta_{filter,i}$ = removal efficiency of filter for particles with diameter d_i (from Equation 2); and ρ_i = density of particles with diameter d_i (g/cm³).

For mass-based removal efficiency estimates, we assumed spherical particles with constant unit density (1 g/cm³) for all particle sizes.^{5,76} The assumption for constant versus varying density has been shown to have a negligible impact on estimates of $PM_{2.5}$ removal efficiency in prior work.²⁶ Statistical comparisons of the resulting 201 estimates of total UFP and $PM_{2.5}$ removal efficiencies for all possible combinations of pairs of filters were made using nonparametric Wilcoxon rank-sum (Mann-Whitney) tests.

3 | RESULTS AND DISCUSSION

3.1 | Size-resolved HVAC filter testing

3.1.1 | Initial filter pressure drops, airflow rates, and face velocities

Figure 1 shows filter pressure drop measured in the test system with each of the 36 filters that had a MERV rating from the manufacturer versus the manufacturer-reported MERV (FPR and MPR are not directly comparable to MERV and thus are not shown in Figure 1). A complete list of measured filters and their airflow rates and filter pressure drops is shown in the SI (Appendix A: Table A.1). Note that in this system, because there was no return duct, the filter pressure drop represents the majority of return-side pressure drop. Overall, there was a weak correlation between initial filter pressure drop and MERV across all depths, but stronger correlations within the same filter depth. For example, filter pressure drop was strongly correlated with MERV for 2.5-cm (1-inch) filters ($R^2 = 0.78$; slope of 7 Pa per MERV), but less so for 5.1-cm (2-inch) ($R^2 = 0.62$; slope of 2 Pa per MERV) and even less so for 10.2-cm (4-inch) and greater depth filters ($R^2 = 0.44$; slope of 1.5 Pa per MERV). These results generally agree with other experimental findings that show a variety of initial filter pressure drops due to differences in filter media, thickness, and other characteristics.^{8,13,50,77}

The maximum initial pressure drops of 2.5-cm (1-inch) MERV 13 filters in our data set were over 90 Pa, while the maximum initial pressure drops of 5.1-cm (2-inch) and 10.2–12.7-cm (4- to 5-inch) MERV 13 filters were only 50 Pa and 40 Pa, respectively. Similar results were observed for MERV 7, 8, and 11 filters of varying depths, as the extended filter depths were effective in maintaining a relatively low pressure drop. In fact, the highest rated efficiency filter in our data set (MERV 16 with 12.7 cm [5-inch] depth) actually had a lower pressure drop (30 Pa) than all but one 2.5-cm [1-inch] filter (only the MERV < 4 was lower). The air handler airflow rate was sensitive to filter pressure drop as are most systems with PSC blowers but was never more than 17% lower than the nominal flow rate measured without a filter. Dividing measured airflow rates by constant filter face area yields estimated filter face velocities ranging approximately from 1.1 to 1.3 m/s, which are generally in line with previous field measurements of face velocities in residential systems

(eg, ASHRAE RP-1299 estimated face velocities ranging from 0.7 to 2.5 m/s, with an average of approximately 1.4 m/s, in 17 residential and light-commercial systems⁷⁸) but are lower than the recommended value of 2.5 m/s in ASHRAE Standard 52.2.¹⁷

3.1.2 | Size-resolved removal efficiencies

Figures 2 and 3 show the resulting size-resolved removal efficiencies measured for each of the 50 tested HVAC filters for particle sizes

0.01 μm to 2.6 μm , which was the size range over which our aerosol generation and measurement system consistently yielded measurable values of removal efficiency with uncertainty values within the range of prior studies. There is a discontinuity between 0.1 μm and 0.3 μm because of known issues with the TSI NanoScan inaccurately reporting above 0.1 μm .^{56,79} Figure 2 shows results for the 36 filters with a manufacturer-reported MERV; Figure 3 shows results for the 14 filters with a manufacturer-reported MPR or FPR. A full list of the size-resolved removal efficiencies for all filters is shown in the

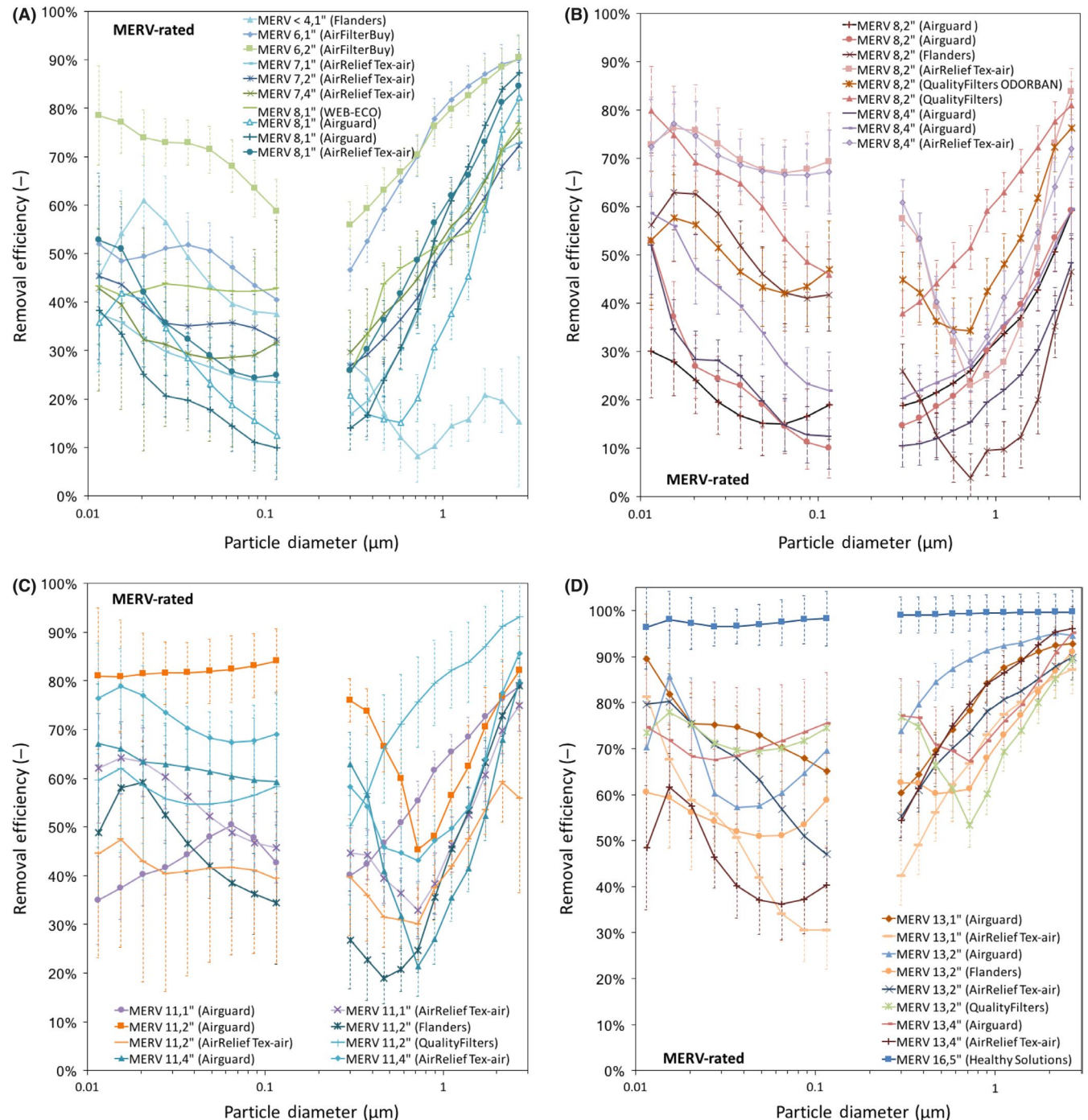


FIGURE 2 Size-resolved removal efficiency of 36 new filters with a manufacturer-reported MERV: (A) 2.5 cm (1-inch) depth; (B) MERV 8 filters, 5.1-10.2 cm (2-4 inches) depth; (C) all MERV 11; and (D) all MERV 13 and higher. Note that 1" = 2.54 cm

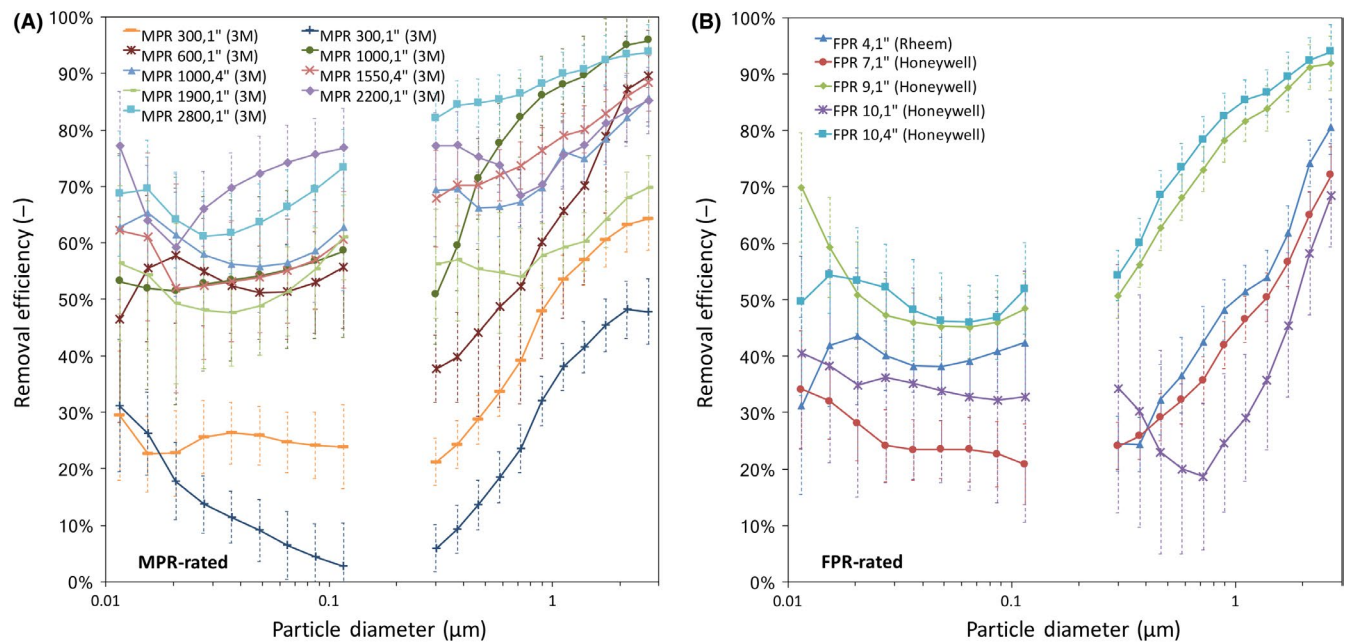


FIGURE 3 Size-resolved removal efficiency of 14 new filters with a manufacturer-reported (A) MPR and (B) FPR. Note that 1" = 2.54 cm

SI (Appendix A: Table A.2). The average absolute uncertainty in removal efficiencies across all filters and all particle sizes was 7%, with the average across all particle sizes ranging from 5% to 16% for individual filters. The magnitudes of these uncertainties are well in line with previous in situ residential filter efficiency testing.^{13,44} Polynomial curve fits through the measured size-resolved removal efficiency data for each of the tested filters for particle sizes 0.01–2.5 μm are shown in the SI (Appendix B).

Consistent with filtration theory and previous in situ measurements,⁴⁴ the most penetrating particle size for most filters was typically between 0.1 μm and 0.5 μm, while the highest removal efficiency was typically for the largest (and often, but not always, the smallest) particle sizes measured. The sole MERV 16 filter that was tested (with 12.7 cm [5-inch] depth) had the highest removal efficiency of all test filters (over 90% for all particle sizes). The filter with the lowest removal efficiency across all particle sizes was the MPR 300 2.5-cm (1-inch)-depth filter, with an average removal efficiency below 25% for all particle sizes. Many of the tested filters with the same manufacturer-reported efficiency rating ranged widely in removal efficiencies (eg, MERV 8 filters in Figure 2B and MERV 11 filters in Figure 2C). A large portion of this variability likely resulted from our testing of new filters rather than using a combination of clean and artificially loaded conditions such as the procedures used in ASHRAE Standard 52.2. The use of electrostatically charged media on some of the filters likely also explains some of the observed variation. Some portion of this variability, particularly in the UFP size range, is also likely due to more substantive differences in filter media that are designed to meet standards for removal in the 0.3 to 10 μm size range but are not necessarily designed to explicitly remove UFPs.

There were also several instances in which a filter with a higher manufacturer-reported rating had lower removal efficiencies for

many particle sizes than a filter with a lower manufacturer-reported rating, particularly for the UFP size ranges that 52.2 and other test standards do not evaluate. For example, one MERV 6 filter in Figure 2A had higher removal efficiencies in the UFP size range than most MERV 8 filters, and some MERV 8 filters in Figure 2B had higher removal efficiencies in the UFP size range than many MERV 11 filters. In other words, even if filters with different manufacturers and models have the same rating number (ie, MERV, FPR, MPR), their initial removal efficiencies across a wide range of particle sizes can still vary widely, particularly in the UFP size range.

3.2 | Indoor particle size distributions from the literature

A summary of the literature sources used to identify existing indoor PSDs and their measurement devices, size ranges, and sampling locations is shown in Table 1. A total of 201 PSDs were identified from 16 studies, primarily conducted in occupied spaces, albeit with some conducted in controlled test conditions with specific emission sources. Tri-modal and in some cases bi-modal distribution fit parameters (including GM, GSD, and number concentrations for each mode), the types of particle sources reported, and the sampling time reported for all 201 collected distributions are provided in the SI (Appendix C: Table C.2).

Smooth fits of all 201 collected PSDs from 0.001 to 10 μm are shown graphically on a number basis in Figure 4A and on an estimated mass basis in Figure 4B, both spanning all size ranges, including extrapolations beyond the original measured size ranges. The individual PSDs are not marked for clarity. The same indoor PSDs are also shown in the SI using only the size ranges measured in the original reference (Appendix C: Figure C.1). While this collection of PSDs does not necessarily represent all types of indoor

TABLE 1 Summary of indoor particle size distributions (PSDs) from the literature

Reference	No. of PSDs	Measurement device(s)	Size range (μm)	Location type	Sampling location
Hussein et al ⁶⁰	36	SMPS 3934C	0.014-0.552	Residential	Kitchen and living room
Hussein et al ⁶¹	25	DMPS, DMA, CPC	0.003-0.4	Residential	Living room
Lazaridis et al ⁶²	33	SMPS 3934C	0.010-0.470 (Oslo) 0.0140.552 (Prague) 0.014-0.764 (Milan)	Residential and office	Living room (Oslo & Prague) Office (Milan)
Ji et al ⁶³	3	CPC 3007 and 3785 SMPS	0.002-1.0 0.01-0.5	Residential (test house)	Kitchen, toilet, corridor, and bedroom
Vette et al ⁶⁴	4	SMPS 3934 LASX	0.01-2.5	Residential/retirement community	Vacant residences
See et al ⁶⁵	12	SMPS 3934	0.01-0.05	Residential	Kitchen
McAuley et al ⁶⁶	9	FMPS 3091	0.0056-0.165	Residential (5 homes)	N/A
Wan et al ⁶⁷	10	SMPS 3936	0.0146-0.6612	Residential (12 homes)	Kitchen and living room
Tu et al ⁶⁸	8	ASAS-X EAA 3030	0.09-3.0	Residential	N/A
Guo et al ⁶⁹	10	SMPS DustTrak 8520	0.015-0.790	School	Classroom and preschool
He et al ⁷⁰	3	CPC 3022 P-Trak 8525 DustTrak 8520	0.007-3 0.02-1 PM _{2.5}	Office/chamber test	Chamber with printer
Li et al ⁷¹	20	DMPS13932 CNC 3022	0.01-1	Residential	Kitchen
Parker et al ⁷²	2	TEOM MiniVol	0.3-10	School	Library
Wallace et al ⁸⁸	4	SMPS 3071 APS 3320 Climet 500 MIE pDR-1000	0.01-20	Residential	Kitchen, living room, upstairs office, basement, and utility room
Buonanno et al ⁷³	10	SMPS 3936 APS 3321	0.006-20	Laboratory test	Setup kitchen
Yeung et al ⁷⁴	12	SMPS 3734	0.0016-0.674	Laboratory test	Mock kitchen
Total	201				

environments, they do represent a wide variety of indoor spaces with and without indoor sources present, as well as a wide variety of sampling locations and thus PSDs that filter are likely to be challenged with indoors (and primarily in residences). Most distributions had a peak number concentration between 10 nm and 90 nm, with estimated peak mass concentrations typically in the 0.3 to 3 μm size range. The highest number and mass concentrations generally resulted from cooking activities as expected. For the mass estimates, there is likely some missing mass for particle sizes 1-10 μm because of limitations in the size resolution on the instrumentation that was used to measure these PSDs on a number basis (Table 1).²⁶

3.3 | Estimates of filter removal efficiency for integral measures of indoor UFPs and PM_{2.5}

Figures 5 through 7 show estimates of total UFP and PM_{2.5} removal efficiency for the 50 tested filters, assuming the filters are challenged with the 201 indoor PSDs from Figure 4, made using

the polynomial curve fits to measured size-resolved removal efficiencies from the SI (Appendix B). A full summary of distributions of UFP and PM_{2.5} removal efficiencies for all filters and statistical comparisons between individual filters is provided in the SI (Appendix D).

3.3.1 | UFP and PM_{2.5} Removal Efficiency for All Filters Grouped by Rating

Figure 5 shows aggregate results of estimates of UFP and PM_{2.5} removal efficiencies for the 50 tested filters, albeit with all filters of the same rating grouped together, regardless of manufacturer or depth. The intent of Figure 5 is to broadly categorize filters based on rating value alone, regardless of depth, make, or model, for others to use in modeling efforts and to help guide filter selection broadly. Note that the number of filters used in each rating group in Figure 5 is not the same but is shown on the x-axis. Thus, the rating groups with higher number of filters could present a more realistic and representative

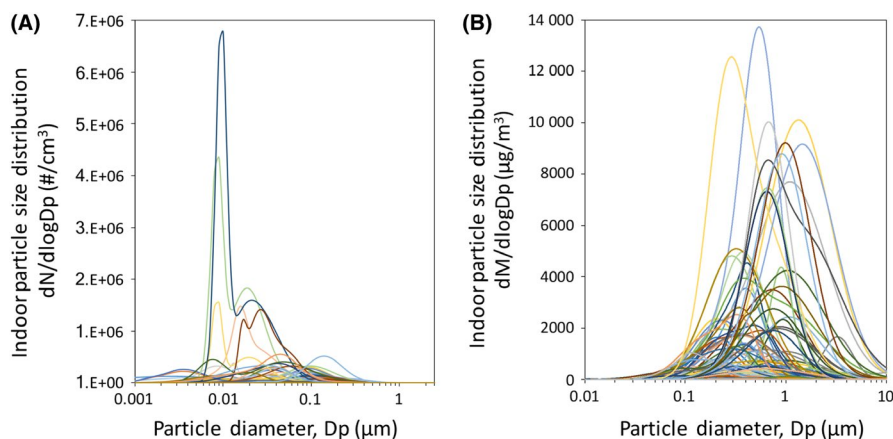


FIGURE 4 Tri-modal and bi-modal fits to a collection of 201 particle size distributions found in 16 studies in the existing literature: (A) number distributions and (B) estimated mass distributions

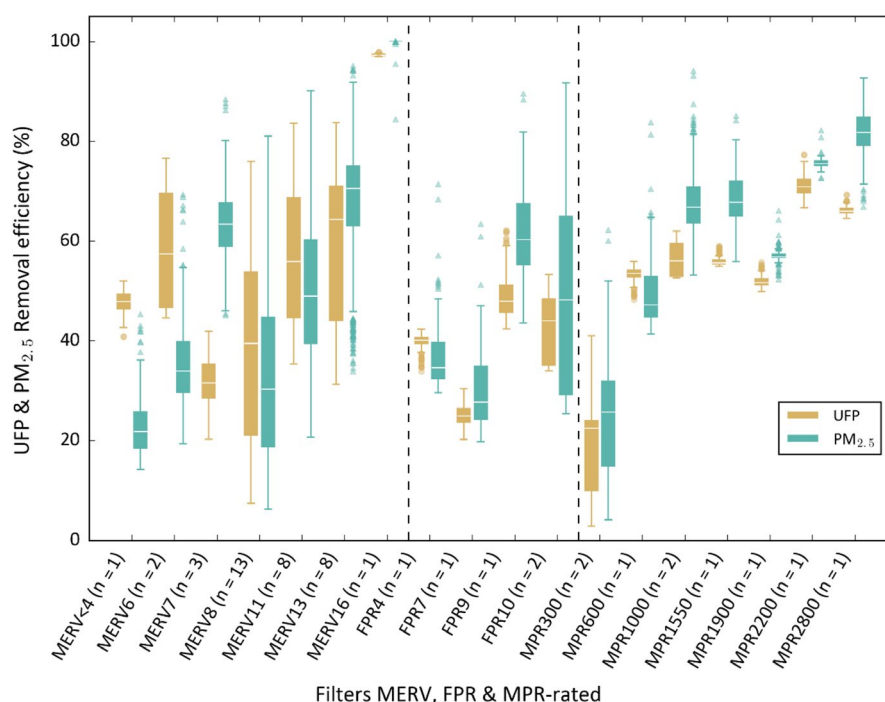


FIGURE 5 Estimates of UFP and $PM_{2.5}$ removal efficiency for all filters with the same rating value

range of UFP and $PM_{2.5}$ removal efficiencies for filters with a given rating. Box plots are used to show the influence of both the shape of the PSDs and variations among individual filters within a group. Notably, indoor PSD characteristics tended to have a much larger impact on $PM_{2.5}$ removal efficiencies than UFP removal efficiencies; the average coefficient of variation (standard deviation divided by the mean) for the 50 test filters was 16% for $PM_{2.5}$ removal efficiency but only 7% for total UFP removal efficiency (SI, Appendix D).

Across these rating categories, the median $PM_{2.5}$ and UFP removal efficiencies generally increased with reported rating values, albeit with some exceptions. For example, the median $PM_{2.5}$ removal efficiencies of MERV 6 and MERV 7 filters were both higher than for MERV 8. The only group of MERV filters to achieve median removal efficiencies for both UFPs and $PM_{2.5}$ >50% were those with MERV

13 or higher. The tested MPR filters tended to have higher removal efficiencies for both $PM_{2.5}$ and UFPs than FPR filters. Similar to the tested MERV filters, median removal efficiencies generally increased with MPR and FPR, again with some exceptions. Also, the median $PM_{2.5}$ removal efficiency was higher than the median UFP removal efficiency for most MPR and FPR filters, which was not the case for the tested MERV filters.

These estimates of total UFP and $PM_{2.5}$ removal efficiencies for MERV 7, MERV 8, MERV 13, and MERV 16 filters are generally in line with limited data from the existing literature, even though those studies have typically used outdoor air or mixed air aerosol distributions in their estimates. For example, the overall median $PM_{2.5}$ removal efficiency for all measured MERV 8 filters herein was 30%, which is very similar to medians of 27% and 25% reported by Azimi

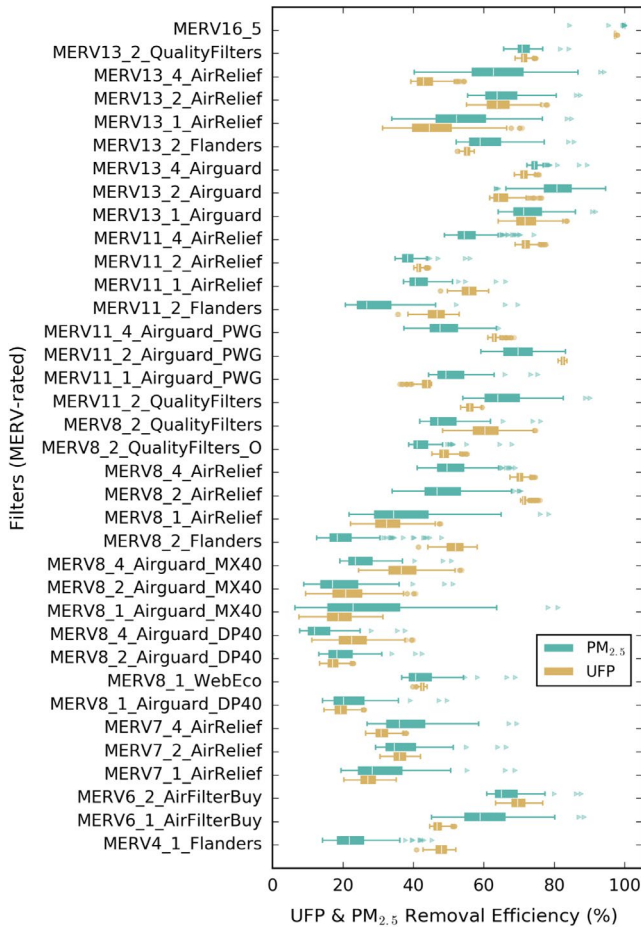


FIGURE 6 Estimates of total UFP and $PM_{2.5}$ removal efficiency for the 36 new test filters with manufacturer-reported MERV, assuming they are challenged with indoor aerosol distributions from Figure 5 ($n = 201$). Note that 1" = 2.5 cm. Boxes represent the first and third quartiles; the white line represents the median; and the whiskers represent 1.5 times the interquartile range. Outliers are shown with symbols

et al (2014)²⁶ and Zaatari et al (2014).⁸ Brown et al (2014)¹ also calculated $PM_{2.5}$ removal efficiencies for indoor aerosols of 22% and 37% for two different MERV 8 filters. Ben-David et al (2018)⁸⁰ measured a lower median $PM_{2.5}$ removal efficiency for a MERV 8 filter in an office building of only 17%. Similarly, the overall median UFP removal efficiencies for the MERV 7 and MERV 8 filters tested herein (32% and 40%, respectively) were similar to the values reported in Azimi et al (2014) for outdoor air: 37% and 36%, respectively.

The overall median $PM_{2.5}$ removal efficiency for the MERV 13 filters tested herein was estimated to be 70%, which is also similar to that estimated by Zaatari et al (2014) for MERV 13 filters in commercial rooftop units.⁸ Azimi et al (2014)²⁶ and Ben-David et al (2018)⁸⁰ did not evaluate MERV 13 filters, but reported median estimates of $PM_{2.5}$ removal efficiencies for MERV 14 filters to be 71% and 72%, respectively. The median total UFP and $PM_{2.5}$ removal efficiencies for the sole MERV 16 filter tested herein (97% and 100%, respectively) were also similar to those reported by Azimi et al (2014)²⁶ (with medians of 98% and 96%, respectively) and by Brown et al

(2014)¹ (97% for indoor $PM_{2.5}$ only). Conversely, the median UFP and $PM_{2.5}$ removal efficiencies for some of the other filters (eg, MERV 6 and MERV 11) tested herein were generally higher than the limited other estimates in the literature. For example, the overall median UFP removal efficiency for MERV 6 filters tested herein was higher than estimates in Azimi et al (2014),²⁶ but lower for MERV 13 filters. We are not aware of previous estimates of removal efficiency for MPR or FPR filters.

3.3.2 | Total UFP Removal Efficiency for Filters with MERV

Figure 6 shows resulting estimates of total UFP and $PM_{2.5}$ removal efficiencies for each of the 36 tested filters with a manufacturer-reported MERV; box plots are used to show the influence of the shape of the PSDs for each filter (ie, $n = 201$ PSDs for all box plot series). Total indoor UFP removal efficiencies generally increased with MERV, albeit with several exceptions. For example, the median total UFP removal efficiency for the sole MERV < 4, 2.5-cm (1-inch)-depth filter was significantly higher than several higher MERV filters ($P < 0.001$), including some MERV 7 and MERV 8 filters. The median UFP efficiencies for MERV 6 filters were also significantly higher than all of the MERV 7 filters and the majority of the MERV 8 filters. The three MERV 7 filters tested, including 2.5 cm (1-inch), 5.1 cm (2-inch), and 10.2 cm (4-inch) depths, had an overall median UFP removal efficiency of 32% and individual estimates ranging from 20% to 42% depending on the indoor PSD used.

The tested MERV 8 filters had the largest ranges of UFP removal efficiency, driven by differences in both filter depth and manufacturer. Deeper bed MERV 8 filters generally had higher UFP removal efficiency, albeit with some exceptions. Differences in total UFP removal efficiency for all MERV 8 filters except for three filters from the same manufacturer (Airguard) were statistically significant ($P < 0.001$). For MERV 11 filters, 27 out of 28 comparisons of total UFP removal efficiency with different manufacturers and depths were statistically significant ($P < 0.001$).

The overall median total UFP removal efficiencies for MERV 13, 2.5-cm (1-inch)-, 5.1-cm (2-inch)-, and 10.2-cm (4-inch)-depth filters were more tightly grouped: 66%, 64%, and 62%, respectively. However, there were still some large differences between MERV 13 filters of the same depth. For example, two MERV 13, 2.5-cm (1-inch)-depth filters from different manufacturers had significantly different total UFP removal efficiencies. Increasing to MERV 13, 10.2 cm (4-inch) depth did not yield substantially higher UFP removal efficiencies, with median values of 43% and 71% for the two filters in this category. Five out of 28 comparisons between MERV 13 filters with different manufacturers and depths were not statistically significant, while, interestingly, there were more comparisons between MERV 13 and MERV 11 filters that were not significantly different (6 out of 28 comparisons). The sole MERV 16, 12.7-cm (5-inch)-depth filter had a median total UFP removal efficiency of 97%, with a tight range from 97% to 98% due to PSD shape.

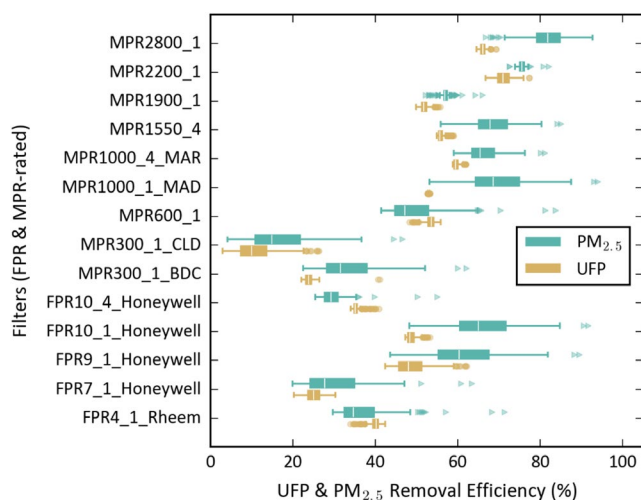


FIGURE 7 Estimates of total UFP and $PM_{2.5}$ removal efficiency for the 14 new test filters with manufacturer-reported MPR or FPR, assuming they are challenged with 201 indoor aerosol distributions ($n = 201$). Note that 1" = 2.5 cm. Boxes represent the first and third quartiles; the white line represents the median; and the whiskers represent 1.5 times the interquartile range. Outliers are shown with symbols

All of the differences in total UFP removal efficiency for individual filters with the same MERV but different depths were statistically significant ($P < 0.001$) except for the following: (a) MERV 8, 5.1-cm (2-inch)-depth and MERV 8, 10.2-cm (4-inch)-depth filters ($P = 0.090$); (b) MERV 13, 2.5-cm (1-inch)-depth and MERV 13, 5.1-cm (2-inch)-depth filters ($P = 0.003$); and (c) MERV 13, 2.5-cm (1-inch)-depth and MERV 13, 10.2-cm (4-inch)-depth filters ($P = 0.154$). In total, 94% of the comparisons of total UFP removal efficiency between individual filters with MERV were statistically significant ($P < 0.001$).

3.3.3 | $PM_{2.5}$ Removal Efficiency for Filters with MERV

Similar to total UFP removal efficiencies, indoor $PM_{2.5}$ removal efficiencies were generally higher with higher MERV, albeit with some high variability depending on manufacturer and depth, particularly for filters with MERV 6 through 13. All differences in total $PM_{2.5}$ removal efficiency for MERV 7 filters with different depths were statistically significant ($P < 0.001$) except for comparisons between MERV 7, 5.1-cm (2-inch) and MERV 7, 10.2-cm (4-inch) filters ($P = 0.122$).

Median estimates of $PM_{2.5}$ removal efficiencies for MERV 8 filters with different depths ranged from 12% to 50%, with wide ranges for individual filters from 6% to 81% based on indoor PSD shape. Seventy-one out of 78 (91%) of the statistical comparisons of $PM_{2.5}$ removal efficiency for MERV 8 filters with different models, depths, and manufacturers were statistically significant ($P < 0.001$). However, surprisingly, comparisons of total $PM_{2.5}$ removal efficiency for MERV 8 filters across different depths alone were not statistically significant ($P > 0.001$), which suggests that for these MERV

8 filters, increasing depth does not significantly increase $PM_{2.5}$ removal efficiency.

Median estimates of $PM_{2.5}$ removal efficiencies for all tested MERV 11 filters ranged 27% to 70% depending on filter make/model/depth, with wide individual ranges from 21% to 90% depending on the indoor PSD assumption. All of the differences in $PM_{2.5}$ removal efficiencies for MERV 11 filters with different models, depths, and manufacturers were statistically significant ($P < 0.001$). Differences in total $PM_{2.5}$ removal efficiency for MERV 11 filters with different depths were significant for comparisons between MERV 11, 2.5-cm (1-inch) and 10.2-cm (4-inch) filters ($P < 0.001$) but were not statistically significant for comparisons between MERV 11, 2.5-cm (1-inch) and 5.1-cm (2-inch) ($P = 0.085$) or between MERV 11, 5.1-cm (2-inch) and 10.2-cm (4-inch) filters ($P = 0.482$).

Median values of $PM_{2.5}$ removal efficiencies of the MERV 13 filters were all above 65% regardless of depth and were almost 100% for the single MERV 16, 12.7-cm (5-inch)-depth filter. The majority of differences in $PM_{2.5}$ removal efficiencies for individual MERV 13 filters with different models, depths, and manufacturers (26 out of 28 comparisons, or 93%) were statistically significant ($P < 0.001$). Differences in total $PM_{2.5}$ removal efficiency for MERV 13 filters with different depths were statistically significant ($P < 0.001$) except for comparisons between MERV 13, 5.1 cm (2-inch) and 10.2 cm (4-inch) ($P = 0.026$).

3.3.4 | Total UFP Removal Efficiency for Filters with MPR or FPR

Figure 7 shows estimates of total UFP and $PM_{2.5}$ removal efficiencies for each of the 14 tested filters with a manufacturer-reported FPR or MPR; again, box plots are used to show the influence of the shape of the PSDs for each filter (ie, $n = 201$ PSDs for all box plot series). No FPR filter tested resulted in a median UFP removal efficiency of greater than 50%. The median UFP removal efficiency of the sole FPR 4 filter (2.5 cm [1-inch] depth) was actually higher than the median UFP removal efficiency for both the sole FPR 7 filter (2.5 cm [1-inch] depth) and the sole FPR 10 filter (10.2 cm [4-inch] depth). The FPR 9, 2.5-cm (1-inch)-depth and FPR 10, 2.5-cm (1-inch)-depth filters had the highest median UFP removal efficiencies among the tested FPR filters (both 48%) and were tightly grouped, ranging from 42% to 62% and 47% to 53% based on PSD, respectively. All comparisons of total UFP removal efficiencies between FPR filters were statistically significant ($P < 0.001$) except for comparisons between the FPR 9, 2.5-cm (1-inch)-depth and FPR 10, 2.5-cm (1-inch)-depth filters ($P = 0.044$).

The MPR 300, 2.5-cm (1-inch)-depth filter ("Basic Dust") had a lower median UFP removal efficiency than the other MPR 300 filter, the 2.5-cm (1-inch)-depth filter ("Clean Living"). The median UFP removal efficiencies for MPR 600, 2.5-cm (1-inch)-, MPR 1000, 2.5-cm (1-inch)-, MPR 1000, 10.2-cm (4-inch)-, MPR 1550, 10.2-cm (4-inch)-, and MPR 1900, 2.5-cm (1-inch)-depth filters were similar to each other and relatively tightly grouped, with median efficiencies ranging from 52% to 59%. The MPR 2200, 2.5-cm (1-inch)-depth filter

had the highest median UFP removal efficiency among the tested MPR filters. Finally, the highest rated MPR filter, the MPR 2800, 2.5-cm (1-inch)-depth filter, had a median UFP removal efficiency of 66%. All comparisons of total UFP removal efficiencies between MPR filters were statistically significant ($P < 0.001$).

3.3.5 | $PM_{2.5}$ Removal Efficiency for Filters with MPR or FPR

The FPR filter with the highest $PM_{2.5}$ removal efficiency was the FPR 10, 2.5-cm (1-inch)-depth filter, with a median of 65%. The FPR 7, 2.5-cm (1-inch)-depth filter had the lowest median $PM_{2.5}$ removal efficiency (28%), which was even lower than the FPR 4, 2.5-cm [1-inch] filter (with a median of 35%). Unexpectedly, the FPR 10, 10.2-cm (4-inch) had one of the lowest $PM_{2.5}$ removal efficiencies and was similar to the FPR 7, 2.5-cm [1-inch]-depth filter. All comparisons of total $PM_{2.5}$ removal efficiency between FPR filters were statistically significant ($P < 0.001$) except for comparison between the FPR 7, 2.5-cm (1-inch) and FPR 10, 10.2-cm (4-inch) filters ($P = 0.004$).

The MPR 300, 2.5-cm (1-inch)-depth filter ("Basic Dust") again had the lowest $PM_{2.5}$ removal efficiency, with a median of 15%, while the other MPR 300, 2.5-cm (1-inch)-depth filter ("Clean Living") had a higher median $PM_{2.5}$ removal efficiency of 32%. All MPR tested filters above MPR 600 consistently yielded $PM_{2.5}$ removal efficiencies above 50%. The MPR 1000, 2.5-cm (1-inch)- and MPR 1550, 10.2-cm (4-inch)-depth filters had the most similar median $PM_{2.5}$ removal efficiencies (differences were not statistically significant; $P = 0.212$). The median $PM_{2.5}$ removal efficiency for the MPR 1990, 2.5-cm (1-inch)-depth filter was surprisingly somewhat lower than the MPR 1550, 10.2-cm (4-inch)-depth filter (57% compared to 68%). Finally, the indoor $PM_{2.5}$ removal efficiency for MPR 2200 and MPR 2800 filters was also relatively tightly grouped, with median efficiencies of 76% and 82%, respectively. Differences in $PM_{2.5}$ removal efficiencies for all other MPR filters were statistically significant ($P < 0.001$).

3.4 | Limitations

There are a number of limitations to this work that should be considered in interpreting these results. For one, although a large number of commercially available filters were tested, filters were selected from a sample of convenience and do not represent all filters on the market. Moreover, since we tested only one filter of each make/model, including some purchased and some donated, these data may not be representative of all products manufactured with the same make and model if variability among individual filters exists. Second, as mentioned previously, only initial removal efficiencies were measured; this work does not consider dust loading, which is well known to influence removal efficiency over time. Third, the measured removal efficiencies reported herein are limited to the particular characteristics of the test air-handling unit; performance is likely to vary at other location with different fan motors, pressure drops, airflow rates, and face velocities. Fourth, the aerosol instrumentation used

herein left gaps between 0.1 μm and 0.3 μm and could not measure below 0.01 μm , and our aerosol generation system failed to yield meaningful concentrations above 2.5 μm . Thus, our data are limited to 0.01- to 2.5- μm particles with a gap between 0.1 and 0.3 μm . Finally, we also assumed that removal efficiencies measured using incense and NaCl particles as the challenge aerosol at the concentrations and conditions under which measurements were conducted can be directly applied to the 201 particle size distributions from a wide variety of indoor sources gathered from the literature. However, this may not be the case, as different aerosol sources can carry different charge distributions^{81,82} and other aerosol characteristics that can affect filtration efficiency, particularly for electrostatically charged media.^{46,83-85} Future research should improve upon these limitations. It is also worth mentioning that filter removal efficiency alone is not the only metric that governs removal effectiveness in real residential indoor environments; low system runtimes often limit the effectiveness of even very-high-efficiency filters.^{14,86,87}

4 | CONCLUSION

A total of 201 indoor bi- and tri-modal particle size distributions (PSDs) from various indoor sources were combined with novel measured filter removal efficiency data to estimate integral measures of total UFP and $PM_{2.5}$ removal efficiencies for 50 commercially available residential HVAC filters. Results demonstrate that although commonly used filter performance rating metrics do not explicitly account for UFP and $PM_{2.5}$ removal efficiency, both tend to increase in efficiency with increasing rating value and depth, albeit with a number of exceptions. The median estimates of UFP removal efficiency ranged from 16% for one 2.5-cm (1-inch) MERV 8 filter to over 97% for one 12.7-cm (5-inch) MERV 16 filter. Similarly, median estimates of $PM_{2.5}$ removal efficiency ranged from 12% for one MERV 8 filter to 100% for the sole MERV 16 filter. These data also demonstrate that the manufacturer-reported rating value alone cannot always be used to predict initial UFP or $PM_{2.5}$ removal efficiency, as different makes and models can have very different UFP and $PM_{2.5}$ removal efficiencies depending on their measured size-resolved removal efficiencies and the nature of the indoor PSDs that challenge filters. However, the impact of indoor PSD was shown to be generally lower for UFPs than for $PM_{2.5}$.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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