atmosphere

Article

Evaluation of Filtration Efficiency of Various Filter Media in Addressing Wildfire Smoke in Indoor Environments: Importance of Particle Size and Composition

Tanya Shirman *, Elijah Shirman and Sissi Liu

Metalmark Innovations, PBC, Cambridge, MA 02138, USA; elijah@metalmark.xyz (E.S.); sissi@metalmark.xyz (S.L.)
* Correspondence: tanya@metalmark.xyz

Abstract: Sub-micron particles are ubiquitous in the indoor environment, especially during wildfire smoke episodes, and have a higher impact on human health than larger particles. Conventional fibrous air filters installed in heating, ventilation, and air conditioning (HVAC) systems play an important role in controlling indoor air quality by removing various air pollutants, including particulate matter (PM). However, it is evident that the removal efficiency of wildfire smoke PM and its effect on filter performance is significantly under-studied. This study delves into the size-specific removal efficiency of pine needle smoke, a representative of wildfire smoke and emissions. We test an array of filter media with minimum efficiency reporting values (MERV) spanning 11–15. Both size-resolved particle number concentrations and mass concentrations were measured using an Optical Particle Sizer (OPS, TSI, Inc.) and a Scanning Mobility Particle Sizer (SMPS, TSI, Inc.). Furthermore, we characterize the filter media morphology and smoke particles deposited on filter fibers using Scanning Electron Microscopy (SEM) to gain insights into the interaction dynamics of these particles. Our findings add to the comprehension of the relationship between MERV designations and smoke removal efficiency. Such insight can inform standards and guidelines and equip decision-makers with the knowledge needed to initiate measures for mitigating the impact of air pollution, specifically on the indoor environment.

Keywords: wildfire smoke; particulate matter; air pollution; HVAC; indoor air quality; air filtration; filter standard; health effect

Citation: Shirman, T.; Shirman, E.; Liu, S. Evaluation of Filtration Efficiency of Various Filter Media in Addressing Wildfire Smoke in Indoor Environments: Importance of Particle Size and Composition. *Atmosphere* **2023**, *14*, 1729. https://doi.org/10.3390/atmos14121729

Academic Editors: Sahar Zahiri, Hasim Altan and Jitka Mohelnikova

Received: 18 October 2023
Revised: 20 November 2023
Accepted: 20 November 2023
Published: 24 November 2023

1. Introduction

Over recent decades, the Western US and Canada have experienced a marked increase in the frequency and intensity of wildfires, posing an escalating environmental and health threat [1,2]. Studies have shown that wildfire smoke can be transported by wind and can affect the air quality, visibility, and atmospheric chemistry of places that are hundreds of kilometers away from the original locations of wildfires. In June 2023, in the wake of 500 ongoing wildfire events in Canada, heavy smoke and particulate emissions blanketed major parts of the northeast and north-central United States, resulting in some of the most polluted days on record and affecting some 122 million people. In late June 2023, the smoke crossed the Atlantic, reaching Europe. Wildfire projections indicate an impending shift to a temperature-driven global fire regime in the 21st century, creating an unprecedentedly fire-prone environment globally and increasing health risks, as well as societal and economic burdens [3–6]. It is estimated that nearly 50 million homes are currently in the wildland–urban interface in the US, a number that is increasing by 1 million houses every 3 years [7].

Current recommendations for wildfire smoke exposure are based on previously established guidelines for non-wildfire particulate matter (PM), specifically for $PM_{2.5}$, which are particles with an aerodynamic diameter of $\leq$2.5 µm, and their pollution levels are reported in terms of mass concentration, typically in µg/m^3. According to the National Emissions

Inventory (NEI) estimate from the US Environmental Protection Agency (EPA), wildland fires (wildfires and prescribed burns) are the largest source of $PM_{2.5}$ emissions in the US, accounting for as much as ~30% of total emissions across the continental U.S., and up to half of total $PM_{2.5}$ on an annual basis in the Western U.S., compared with 9.2% from transportation sources [4,8,9]. These wildfire emissions can traverse continents, leading to PM concentrations that far surpass safe health thresholds. In certain instances, daily $PM_{2.5}$ values have skyrocketed to around 800 $\mu g/m^3$, a stark contrast to the EPA's primary annual $PM_{2.5}$ standard of 10 $\mu g/m^3$ and 24h $PM_{2.5}$ standard of 35 $\mu g/m^3$ [10].

The adverse health effects, including cardiovascular and respiratory diseases and hospital admissions associated with exposure to $PM_{2.5}$, are extensively studied [11,12]. However, much less is known about the health effects of sub-micron particles, which can represent a significant fraction of $PM_{2.5}$. The penetration depth and deposition rate of airborne particles into human airways depend on their size, surface area, and chemical composition. Studies demonstrated that sub-micron particles, PM_1 and $PM_{0.1}$ (particles with an aerodynamic diameter of $\leq$1 μm and $\leq$0.1 μm, respectively), are particularly hazardous to human health, both immediately and over the long term. Studies show that sub-micron particles have detrimental effects on both cardiovascular and respiratory systems, including a higher incidence of atherosclerosis and the exacerbation of asthma [13], cause airway inflammation [14,15], and can lead to a high propensity to penetrate intracellularly and potentially cause DNA damage [16–20]. Multiple studies underscore the health risks associated specifically with exposure to wildfire smoke. Mortality and respiratory morbidity have been the most frequently studied and most consistently reported outcomes of smoke exposure [21]. Recent evidence suggests that smoke exposure is also associated with increased rates of cardiovascular mortality [21], respiratory emergencies [6], hospital admissions for ischemic heart disease [22], and out-of-hospital cardiac arrests [19,23]. Emerging data further links wildfire smoke to reduced birth weight, increased systemic inflammation, and bone marrow effects [24].

Wildfires discharge a multifaceted array of pollutants, including volatile organic compounds (VOCs) and various particulate matter (PM). The exact composition of a wildfire's output can fluctuate based on numerous factors, including the incinerated material (e.g., biomass, building materials, plastics, waste, etc.), the conditions under which it is burnt, ambient temperature, and weather conditions. Numerous studies demonstrate that most PM emitted from wildfires are in the sub-micron size range, typically below 300 nm (PM < 0.3 μm). Their size depends on many factors, including the intensity of the fire, fuel composition, age of the plum, and atmospheric conditions [2,8,9,25–28]. They largely comprise organic compounds (over 90%), followed by elemental carbon (roughly 5–10% by weight) and other inorganic elements [8,9]. In addition, wildfires emit hundreds of VOCs (e.g., formaldehyde, acrolein, and poly-aromatic hydrocarbons (PAHs)), which can subsequently contribute to the creation of ozone (O_3) [29] and secondary organic aerosols [30]. Many studies also show that these VOCs infiltrate into the indoor environment [31,32]. In addition, wildfires contribute to microbial emissions [33,34].

Even though sub-micron particles dominate the wildfire smoke in terms of particle count, their mass contribution to $PM_{2.5}$ becomes less prominent in the presence of larger particles. Consequently, the significance and contribution of wildfire smoke sub-micron particles are often understated when using a $PM_{2.5}$-based air quality framework for assessing ambient and indoor air quality. On an equal mass basis, sub-micron particles may be more potent than larger particles. This may be due in part to a much higher particle count concentration and combined particle surface area. For sub-micron particles, at a given mass concentration, a decrease in size results in a steep increase in PM number and surface area per unit mass (Figure 1). For example, assuming that the average density of smoke particles is 1.5 g/cm^3 [35], 10 $\mu g/m^3$ of 2 μm diameter particles contain about 1.6 particles per mL of air, and the total surface area of particles is about 20 μm^2/mL. In contrast, the same mass concentration of 100 nm particles contains ~12740 particulates in 1 mL with a total surface area of ~400 μm^2. Note that the numbers in the preceding example are based on a relatively low PM mass concentration. During pollution episodes, however, PM counts can rise to the order of 10^9/mL. In the case of combustion emissions, particles were demonstrated to have a highly reactive surface chemistry and adsorb a substantial amount of toxic organic compounds and reactive oxygen species [36]. The large surface area and ability to enter a bloodstream due to their small size are the two most significant characteristics that make them more toxic than larger particles. Given their large number and surface area, it is important to characterize their number concentration [37]. The use of particle count concentration is not a new concept. Current EU vehicle emission standards, for example, already include the application of particle number measurements [38], but this approach has not been adopted more broadly.

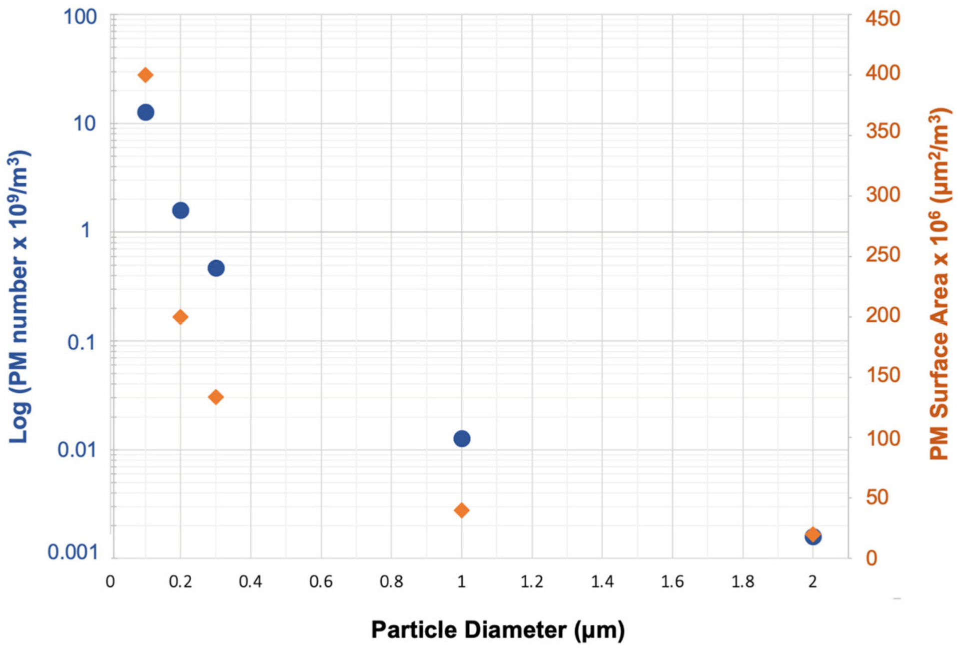


Figure 1. Particle number and surface area as a function of particle diameter at the same mass concentration of 10 μg/m^3. The graph assumes that all particles in each category are spherical and have the same density (1.5 g/cm^3). The blue circles represent the logarithm of PM number concentration (y-axis on the left side) and the orange diamonds show the corresponding PM total surface area (y-axis on the right side).

Another feature of sub-micron PM is that it stays suspended in the air substantially longer than larger particulates, travel long distances, and easily infiltrate inside buildings. Standard public health advisories during episodes of heavy smoke typically counsel residents to stay indoors and vulnerable individuals to visit a nearby public building with central air conditioning to reduce their exposure to smoke. However, there is limited data on the extent to which these "clean indoor air shelters" reduce exposure or health risks from smoke particles. Characterization of indoor air composition in general, and during wildfires, in particular, has emerged as a new area of research. Previous work has identified the influence of wildfire smoke events on indoor particle concentrations in residences [39–44], schools [45], and commercial buildings [46–49]. These studies demonstrate that elevated concentrations of outdoor $PM_{2.5}$ result in elevated concentrations in the indoor environment. For example, O'Dell et al. reported an 82% increase in $PM_{2.5}$ concentration indoors on smoke-impacted days compared to smoke-free days [46]. Moreover, the authors found that on heavily smoke-impacted days, indoor $PM_{2.5}$ concentrations can exceed the 35 μg/m^3 24-h outdoor fine particle standard set by the US EPA. Some studies show that ventilation systems can actually increase the infiltration of PM, suggesting that low and even medium-efficiency filters often used in residential and public buildings may not prevent the infiltration of smoke particles during a wildfire event [44,47]. Dev et al.

demonstrated that during smoke events, the indoor-to-outdoor ratio (I/O) of particulates was considerably elevated, being approximately 83% higher in buildings with ventilation compared to those without, concluding that staying indoors with HVAC-driven filtration and ventilation is not beneficial for health [44]. This finding also points to a potentially concerning inadequacy in HVAC filters commonly installed in residential and commercial structures when it comes to effectively filtering out smoke particles. An even more concerning problem is that most studies aiming to characterize the filtration efficiency of PM_1 and $PM_{0.1}$ utilize commercial, low-cost $PM_{2.5}$ sensors, which are known to be inaccurate or incapable of detecting or quantifying sub-micron particles, especially PM <0.3 μm, the main components of wildfire smoke. Examples of studies that have relied on size-resolved smoke particle measurements are scarce [44,49]. There remains a large gap in research on methods of measuring and mitigating exposure to wildfire-sourced particles in indoor settings.

Currently, HVAC filters represent the dominant means for PM removal in both residential and commercial indoor environments. Their PM removal efficiency largely depends on the material properties of the filter media, followed by filter geometry and HVAC system configuration and runtime. However, most filter test standards, including the most widely used one in the US, ASHRAE Standard 52.2 [50], and its counterpart in Europe, EN779 [51], do not account for PM < 0.3 μm when evaluating particle removal efficiency. For example, ASHRAE Standard 52.2 classifies the single-pass particle removal efficiency of HVAC filters based on the minimum removal efficiency for three broad particle size bins (0.3–1, 1–3, and 3–10 μm) using inorganic salts, such as KCl or NaCl particles, in a laboratory test facility (ASHRAE, 2017). The minimum removal efficiency value among these three size bins is then used to assign an HVAC filter its efficiency rating, called the Minimum Efficiency Reporting Value (MERV). Studies on filtration efficiency vary in estimates of $PM_{2.5}$ removed when passing through the filter of the HVAC system but they are consistent in the determination that increasing MERV ratings lowers indoor concentrations of $PM_{2.5}$. Such a conclusion, however, does not account for PM < 0.3 μm, which predominates wildfire smoke PM size distribution and composition. Hence, current standard test conditions are far from representing the size and composition of smoke particulates.

Several previous studies have investigated the removal efficiency of sub-micron particles in laboratory settings using various filter media [52–54] or HVAC filters in a full-size laboratory test duct [55–57]. Although valuable, such tests were conducted using inorganic salts, dioctyl phthalate (DOP), or other analytes that are vastly different from smoke. Limited information exists about the size-resolved filtration efficiency of a filter media using a representative sample of wildland fuel smoke, such as pine needles or wood chips. When characterizing the smoke removal efficiency of filter media, two parameters need to be considered: (1) the size-resolved removal efficiency of smoke particles and (2) the changes in the performance of the filter media with smoke exposure over time. Schumacher et al. characterized the performance of new and artificially aged electret filters in indoor portable air cleaners and found that their filtration efficiency decreases with particle size [58]. Electret filters are electrostatically charged polymer-based filters that exhibit higher filtration efficiency and low airflow resistance compared to purely mechanical filters [59]. Given the appropriate filter geometry, a filter manufactured with electret filter media, which is also sold at a lower price point than fiberglass media, could thus provide HVAC energy savings advantages. Schumacher, S. et al. found that loading electret filters with cigarette smoke results in a ~80% decrease in the portable air cleaners' Clean Air Delivery Rate (CADR). Similar behavior has been observed in other studies employing cigarette smoke or isopropyl alcohol vapor-treated electret media [60,61]. Cigarette smoke is frequently used for testing filters independently or installed in portable air cleaners. Like pine needle smoke, cigarette smoke contains high concentrations of sub-micron particles, which can be produced in a short amount of time. While the use of cigarettes suggests a close approximation to reality, it turns out that under real-world conditions, a large portion of cigarette smoke is exhaled aerosols, which have vastly different properties from direct cigarette burning. Furthermore, tobacco smoke is listed by the International Agency for Research on Cancer as a Group 1 carcinogen, and indoor smoking is relatively rare in many countries nowadays. There are very few studies examining the effect of wildfire smoke on electret air filters. For example, one study showed that CADR of air cleaners equipped with electret air filters was reduced by 95% without a significant increase in pressure drop (only ~7%) after deposition of only 10 mg of wildfire smoke on the filter [62]. The authors concluded that the electret filter condition had a strong impact on air cleaner effectiveness. Other studies that investigated longer-term and more realistic test conditions note similar findings, with one study observing a substantial reduction in particle removal efficiency over a 19-week period of operation in an air handling unit that supplies outside air [63]. Taking the rapid efficiency degradation of electret filters into account, this points to the need for vastly more frequent filter changes during smoke events. This is worrying since electret filters have gained significant market share and are widely used in both HVAC and portable air cleaners [64–66].

The exact mechanism of the filter media degradation depends on multiple factors, including the amount and composition of the particles. For example, it was demonstrated that with the same loaded mass, carbon particles cause more charge decay and degradation of removal efficiency than NaCl and Al_2O_3 particles [67]. To the best of our knowledge, there are no systematic studies showing the size-resolved filtration efficiency of smoke particles using various grades of commercial filter media and the effect of smoke loading/aging on filter media morphology and performance. Given gaps in the knowledge of wildfire smoke composition and filter media behavior, it is essential to improve the understanding of how different MERV filter media perform in removing wildfire smoke and how smoke loading affects their filtration properties.

The objectives of this study are to (a) measure the size-resolved particle removal efficiency of pine needle (PN) smoke as a wildfire smoke proxy of a group of 7 clean and commercially available HVAC filter media and (b) evaluate the effect of PN smoke loading on media performance of two types of filter media—fiberglass (mechanical) and electret (charged)—with different MERV ratings ranging between MERV 11 to MERV 15 on a custom-built laboratory setup. These evaluated media represent the most relevant MERV grades against smoke for HVAC applications [68]. Two types of media, fiberglass, and electret, with similar MERV ratings, were tested for the effect of smoke loading at a third-party lab. Furthermore, the smoke particles deposited on filter fibers were characterized using Scanning Electron Microscopy (SEM). The findings and results herein can provide guidance for the selection of filter media under the comprehensive and application-specific considerations of air quality and energy consumption as selection criteria.

2. Materials and Methods

2.1. Filter Media

All filter media tested were sourced directly from two filter media manufacturers. Seven different types of filter media were tested in this study. Table 1 provides detailed information for each of the filter media based on the vendor specifications and corresponding MERV ratings as defined by the minimum particle removal efficiencies per three size bins as described in ASHRAE Standard 52.2. Media types A and B are MERV 11 electrostatically charged melt-spun polymer media (referred hereto as electret) that were acquired from different manufacturers. Media types C to G are fiberglass, purely mechanical media. Media types F and G are MERV 15 fiberglass media sourced from different suppliers. All media types were tested for initial filtration efficiency using new, clean media, each time with the felt side toward the challenge.

Table 1. Specifications of filter media as provided by the vendor and corresponding MERV ratings.

Media Type	Vendor Specs						ASHRAE MERV Rating [c] (PM$_{2.5}$ Range)
	MERV	Type	Basis Weight (g/m^2)	Thickness (mm)	Air Flow Resistance [a] (Pa)	Efficiency [b] (%)	
A	11	Polymer electret	100 ± 14	0.6 ± 0.2	8.8	70	0.3–1.0 ≤ 20% 1.0–3.0 ≤ 65% 3.0–10.0 ≤ 85%
B	11	Polymer electret	120 ± 14	0.7 ± 0.2	5	70	0.3–1.0 ≤ 20% 1.0–3.0 ≤ 65% 3.0–10.0 ≤ 85%
C	12	Fiberglass	78 ± 6	0.4 ± 0.0	15	30	0.3–1.0 ≤ 35% 1.0–3.0 ≤ 80% 3.0–10.0 ≤ 90%
D	13	Fiberglass	78 ± 6	0.4 ± 0.0	20	45	0.3–1.0 ≤ 50% 1.0–3.0 ≤ 85% 3.0–10.0 ≤ 90%
E	14	Fiberglass	78 ± 6	0.4 ± 0.0	35	55	0.3–1.0 ≤ 75% 1.0–3.0 ≤ 90% 3.0–10.0 ≤ 95%
F	15	Fiberglass	78 ± 7	0.4 ± 0.1	113	93	0.3–1.0 ≤ 85% 1.0–3.0 ≤ 90% 3.0–10.0 ≤ 95%
G	15	Fiberglass	78 ± 7	0.4 ± 0.1	120	94	0.3–1.0 ≤ 85% 1.0–3.0 ≤ 90% 3.0–10.0 ≤ 95%

[a] Measured at 5.33 cm/s (10.5 FPM) [b] Measured at 5.33 cm/s for MPPS 0.3 µm using NaCl or KCl particles [c] Minimum Efficiency Reporting Values, or MERVs, report a filter's ability to capture particles between 0.3 µm and 10 µm. Available online: https://www.epa.gov/indoor-air-quality-iaq/what-merv-rating (accessed on 25 October 2023).

2.2. Instrumentation and Measurements

2.2.1. Filtration Efficiency Test Setup

The experimental setup used for testing the performance of filter media is schematically shown in Figure 2a. The setup comprises a few key components: (1) a 100 ft^3 stainless steel environmental chamber with a mixing fan (referred hereto to as the smoke chamber, which serves as a smoke reservoir); (2) attached to this chamber is a 1.5-inch diameter stainless steel sanitary tubing conduit that features two arms, allowing for air from the chamber to pass either through the sample or a bypass arm. The conduit features a pressure gauge (Sensirion, SDP811) for monitoring the pressure drop across the media sample; (3) a mass flow controller (MFC, Alicat, Tucson, AZ, USA) is employed to regulate the flow, while a peristaltic pump (4) generates the airflow; (5) a gas collection vessel, with outlets for probing the air stream composition with OPS, SMPS, and environmental sensors; and (6) a dedicated personal computer for collecting and analyzing the data from the experiments. For this study, the smoke produced from dried PN (USA Pinestraw, Atlanta, GA, USA) was used as a model analyte for wildfire smoke. A representative filter media sample is shown in Figure 2b, with the dotted line demarcating the area exposed to the air stream, approximately 5.1 cm^2 or 1 in^2. For each experimental run, a predetermined weight of PN was cut into approximately 1 cm long pieces, then combusted using a portable smoke infuser (Vikua) directly into the smoke chamber, as depicted in Figure 2c,d.

The PM count of the air stream was performed with (1) an optical particle sizer (OPS Model 3330, TSI, Inc., Shoreview, MN, USA) capable of counting particles with diameter in the range of 365 nm to 10 µm at 16 channels per decade resolution in the concentration range of 0–3,000 particles/cm^3, and (2) a Scanning Mobility Particle Sizer (Nanoscan SMPS Model 3910, TSI, Inc., USA) capable of counting particles in the 10–365 nm size range at 16 channels per decade resolution at concentration range of 100–1,000,000 particles/cm^3. In addition, a high-resolution SMPS (Model 3839L50, TSI, Inc., USA) with 128 channels/decade, capable of counting particles of 1 nm to 1μm and dynamic concentration range of single and up to 107 particles/cm^3, was used to corroborate some of the SMPS and OPS results as described below.

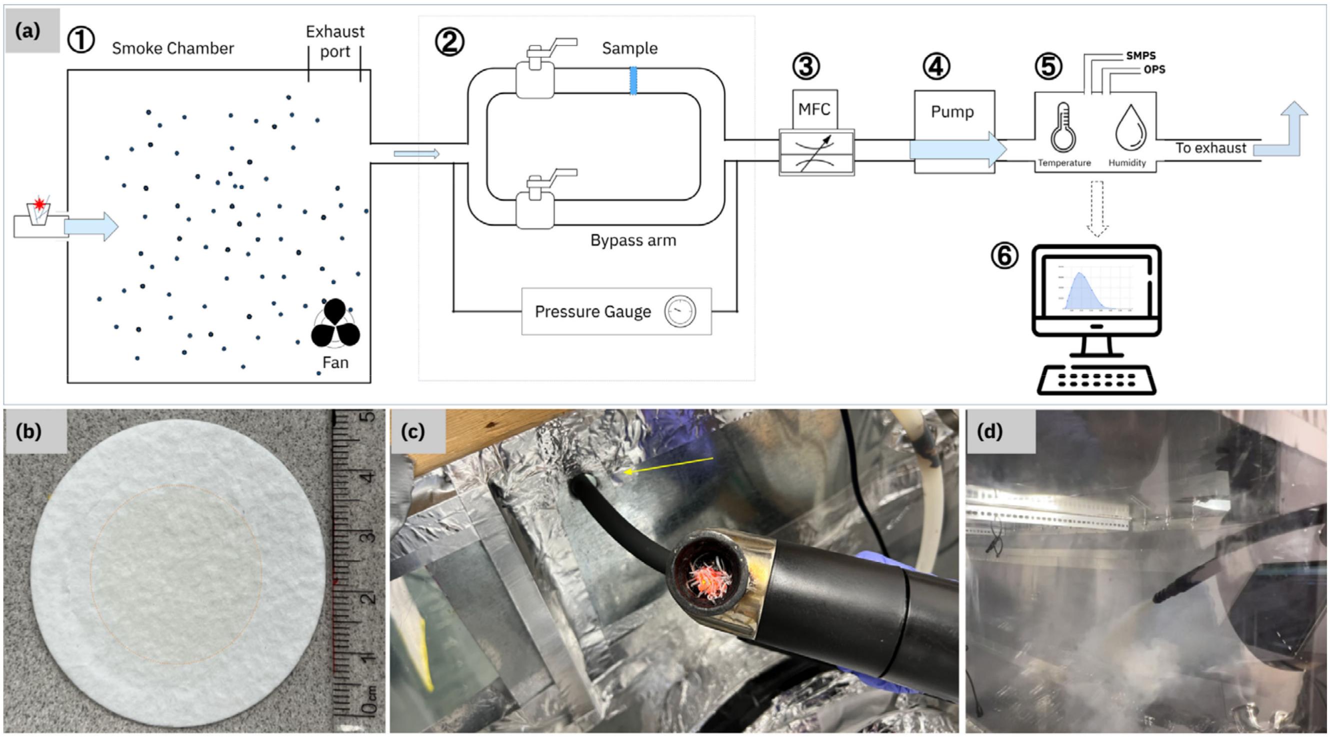


Figure 2. Experimental setup for testing filter media performance. (**a**) Schematic representation of the setup's key components: (1) smoke chamber, (2) stainless steel conduit with valves and sample holder, (3) mass flow controller, (4) peristaltic pump, (5) probing vessel, and (6) personal computer. (**b**) Photograph of a typical filter media sample, with the dotted line demarcating the area exposed to the airstream. (**c**) Infuser actively combusts pine needles (PN) to introduce smoke into the smoke chamber. The yellow arrow points at the smoke injection port. (**d**) Interior view of the smoke chamber, highlighting the end of the infuser pipe during smoke generation.

All of the filter media were tested at a flow rate of 10 L/min, corresponding to a face velocity of ~33 cm/s or ~60 fpm. This airflow velocity falls within the range of the flow velocities experienced by a media incorporated into a MERV filter in practical applications. The face velocity is calculated by dividing volumetric flow in CFM (f^3/min) by the surface area of the filter media in f^2. The surface area of common HVAC filters is determined by the size of the filter, depth, and number of pleats and typically ranges between ~3 f^2 to ~35 f^2 for MERV filters with a rating of 8 to 16 [55,69–71]. For example, given an HVAC flow range between 400–800 CFM and the above-mentioned filter surface area, the face velocities would be in the range of ~5 to 135 cm/s. Many HVAC systems flow at the rate of thousands of CFM. It is therefore worth noting that a 5.3 cm/s face velocity is typically used for mechanical (fiberglass) HEPA media testing, and here, standard comparison between media is not adequately representative of real-world, application-oriented HVAC usage, except if the filter media area is proportionally sized. For all experiments, the temperature and relative humidity were monitored (SEN55, Sensirion, Stäfa, Switzerland) inside the smoke chamber and stayed within the ranges of 24–28 °C and 45–65% RH, respectively.

2.2.2. Data Collection and Analysis

Each analytical tool used in this study utilizes a dedicated software application for data monitoring and recording. A typical test with the corresponding particle counts for selected channels (48, 115, 154, and 205 nm) and the sequence of steps is shown in Figure A1.

In a typical test, we used ~35 mg of PN, which resulted in ~4 × 10^5 particles/cm^3 and ~400 μg/m^3, as reported by SMPS. The test started with smoke generation, followed by a period of ~5 min, during which the system was set to run in bypass mode to allow the signal to stabilize. This was followed by a 3 min filtration phase and then another 3 min in bypass mode. This cycle was repeated once more for the same sample and two more cycles for two additional samples before the chamber atmosphere was vented in preparation for the next round of testing. Each type of media was tested at least three times.

Following data collection, the filtration efficiency of the tested media samples was calculated using Equation (1), where C_{filter} is the average of the signals recorded during filtration mode, and C_{bypass} is the average of the signals recorded in the bypass mode immediately before and after the filtration mode.

$$FE\% = (1 - C_{filter}/C_{bypass}) \times 100\% \quad (1)$$

2.2.3. Independent Lab Testing

The filtration efficiency of selected media types was tested at an independent lab (LMS Technologies, Inc., Edina, MN, USA) according to the ASHRAE Standard 52.2 before and after smoke loading (aging). Initial filtration efficiency of media types A (polymer electret media, MERV 11) and C (fiberglass media, MERV 12) were tested using neutralized KCl particles in the size range of 0.3–10 μm. The typical flat sheet media sample size was 12 in by 12 in. After initial filtration efficiency measurements, the sample was left in the setup for continuous deposition of smoke for smoke loading (aging) experiments. During all smoke-loading experiments, the type of PN used was the same as the one used in the rest of this study. To produce smoke, PNs were placed in a ceramic boat mounted on a heating plate and lit on fire under atmospheric pressure. The generated smoke was sent through a 61 × 61 cm duct with the heating plate inside at a flow rate of 5.3 cm/s (10 fpm, 58.3 CFM) for ~10 min. The flow was generated using a blower and regulated with MFC. For the smoke loading (aging) experiment, about 3 g of PN were burned. Post-smoke deposition, the media sample was tested again for filtration efficiency using KCl particles based on ASHRAE Standard 52.2 at two flow rates, 5.3 cm/s, and ~33 cm/s. A pressure gauge (MKS Instruments, Inc., Andover, MA, USA) was used to monitor the pressure drop across the media sample.

2.3. Filter Media Characterization

The filter morphology was analyzed using Field Emission Scanning Electron Microscopy (FE SEM, Gemini 360, Zeiss). The samples for SEM images were prepared by cutting filter media into small pieces of ~0.5 × 0.5 cm and placing them on an SEM holder.

3. Results and Discussion

3.1. Generation of Pine Needle (PN) Smoke Particles and Their Size Distribution

PN smoke is considered a good model analyte for wildfire smoke and has been used by the US EPA for laboratory studies as a proxy for biomass burning [72]. There is currently no standard protocol for testing the filtration efficiency of flat filter media with smoke. As discussed earlier, pine needle smoke composition and particle size distribution are complex and depend on various factors, including the specific type of pine, the condition and purity of the needles, and combustion temperature. The size distribution of particles originating from combusting PN was characterized in this study using analytical tools described previously in Section 2 (Materials and Methods).

According to our observations, the composition of the smoke is dynamic during the initial seconds to minutes following its generation. During this timeframe, some ultrafine particles undergo coalescence to form larger particles, although these resulting particles remain in the lower sub-micron size range. The majority of these transformations occur rapidly, resulting in a typical particle size distribution that ranges from 20 to 250 nm, as shown in Figure 3. The resultant size distribution is characteristic of fresh smoke in accumulation mode and is in good agreement with other studies [73–75]. Importantly, in realistic conditions, as wildfire plume undergoes atmospheric transformations (ages), particle size has been found to increase by 100–150 nm, but remaining in a submicron range, as discussed above [25–27,75].

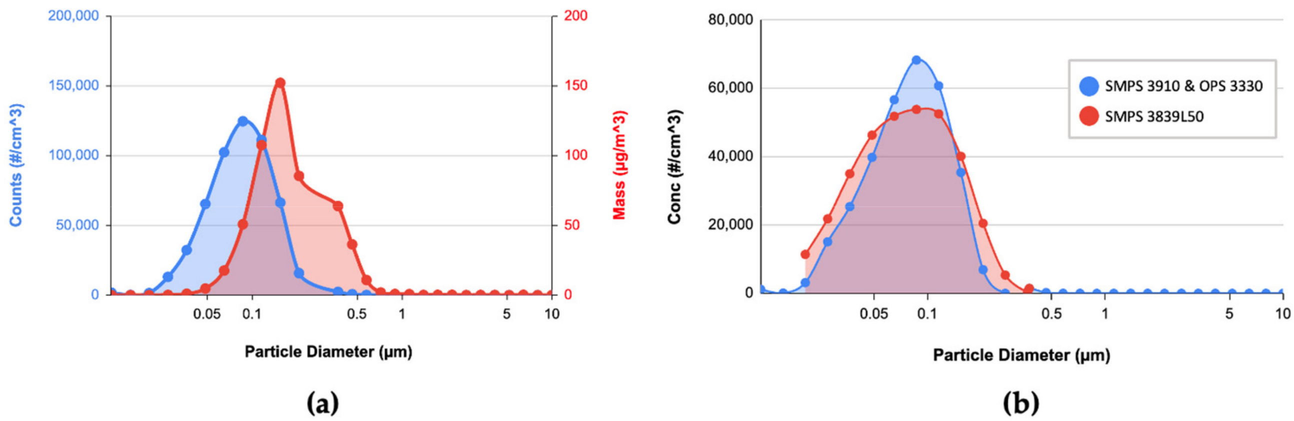


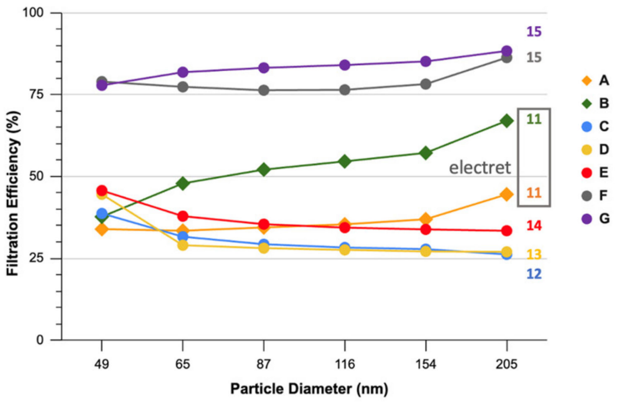
Figure 3. (**a**) PM size distribution in pine needle smoke recorded by TSI Nanoscan SMPS 3910 and TSI OPS 3330 (stitched signal to cover the entire range). (**b**) Characterization of PN smoke particle size distribution using three analytical systems: (1) TSI Nanoscan SMPS 3910 combined with OPS 3300 (blue trace) and high-resolution SMPS 3839L50 (red trace).

The SMPS (Model 3910) was used to measure particles with mobility diameters from 10 nm to 365 nm. To account for larger particles, in the range of 365 nm to 10 µm, the OPS (Model 3330) was utilized. The combined result of both measurements is shown in Figure 3a (blue trace).

This result was also corroborated using a high-resolution model SMPS (Model 3839L50) that is capable of counting particles in the range of 1 nm to 1 µm (Figure 3b). The results indicated that PN smoke in our study has a primarily mono-modal size distribution in the range of 20–250 nm with a median diameter of ~100 nm. No particles greater than 1 µm were detected. The concentration of PM in our typical experiment underwent a decay, with the median diameter slightly increasing in the first minutes following smoke generation due to various processes, including coagulation, diffusion, and settling (Figure A2). Coagulation effects have also been observed in various studies of cigarette smoke [76]. When presenting the same PM size distribution by mass, however, the median diameter shifts by more than 150 nm, and the shape of the distribution changes due to a significant contribution to mass coming from just a few large PMs. As mentioned above, under real-world conditions, as smoke particles age and change in size and composition in the atmosphere due to the coagulation and condensation/evaporation processes, their mass-based size distribution would be shifted even further toward larger diameters. Hence, it is important to report both values. Generation of smoke using various weights of PNs did not show a significant variation in the PM size distribution within the tested range of PN weight of 20 to 100 mg (Figure A3). Given the knowledge of PN smoke particle size distribution, setup, and instrument limitations, we chose to use ~35 mg of PN and only use SMPS (Model 3910) to measure the filtration efficiency of filter media samples.

3.2. Characterization of Initial Filtration Efficiency of Pine Needle Smoke

Seven medium-efficiency flat filter media samples were used for the testing to provide a comparison of filtration efficiency versus PN smoke particle diameter. The specific details about the media are provided in Section 2 (Materials and Methods) (Table 1). Only MERV 11 and higher-grade media were tested due to their relevance for wildfire smoke applications. In 2015, ASHRAE published new recommendations for residential homes to install MERV 13 filters or higher in guideline 24-2015, and in January 2021, recommended a MERV of no less than 13 filters for building HVAC systems to reduce the transmission of indoor infectious airborne viruses during the COVID-19 pandemic [77]. Other studies demonstrated a very low or no removal efficiency (<10%) of sub-micron particles of MERV 10 and below [78]. Samples were cut into ~5 cm diameter (~2 inch) circles and installed into the test setup (see Section 2 (Materials and Methods) for details). The cross-sectional area of the sample media exposed to the gas stream in this study was approximately 5 cm^2. In a typical filtration efficiency test, 35 ± 5 mg of pine needles were used to produce the smoke that was allowed to equilibrate for five minutes before starting the test. Following this equilibration phase, the smoke particle size distribution and concentration remained reasonably stable for the purposes of the experiment for approximately 60 min (Figure A1). The gradual shift in the median diameter from slightly below 100 nm to slightly above 100 nm, following the initial equilibration phase, had a minimal impact on the filtration efficiency tests. Given the distinct PM size distribution of PN smoke, the most reliable size channels of the SMPS instrument fell within the ~50–205 nm range. Therefore, this was the data we prioritized for analysis and presentation. The recorded initial size-resolved filtration efficiencies are shown in Figure 4. Each data point is an average of at least three media tests. All data were collected at 10 L/min, corresponding to a face velocity of 33.5 cm/s, which is in the range of typical velocities experienced by filter media in practical applications, as discussed above.



(a)

Media Type	Vendor Grade	Change in Pressure Drop (%)	Size Resolved PM Filtration Efficiency		
			0.1 µm[a] (%)	0.3 µm[b] (%)	Reduction (%)
A	MERV 11	1.2	35	70	49
B	MERV 11	2.8	55	70	22
C	MERV 12	1.3	28	30	6
D	MERV 13	0.3	28	45	39
E	MERV 14	0.9	34	55	37
F	MERV 15	2.5	76	94.5	19
G	MERV 15	3.1	84	94	11

a) Filtration efficiency measured in this study
b) Filtration efficiency provided by vendor

(b)

Figure 4. (**a**) Size-resolved initial filtration efficiency of pine needle (PN) smoke tested using seven new filter media with various manufacturer-reported MERV values. (**b**) Summary of the filtration efficiencies for ~100 nm particles of tested samples, their corresponding MERV rating and filtration efficiency at 0.3 µm as provided by the vendor, and calculated difference (reduction in the filtration efficiency) for these two particle sizes.

The samples in Figure 4a can be categorized into three sets based on their type and average single-pass removal efficiencies. One set consists of fiberglass media samples C (MERV 12), D (MERV 13), and E (MERV 14), with recorded filtration efficiencies for ~100 nm particles of 28%, 28%, and 34%, respectively. The filtration efficiencies of samples C and D for PN smoke particles were very similar over the entire range of PM sizes, while sample E demonstrated a slight increase in efficiency for particles smaller than 60 nm. All three media samples were obtained from the same vendor and exhibited similar physical properties, such as weight and thickness, as detailed in Table 1. As can be seen in Figure 4b, while the most penetrating particle size (MPPS) values at 0.3 µm and 0.3–1 µm provided by the vendors are in agreement with their respective MERV ratings—gradually increasing from 30% for MERV 12 to 55% for MERV 14—the filtration efficiency for PN smoke is quite similar for MERV 12 and 13 media (28%) and only slightly higher for MERV 14 samples.

Another set of samples, A and B, form a representative group for electret filter media from two different vendors, both rated as MERV 11. Typically, the reported MERV rating of polymer electret media is based on its performance in a discharged state, i.e., mechanical filtration. If not discharged, electret media generally exhibit a higher initial filtration efficiency compared to purely mechanical filter media. However, this enhanced performance is transient and can diminish rapidly when exposed to certain environmental factors in real-world applications [59,65]. For example, media types A and B are rated as MERV 11, which corresponds to a filtration efficiency of $\leq$ 20% for particles in the 0.3–1 µm range, as specified in the ASHRAE Standard 52.2 (Table 1). However, the efficiencies provided by vendors (and confirmed experimentally in this study) at 0.3 µm are much higher (70%). When challenging samples A and B with PN smoke, significantly lower filtration efficiencies for $PM_{0.1}$ compared to the values for the specified 0.3 µm were observed (~35% and ~55% for A and B, respectively). Several factors could account for the differences between these samples. First, media type B has a greater weight and thickness, as indicated in Table 1. Additionally, while both media types are classified as "electret", their performance and characteristics depend on the particular manufacturer's fabrication technology, which determines the media's structure, charge distribution, stability, and magnitude of the internal electric fields [59,65].

The third set of samples, F and G, included two fiberglass media rated at MERV 15, produced by two different manufacturers (Figure 4a). As expected, both samples exhibited higher filtration efficiency for PN smoke particles of ~100 nm (~80%) than the lower-grade MERV media assessed in this study. For all media samples, there was no significant change in the pressure drop after smoke filtration, as indicated in the table in Figure 4b.

From our initial filtration efficiency tests, the purely mechanical MERV 15 fiberglass media (samples F and G) was the most efficient (>50%) in removing most particle sizes of PN smoke. Electret media A also demonstrated efficiency, although to a lesser degree. Our data yielded quite similar, almost linear trend values of filtration efficiency across the tested range of 50–200 nm. This is in contrast to the widely reported and anticipated trend in this size range based on the removal efficiency of inorganic PM < 0.3 µm (e.g., KCl) for a wide range of MERV designations. The expected trend is one that features a steep increase in filtration efficiency with decreasing particle diameter below 100 nm consistent with the theoretical Brownian capture model [52,78–80]. Smoke particles are characterized by a complex composition, including solid (e.g., black carbon) and liquid/oil-like organic phases (e.g., SVOCs). Some studies reported an increase in a liquid-like character for smaller particles [75,81]. The dynamics of the liquid and solid particle filtration differ significantly due to the differences in deposition modes (dendritic structures formed by solid particles vs. film formation by liquids), collision kinetics, and differences in the particle/fiber surface interactions. Some studies indicated that the presence of oil in the particle causes a reduction in the media's filtration efficiency in comparison to solid particles of the same size [82]. Numerous studies have shown that the MPPS for non-charged (mechanical) filter media lies indeed in the 0.1 to 0.3 µm range, while for electret media, it is around 20–30 nm [53,79]. Solely relying on salt particles in standardized testing methods for evaluating the performance of filters is insufficient in the context of real-world HVAC systems challenged with environmental pollutants such as smoke particles.

Finally, testing only the initial filtration efficiency misses an important parameter for assessing media performance, and that is its performance over its time in use, again in the context of real-world applications. This is an especially key factor of consideration in the case of electret media as exposure to environmental factors can have a detrimental effect on its long-term performance. As discussed previously, many studies indicate that cigarette smoke particles can substantially impair the removal efficiency of electret media [58,60]. We further investigated this aging effect using PN smoke, as described below.

3.3. Effect of Smoke Loading on the Filtration Efficiency and Morphology of the Filter Media—Aging Test

The evaluation of filtration efficiency of two media types, A and C, before and after PN smoke loading was performed at the independent lab (LMS Technologies, Inc.) according to ASHRAE Standard 52.2 for flat media testing. The details of the test method are provided in the Section 2 (Materials and Methods). First, clean samples were challenged with KCl particles with sizes in the range of 0.3–10 μm at two different air velocities, 5.3 cm/s (10.5 fpm) and 33 cm/s (60 fpm). Size-resolved initial filtration efficiency measurements for fresh and aged samples are shown in Figure 5a. For particles in the sub-micron range, media type A (electret, MERV 11) registered an initial filtration efficiency of ~75% at 5.3 cm/s in agreement with the vendor's specifications (Figure 5a, light brown squares). However, at a higher face velocity of 33 cm/s, the initial filtration efficiency of media A dropped to ~48% (Figure 5a, light brown circles). Such efficiency drop with the increase in airflow for electret media is well established in the literature [64,65]. In contrast, the initial efficiency of fiberglass media type B (MERV 12) remained fairly consistent at both velocities, 5.3 cm/s and 33 cm/s, in the sub-micron PM range and further improved with the increase in the particle size, especially above 1 μm (Figure 5a, bright blue squares and circles, respectively). The improvement in the filtration efficiency with the increase in particle size was observed for both media types.

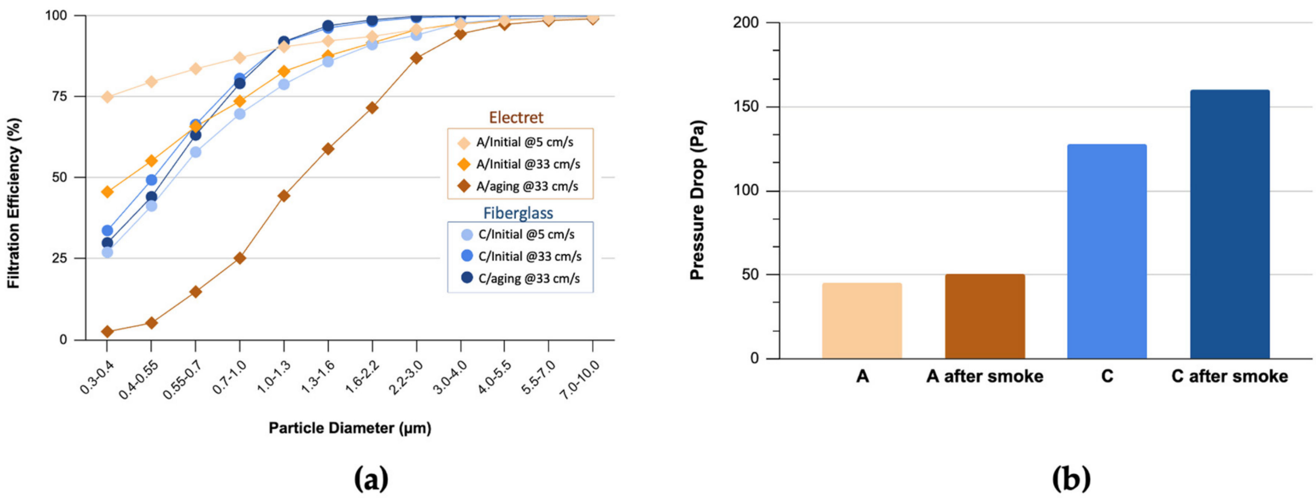


Figure 5. (**a**) Initial filtration efficiencies at two different flows, 5 cm/s and 33 cm/s (squares) of sample A (bright brown) and C (bright blue), and the efficiencies measured after smoke loading at 33 cm/s (dark brown and dark blue, respectively) tested according to ASHRAE Standard 52.2 media testing standards. Test analyte: neutralized KCl particles. (**b**) Change in the pressure drop across samples A and C before (bright brown and bright blue) and after (dark brown and dark blue) smoke loading.

In the smoke loading (aging) experiment, approximately 3 g of PNs were combusted to deposit smoke on each sample. The deposition of PN smoke visibly altered the color of the media from white to brown. For media type A, this smoke loading led to a significant decrease in the filtration efficiency for most of the particle sizes, but especially in the sub-micron range, plummeting to ~2.5%, a staggering 95% drop in performance. In contrast, for media type C, smoke exposure did not have a significant effect on filtration efficiency. As shown in Figure 5b, the change in pressure drop after smoke exposure was minimal for the type A media despite the significant reduction in filtration efficiency. The initial pressure drop of sample A was 45.5 Pa and increased slightly to 50.8 Pa after smoke loading (11.6%). For sample C, the initial pressure drop was 127.4 Pa and increased to ~160 Pa post-smoke loading, corresponding to a greater increase of 26.0%. These results indicate that the structural integrity of the filter media remained largely intact in both samples. However, while PN smoke particles can alter the electrostatic charge properties of the electret media and cause a significant drop in the filtration efficiency, they have a negligible effect on the filtration efficiency of fiberglass media. Although previous research on the long-term performance of electret filters indicates a variety of factors (e.g., humidity, exposure to certain chemicals, dust loading, elevated temperature, etc.) that can contribute to the loss of the charge and, consequently, the decline in their efficiency [83,84], most recent research shows that the effect of the smoke deposition seems to be much more detrimental in accelerating the media aging and deterioration in real-world applications [60,62].

To gain a further understanding of the effect of PN smoke loading on the morphology of the media fibers, we analyzed media sample types A and C using Scanning Electron Microscopy (SEM). Figure 6a–f show SEM images of samples of media types A and C, respectively, at various stages of aging testing.

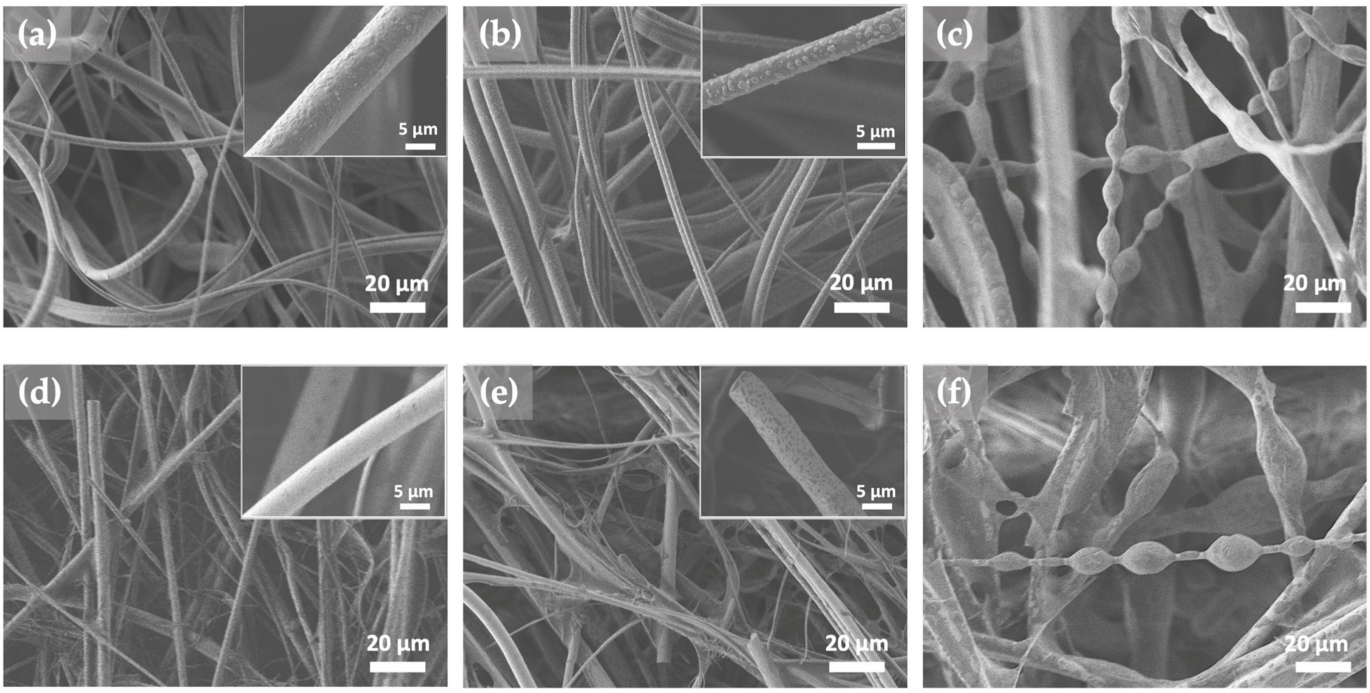


Figure 6. Representative Scanning Electron Microscopy (SEM) images of media type A (electret, MERV 11, panels (**a**–**c**) and C (fiberglass, MERV 12, panels (**d**–**f**)). (**a**) and (**d**) represent images of a clean, as received samples of media types A and C, respectively. (**b**) and (**e**) represent media samples after initial filtration efficiency tests with pine needle smoke and (**c**) and (**f**) after smoke loading of samples of media types A and C, respectively. The inserts show high-magnification images of individual media fibers.

Both samples demonstrate smooth fiber morphology in their clean state. Following intermediate levels of smoke deposition, high-resolution images reveal the formation of small droplets on the fiber surface. These droplets were notably larger on electret fiber compared with those on fiberglass fibers. After a complete aging test with PN smoke, the fibers' surface was found to be covered with droplets resembling "beads on string" morphology for both samples, predominantly on the finer fibers. The SEM analysis provides support that PN smoke exposure did not affect the physical structure of the media but significantly altered the fiber morphology and surface in general. This observation is in sharp contrast to the effects of loading inorganic particles (e.g., KCl). Studies utilizing microscopy for characterizing challenged filter surfaces are scarce. Observation of "beading" morphologies was observed in several publications focusing on liquid-phase organic aerosols [82,85].

4. Conclusions

In this study, we systematically examined size-resolved removal efficiencies of pine needle smoke (as a surrogate for wildfire smoke) of seven filter media types that belonged to two categories -- fiberglass and electret-- with ratings ranging from MERV11 to 15. To the best of our knowledge, this is the first systematic study comparing various fibrous media for their efficacy in removing pine needle smoke as a wildfire smoke proxy. The selected filter media were chosen specifically to span a range of manufacturer-reported and rated efficiencies relevant to wildfire smoke removal applications. Conventionally, it is widely accepted and expected that particle filtration efficiencies of filter media follow the general shape of a positive quadratic equation, with the minimum efficiency deep at around the size of 0.3 μm and a steep increase in filtration efficiency as particle size decreases. Such filtration efficiency trends typically result from testing using inorganic particles (e.g., KCl). However, our results deviate from this established and anticipated pattern when assessing the filtration efficiency of pine needle smoke particles. In the case of fiberglass filter media, a purely mechanical filter material, initial filtration efficiency for PN smoke particles was lower than expected based on the designated MERV rating. This suggests that current testing standards overrate the efficiency of filters if considering only inorganic particles larger than 0.3 μm and overestimate the filter capability of removing sub-micron particles. The results also suggest that mechanical media MERV 11–14 and MERV 15 can be grouped into two distinct categories in terms of removal efficiency of smoke particles with efficiencies of ~30 and ~80% for MERV 11–14 and MERV 15, respectively.

For mechanical filter media targeting the removal of wildfire smoke, a higher MERV-rated (e.g., MERV 15 or 16) media may be more effective and advisable. However, a media with a higher MERV rating typically causes significantly higher resistance to airflow within the HVAC system, thereby increasing energy use and reducing equipment lifetime. In practice, most HVAC systems would require major upgrades to be compatible with such filters. Part of the reason is that a large fraction of the HVAC systems utilizes charged electret media that have a far lower pressure, higher initial filtration efficiency, and attractive cost. In our tests, electret media demonstrated higher initial removal efficiency of PN smoke than fiberglass media of the same grade. However, there were some major differences in performance between electret media sourced from different manufacturers. Our results show that two different electret filter media with the same MERV rating could have very different efficiencies for particles smaller than 0.3 μm. Unlike fiberglass media, the filtration efficiency of electret media diminishes sharply when aged with PN smoke, plummeting by as much as 95% in our tests. In summary, electret media has been shown to have a poorer efficiency for PN smoke removal than expected based on MERV rating, and its performance declines precipitously when filtering smoke.

Climate change-induced intensification and frequency of wildfires around the globe necessitate improved IAQ solutions that address wildfire smoke. The same premise also calls for solutions considering multifaceted factors, such as balancing human health with climate resilience, energy efficiency, and green building parameters. This study aims to bring attention to several important aspects of advancing IAQ solutions. First, it is vital to start by accurately assessing and monitoring IAQ with special attention to particle size distribution. Since submicron particles are ubiquitous in the indoor environment, especially during wildfire smoke events, and have a higher potential impact on human health than larger particles, technology development and policy formulations should elevate the priority of sub-micron PM range, especially below 0.3 μm. Furthermore, particulate mass concentrations reported in terms of mass per volume ($\mu g/m^3$) for $PM_{2.5}$ may not fully convey the qualitative differences between indoor and outdoor air quality, especially during wildfire smoke episodes. While sub-micron particles are often dominant in indoor environments in terms of particle counts, their contribution to the total mass of $PM_{2.5}$ can be relatively small. This discrepancy highlights the importance of considering both particle mass and number concentration when assessing air quality, as the health impacts of particulate matter depend on both factors. More specifically, during wildfire smoke events, the influx of PM <300 nm from outdoor sources can significantly alter the indoor air quality, thus necessitating a comprehensive approach to air quality assessment that accounts for both particle counts and mass concentrations across different size ranges. Approaches to IAQ solutions should rely on using appropriate measurement tools, communicating using relevant units of measure, and aligning with the evolving understanding of health risks posed by different PM and other types of pollutants.

Considering the many IAQ policies for public actions centered around HVAC filters, testing the filtration efficiency of smoke aerosols by commercial HVAC filters in the appropriate, application-based context is crucial. It is equally important to understand the mechanisms and interactions of smoke with filter media since they determine the filtration efficacy. The development of standardized measurements that are relevant for specific applications is necessary to promote better understanding and drive the innovation of solutions. For addressing the wildfire smoke specifically, presuming that the most widely used filter media for HVAC filters—electret media—rated at MERV 11–14 according to the ASHRAE 52.2 Standard would be sufficient for protecting occupants from wildfire smoke may prove misguided. In summary, a better appreciation and further research of filter media testing and rating, ambient pollution sources and levels of $PM_{2.5}$ versus PM <300 nm measurement and reporting, and particle removal efficiencies of commercial filter media in these particle size ranges, in combination with the assessment of relevant standards and guidelines, the corresponding energy impact of various filter media and filters are necessary for informing filter selection and recommendations for countering increasingly challenging real-world IAQ problems.

Author Contributions: Conceptualization T.S. and S.L.; Methodology, E.S.; Writing—Original Draft Preparation T.S.; Supervision T.S. and E.S.; Data analysis E.S. and T.S.; Characterization T.S.; Data Curation, T.S., S.L. and E.S.; Writing—Review and Editing T.S., E.S. and S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the NSF SBIR Phase II Grant Number 2026128.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. All relevant data used to support the findings (Sections 3.1 and 3.2) are summarized in figures and tables and presented in the article. The data presented in Section 3.3 was collected from an independent lab third-party, LMS Technologies, Inc., Edina, MN, USA and can be shared upon request after the third-party LMS Technologies, Inc., Edina, MN, USA permission. The electron microscopy characterization data are not posted publicly due to their file sizes and operating system requirements but can be shared upon a request.

Acknowledgments: This work was performed in part at the Harvard University Center for Nanoscale Systems (CNS), a member of the National Nanotechnology Coordinated Infrastructure Network (NNCI), which is supported by the National Science Foundation under NSF award no. ECCS-2025158. We thank Al Vatine for the media testing and helpful discussions. We thank Daanish Qureshi for his help with experimental setup and testing.

Conflicts of Interest: Tanya Shirman, Elijah Shirman and Sissi Liu employees of Metalmark. The paper reflects the views of the scientists and not the company.

Appendix A

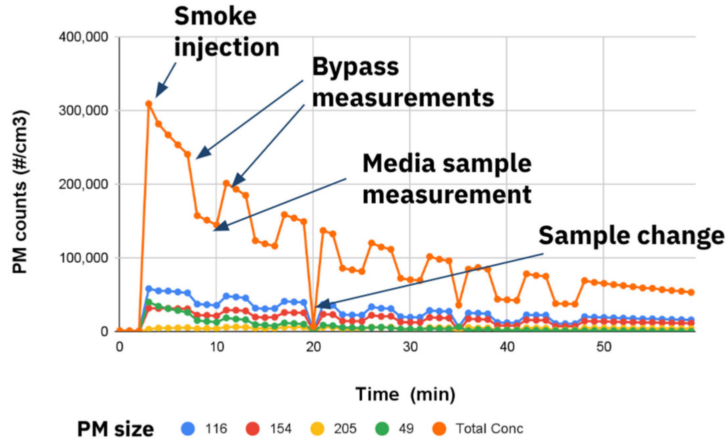


Figure A1. PM counts recorded by the SMPS 3910 for selected channels, with annotations indicating the sequential steps of a representative test. Different colors correspond to the different PM sizes (nm) as indicated below the graph.

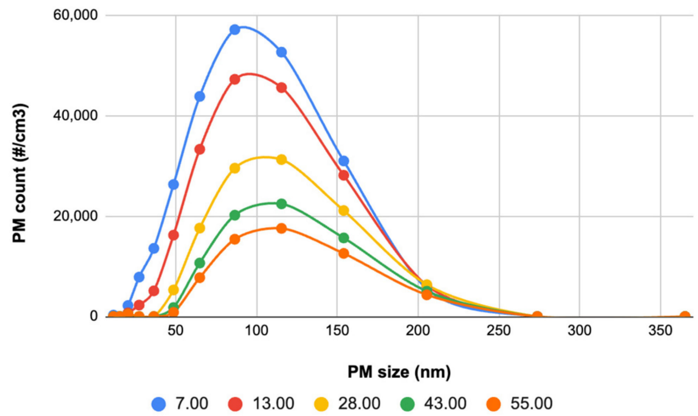


Figure A2. Size distribution of PM in pine needle smoke measured with TSI Nanoscan SMPS 3910 at various time points following smoke generation in the course of a typical filtration efficiency test (~1 h) under experimental conditions described in the Section 2 (Materials and Methods).

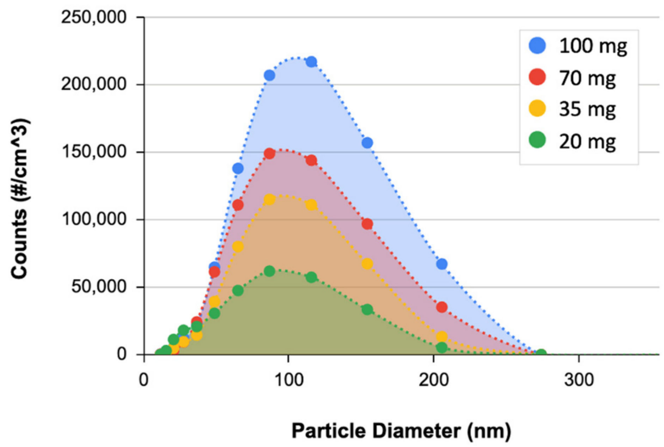


Figure A3. Size distributions of PM particles resulting from combusting various weights of PN and recorded by TSI Nanoscan SMPS 3910. The PM distribution was measured ~5 min after smoke generation.

References

1. Wilmot, T.Y.; Hallar, A.G.; Lin, J.C.; Mallia, D.V. Expanding number of Western US urban centers face declining summertime air quality due to enhanced wildland fire activity. *Environ. Res. Lett.* **2021**, *16*, 054036. [CrossRef]
2. Jaffe, D.A.; O'Neill, S.M.; Larkin, N.K.; Holder, A.L.; Peterson, D.L.; Halofsky, J.E.; Rappold, A.G. Wildfire and prescribed burning impacts on air quality in the United States. *J. Air Waste Manag. Assoc.* **2020**, *70*, 583–615. [CrossRef] [PubMed]
3. Pechony, O.; Shindell, D.T. Driving forces of global wildfires over the past millennium and the forthcoming century. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 19167–19170. [CrossRef] [PubMed]
4. Yang, C.E.; Fu, J.S.; Liu, Y.; Dong, X.; Liu, Y. Projections of future wildfires impacts on air pollutants and air toxics in a changing climate over the western United States. *Environ. Pollut.* **2022**, *304*, 119213. [CrossRef]
5. Kabeshita, L.; Sloat, L.L.; Fischer, E.V.; Kampf, S.; Magzamen, S.; Schultz, C.; Wilkins, M.J.; Kinnebrew, E.; Mueller, N.D. Pathways framework identifies wildfire impacts on agriculture. *Nat. Food* **2023**, *4*, 664–672. [CrossRef] [PubMed]
6. Thurston, G.; Yu, W.; Luglio, D. An Evaluation of the Asthma Impact of the June 2023 New York City Wildfire Air Pollution Episode. *Am. J. Respir. Crit. Care Med.* **2023**, *208*, 898–900. [CrossRef] [PubMed]
7. Burke, M.; Driscoll, A.; Heft-Neal, S.; Xue, J.; Burney, J.; Wara, M. The changing risk and burden of wildfire in the United States. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2011048118. [CrossRef]
8. Aurell, J.; Gullett, B.K. Emission Factors from Aerial and Ground Measurements of Field and Laboratory Forest Burns in the Southeastern U.S.: PM2.5, Black and Brown Carbon, VOC, and PCDD/PCDF. *Environ. Sci. Technol.* **2013**, *47*, 8443–8452. [CrossRef]
9. Sparks, T.L.; Wagner, J. Composition of particulate matter during a wildfire smoke episode in an urban area. *Aerosol Sci. Technol.* **2021**, *55*, 734–747. [CrossRef]
10. Revised Air Quality Standards For Particle Pollution And Updates To The Air Quality Index (Aqi). Available online: https://www.epa.gov/sites/default/files/2016-04/documents/2012_aqi_factsheet.pdf (accessed on 10 November 2023).
11. Krittanawong, C.; Qadeer, Y.K.; Hayes, R.B.; Wang, Z.; Thurston, G.D.; Virani, S.; Lavie, C.J. PM2.5 and cardiovascular diseases: State-of-the-Art review. *Int. J. Cardiol. Cardiovasc. Risk Prev.* **2023**, *19*, 200217. [CrossRef]
12. Wei, Y.; Danesh Yazdi, M.; Ma, T.; Castro, E.; Liu, C.S.; Qiu, X.; Healy, J.; Vu, B.N.; Wang, C.; Shi, L.; et al. Additive effects of 10-year exposures to PM(2.5) and NO(2) and primary cancer incidence in American older adults. *Environ. Epidemiol.* **2023**, *7*, e265. [CrossRef] [PubMed]
13. Xu, X.; Zhang, J.; Yang, X.; Zhang, Y.; Chen, Z. The Role and Potential Pathogenic Mechanism of Particulate Matter in Childhood Asthma: A Review and Perspective. *J. Immunol. Res.* **2020**, *2020*, 8254909. [CrossRef] [PubMed]
14. Meek, H.C.; Bush, K. Notes from the Field: Asthma-Associated Emergency Department Visits During a Wildfire Smoke Event —New York, June 2023. *Morb. Mortal Wkly. Rep.* **2023**, *72*, 933–935. [CrossRef] [PubMed]
15. Møller, P.; Danielsen, P.H.; Karottki, D.G.; Jantzen, K.; Roursgaard, M.; Klingberg, H.; Jensen, D.M.; Christophersen, D.V.; Hemmingsen, J.G.; Cao, Y.; et al. Oxidative stress and inflammation generated DNA damage by exposure to air pollution particles. *Mutat. Res. Rev. Mutat. Res.* **2014**, *762*, 133–166. [CrossRef] [PubMed]
16. Schraufnagel, D.E. The health effects of ultrafine particles. *Exp. Mol. Med.* **2020**, *52*, 311–317. [CrossRef] [PubMed]
17. Utell, M.J.; Frampton, M.W. Acute health effects of ambient air pollution: The ultrafine particle hypothesis. *J. Aerosol Med.* **2000**, *13*, 355–359. [CrossRef] [PubMed]
18. Peters, A.; Wichmann, H.E.; Tuch, T.; Heinrich, J.; Heyder, J. Respiratory effects are associated with the number of ultrafine particles. *Am. J. Respir. Crit. Care Med.* **1997**, *155*, 1376–1383. [CrossRef] [PubMed]
19. Li, N.; Georas, S.; Alexis, N.; Fritz, P.; Xia, T.; Williams, M.A.; Horner, E.; Nel, A. A work group report on ultrafine particles (American Academy of Allergy, Asthma & Immunology): Why ambient ultrafine and engineered nanoparticles should receive special attention for possible adverse health outcomes in human subjects. *J. Allergy Clin. Immunol.* **2016**, *138*, 386–396. [CrossRef]
20. Kumar, P.; Kalaiarasan, G.; Porter, A.E.; Pinna, A.; Kłosowski, M.M.; Demokritou, P.; Chung, K.F.; Pain, C.; Arvind, D.K.; Arcucci, R.; et al. An overview of methods of fine and ultrafine particle collection for physicochemical characterisation and toxicity assessments. *Sci. Total Environ.* **2021**, *756*, 143553. [CrossRef]
21. Johnston, F.; Hanigan, I.; Henderson, S.; Morgan, G.; Bowman, D. Extreme air pollution events from bushfires and dust storms and their association with mortality in Sydney, Australia 1994–2007. *Environ. Res.* **2011**, *111*, 811–816. [CrossRef]
22. Haikerwal, A.; Akram, M.; Del Monaco, A.; Smith, K.; Sim, M.R.; Meyer, M.; Tonkin, A.M.; Abramson, M.J.; Dennekamp, M. Impact of Fine Particulate Matter ($PM_{2.5}$) Exposure During Wildfires on Cardiovascular Health Outcomes. *J. Am. Heart Assoc.* **2015**, *4*, e001653. [CrossRef] [PubMed]
23. Liu, J.C.; Pereira, G.; Uhl, S.A.; Bravo, M.A.; Bell, M.L. A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke. *Environ. Res.* **2015**, *136*, 120–132. [CrossRef] [PubMed]
24. Reid Colleen, E.; Brauer, M.; Johnston Fay, H.; Jerrett, M.; Balmes John, R.; Elliott Catherine, T. Critical Review of Health Impacts of Wildfire Smoke Exposure. *Environ. Health Perspect.* **2016**, *124*, 1334–1343. [CrossRef] [PubMed]
25. Reid, J.S.; Koppmann, R.; Eck, T.F.; Eleuterio, D.P. A review of biomass burning emissions part II: Intensive physical properties of biomass burning particles. *Atmos. Chem. Phys.* **2005**, *5*, 799–825. [CrossRef]
26. Laing, J.R.; Jaffe, D.A.; Hee, J.R. Physical and optical properties of aged biomass burning aerosol from wildfires in Siberia and the Western USA at the Mt. Bachelor Observatory. *Atmos. Chem. Phys.* **2016**, *16*, 15185–15197. [CrossRef]
27. Sakamoto, K.M.; Allan, J.D.; Coe, H.; Taylor, J.W.; Duck, T.J.; Pierce, J.R. Aged boreal biomass-burning aerosol size distributions from BORTAS 2011. *Atmos. Chem. Phys.* **2015**, *15*, 1633–1646. [CrossRef]

28. Sinha, A.; Saleh, R.; Robinson, E.S.; Ahern, A.T.; Tkacik, D.S.; Presto, A.A.; Sullivan, R.C.; Robinson, A.L.; Donahue, N.M. Mass accommodation coefficients of fresh and aged biomass-burning emissions. *Aerosol Sci. Technol.* **2018**, *52*, 300–309. [CrossRef]
29. Buysse, C.E.; Kaulfus, A.; Nair, U.; Jaffe, D.A. Relationships between Particulate Matter, Ozone, and Nitrogen Oxides during Urban Smoke Events in the Western US. *Environ. Sci. Technol.* **2019**, *53*, 12519–12528. [CrossRef]
30. Fang, T.; Hwang, B.C.H.; Kapur, S.; Hopstock, K.S.; Wei, J.; Nguyen, V.; Nizkorodov, S.A.; Shiraiwa, M. Wildfire particulate matter as a source of environmentally persistent free radicals and reactive oxygen species. *Environ. Sci. Atmos.* **2023**, *3*, 581–594. [CrossRef]
31. Li, J.; Link, M.F.; Pandit, S.; Webb, M.H.; Mayer, K.J.; Garofalo, L.A.; Rediger, K.L.; Poppendieck, D.G.; Zimmerman, S.M.; Vance, M.E.; et al. The persistence of smoke VOCs indoors: Partitioning, surface cleaning, and air cleaning in a smoke-contaminated house. *Sci. Adv.* **2023**, *9*, eadh8263. [CrossRef]
32. Ghetu, C.C.; Rohlman, D.; Smith, B.W.; Scott, R.P.; Adams, K.A.; Hoffman, P.D.; Anderson, K.A. Wildfire Impact on Indoor and Outdoor PAH Air Quality. *Environ. Sci. Technol.* **2022**, *56*, 10042–10052. [CrossRef] [PubMed]
33. Kobziar, L.N.; Thompson, G.R. Wildfire smoke, a potential infectious agent. *Science* **2020**, *370*, 1408–1410. [CrossRef] [PubMed]
34. Kobziar, L.N.; Vuono, D.; Moore, R.; Christner, B.C.; Dean, T.; Betancourt, D.; Watts, A.C.; Aurell, J.; Gullett, B. Wildland fire smoke alters the composition, diversity, and potential atmospheric function of microbial life in the aerobiome. *ISME Commun.* **2022**, *2*, 8. [CrossRef]
35. Li, C.; Hu, Y.; Chen, J.; Ma, Z.; Ye, X.; Yang, X.; Wang, L.; Wang, X.; Mellouki, A. Physiochemical properties of carbonaceous aerosol from agricultural residue burning: Density, volatility, and hygroscopicity. *Atmos. Environ.* **2016**, *140*, 94–105. [CrossRef]
36. Kwon, H.-S.; Ryu, M.H.; Carlsten, C. Ultrafine particles: Unique physicochemical properties relevant to health and disease. *Exp. Mol. Med.* **2020**, *52*, 318–328. [CrossRef] [PubMed]
37. Kodros, J.K.; Volckens, J.; Jathar, S.H.; Pierce, J.R. Ambient Particulate Matter Size Distributions Drive Regional and Global Variability in Particle Deposition in the Respiratory Tract. *GeoHealth* **2018**, *2*, 298–312. [CrossRef]
38. Bischof, O.F. Recent Developments in the Measurement of Low Particulate Emissions from Mobile Sources: A Review of Particle Number Legislations. *Emiss. Control Sci. Technol.* **2015**, *1*, 203–212. [CrossRef]
39. Henderson, D.E.; Milford, J.B.; Miller, S.L. Prescribed burns and wildfires in Colorado: Impacts of mitigation measures on indoor air particulate matter. *J. Air Waste Manag. Assoc.* **2005**, *55*, 1516–1526. [CrossRef]
40. Xiang, J.; Huang, C.-H.; Shirai, J.; Liu, Y.; Carmona, N.; Zuidema, C.; Austin, E.; Gould, T.; Larson, T.; Seto, E. Field measurements of PM2.5 infiltration factor and portable air cleaner effectiveness during wildfire episodes in US residences. *Sci. Total Environ.* **2021**, *773*, 145642. [CrossRef]
41. Liang, Y.; Sengupta, D.; Campmier, M.J.; Lunderberg, D.M.; Apte, J.S.; Goldstein, A.H. Wildfire smoke impacts on indoor air quality assessed using crowdsourced data in California. *Proc. Natl. Acad. Sci. USA* **2021**, *118*, e2106478118. [CrossRef]
42. May, N.W.; Dixon, C.; Jaffe, D.A. Impact of Wildfire Smoke Events on Indoor Air Quality and Evaluation of a Low-cost Filtration Method. *Aerosol Air Qual. Res.* **2021**, *21*, 210046. Available online: https://aaqr.org/articles/aaqr-21-03-tn-0046 (accessed on 10 November 2023). [CrossRef]
43. Reisen, F.; Powell, J.C.; Dennekamp, M.; Johnston, F.H.; Wheeler, A.J. Is remaining indoors an effective way of reducing exposure to fine particulate matter during biomass burning events? *J. Air Waste Manag. Assoc.* **2019**, *69*, 611–622. [CrossRef] [PubMed]
44. Dev, S.; Barnes, D.; Kadir, A.; Betha, R.; Aggarwal, S. Outdoor and indoor concentrations of size-resolved particulate matter during a wildfire episode in interior Alaska and the impact of ventilation. *Air Qual. Atmos. Health* **2022**, *15*, 149–158. [CrossRef]
45. Carmona, N.; Seto, E.; Gould, T.R.; Rasyid, E.; Shirai, J.H.; Cummings, B.; Hayward, L.; Larson, T.V.; Austin, E. Indoor Air Quality Intervention in Schools: Effectiveness of a Portable HEPA Filter Deployment in Five Schools Impacted by Roadway and Aircraft Pollution Sources. *Atmosphere* **2022**, *13*, 1623. [CrossRef]
46. O'Dell, K.; Ford, B.; Burkhardt, J.; Magzamen, S.; Anenberg, S.C.; Bayham, J.; Fischer, E.V.; Pierce, J.R. Outside in: The relationship between indoor and outdoor particulate air quality during wildfire smoke events in western US cities. *Environ. Res. Health* **2023**, *1*, 015003. [CrossRef]
47. Wheeler, A.J.; Allen, R.W.; Lawrence, K.; Roulston, C.T.; Powell, J.; Williamson, G.J.; Jones, P.J.; Reisen, F.; Morgan, G.G.; Johnston, F.H. Can Public Spaces Effectively Be Used as Cleaner Indoor Air Shelters during Extreme Smoke Events? *Int. J. Environ. Res. Public Health* **2021**, *18*, 4085. [CrossRef] [PubMed]
48. Stauffer, D.A.; Autenrieth, D.A.; Hart, J.F.; Capoccia, S. Control of wildfire-sourced PM2.5 in an office setting using a commercially available portable air cleaner. *J. Occup. Env. Hyg.* **2020**, *17*, 109–120. [CrossRef] [PubMed]
49. Chen, A.; Cao, Q.; Zhou, J.; Yang, B.; Chang, V.W.C.; Nazaroff, W.W. Indoor and outdoor particles in an air-conditioned building during and after the 2013 haze in Singapore. *Build. Environ.* **2016**, *99*, 73–81. [CrossRef]
50. *ASHRAE 52.2-2017*; Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size (ANSI Approved). ASHRAE: Peachtree Corners, GA, USA, 2017. Available online: https://www.techstreet.com/ashrae/standards/ashrae-52-2-2017?product_id=1942059 (accessed on 25 October 2023).
51. *EN 779:2002*; Particulate Air Filters for General Ventilation—Determination of the Filtration Performance. BSI: London, UK, 2002. Available online: https://standards.iteh.ai/catalog/standards/cen/c2ca45a4-fdd8-40d4-a751-ba7c04de7ebb/en-779-2002 (accessed on 25 October 2023).
52. Japuntich, D.A.; Franklin, L.M.; Pui, D.Y.; Kuehn, T.H.; Kim, S.C.; Viner, A.S. A comparison of two nano-sized particle air filtration tests in the diameter range of 10 to 400 nanometers. *J. Nanoparticle Res.* **2007**, *9*, 93–107. [CrossRef]

53. Chang, D.-Q.; Chen, S.-C.; Fox, A.R.; Viner, A.S.; Pui, D.Y.H. Penetration of Sub-50 nm Nanoparticles Through Electret HVAC Filters Used in Residence. *Aerosol Sci. Technol.* **2015**, *49*, 966–976. [CrossRef]
54. Chen, C.; Ji, W.; Zhao, B. Size-dependent efficiencies of ultrafine particle removal of various filter media. *Build. Environ.* **2019**, *160*, 106171. [CrossRef]
55. Wu, J.; Chen, J.; Olfert, J.S.; Zhong, L. Filter evaluation and selection for heating, ventilation, and air conditioning systems during and beyond the COVID-19 pandemic. *Indoor Air* **2022**, *32*, e13099. [CrossRef]
56. Fazli, T.; Zeng, Y.; Stephens, B. Fine and ultrafine particle removal efficiency of new residential HVAC filters. *Indoor Air* **2019**, *29*, 656–669. [CrossRef] [PubMed]
57. Karjalainen, P.; Saari, S.; Kuuluvainen, H.; Kalliohaka, T.; Taipale, A.; Rönkkö, T. Performance of ventilation filtration technologies on characteristic traffic related aerosol down to nanocluster size. *Aerosol Sci. Technol.* **2017**, *51*, 1398–1408. [CrossRef]
58. Schumacher, S.; Spiegelhoff, D.; Schneiderwind, U.; Finger, H.; Asbach, C. Performance of New and Artificially Aged Electret Filters in Indoor Air Cleaners. *Chem. Eng. Technol.* **2018**, *41*, 27–34. [CrossRef]
59. Myers, D.L.; Arnold, B.D. Electret Media for HVAC Filtration Applications. *Int. Nonwovens J.* **2003**, *4*, 43–54. [CrossRef]
60. Heo, K.J.; Lee, G.D.; Doh, S.J.; Jung, J.H. Effect of cigarette smoke on the lifetime of electret air filters. *Sci. Total Environ.* **2022**, *807*, 150754. [CrossRef]
61. He, W.; Guo, Y.; Liu, J.; Yue, Y.; Wang, J. Filtration Performance Degradation of In-Use Masks by Vapors from Alcohol-Based Hand Sanitizers and the Mitigation Solutions. *Glob. Chall.* **2021**, *5*, 2100015. [CrossRef]
62. Holder, A.L.; Halliday, H.S.; Virtaranta, L. Impact of do-it-yourself air cleaner design on the reduction of simulated wildfire smoke in a controlled chamber environment. *Indoor Air* **2022**, *32*, e13163. [CrossRef]
63. Raynor, P.C.; Chae, S.J. The long-term performance of electrically charged filters in a ventilation system. *J. Occup. Env. Hyg.* **2004**, *1*, 463–471. [CrossRef]
64. Li, X.; Wang, Y.; Xu, M.; Shi, Y.; Wang, H.; Yang, X.; Ying, H.; Zhang, Q. Polymer electrets and their applications. *J. Appl. Polym. Sci.* **2021**, *138*, 50406. [CrossRef]
65. Thakur, R.; Das, D.; Das, A. Electret Air Filters. *Sep. Purif. Rev.* **2012**, *42*, 87–129. [CrossRef]
66. MarketsandMarkets. HVAC Filters Market—Global Forecast to 2026. Markets and Markets 2022. Available online: https://www.marketsandmarkets.com/Market-Reports/hvac-filter-market-205419850.html#:~:text=The%20global%20HVAC%20filters%20market,5.0%25%20from%202021%20to%202026 (accessed on 25 October 2023).
67. Cai, R.-R.; Lu, H.; Zhang, L.-Z. Mechanisms of performance degradation and efficiency improvement of electret filters during neutral particle loading. *Powder Technol.* **2021**, *382*, 133–143. [CrossRef]
68. Elliott, C.; Rideout, K.; Keefe, P. Evidence review: Filtration in institutional settings during wildfire smoke events. In *Wildfire and Smoke Guidelines*; British Columbia Centre for Disease: Vancouver, BC, USA, 2014.
69. Brochot, C.B.; Abdolghader, P.; Haghighat, F. Performance of mechanical filters used in general ventilation against nanoparticles. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *609*, 032044. [CrossRef]
70. Hanley, J.T.; Ensor, D.S.; Smith, D.D.; Sparks, L.E. Fractional Aerosol Filtration Efficiency of In-Duct Ventilation Air Cleaners. *Indoor Air* **1994**, *4*, 169–178. [CrossRef]
71. Rivers, R.D., Jr. Air filter performance under variable air volume conditions. *ASHRAE Trans.* **2000**, *106*, 4380.
72. Kim, Y.H.; Warren, S.H.; Krantz, T.; King, C.; Jaskot, R.; Preston, W.T.; George, B.J.; Hays, M.D.; Landis, M.S.; Higuchi, M.; et al. Mutagenicity and Lung Toxicity of Smoldering vs. Flaming Emissions from Various Biomass Fuels: Implications for Health Effects from Wildland Fires. *Environ Health Perspect* **2018**, *126*, 017011. [CrossRef]
73. Mustafa, B.; Mat Kiah, M.H.B.; Andrews, G.; Phylaktou, R.; Li, H. *Smoke Particle Size Distribution in Pine Wood Fires*; Saint-Petersburg Polytechnic University Press: Saint-Petersburg, Russia, 2019; pp. 930–939.
74. Ordou, N.; Agranovski, I.E. Contribution of Fine Particles to Air Emission at Different Phases of Biomass Burning. *Atmosphere* **2019**, *10*, 278. [CrossRef]
75. Liu, Y.; Meng, X.; Wu, Z.; Huang, D.; Wang, H.; Chen, J.; Chen, J.; Zong, T.; Fang, X.; Tan, T.; et al. The particle phase state during the biomass burning events. *Sci. Total Environ.* **2021**, *792*, 148035. [CrossRef]
76. Johnson, T.J.; Olfert, J.S.; Cabot, R.; Treacy, C.; Yurteri, C.U.; Dickens, C.; McAughey, J.; Symonds, J.P.R. Steady-state measurement of the effective particle density of cigarette smoke. *J. Aerosol Sci.* **2014**, *75*, 9–16. [CrossRef]
77. EPA United State Environmental Protection Agency. Wildfire Smoke Resources to Protect Your Health. 2023. Available online: https://www.epa.gov/smoke-ready-toolbox-wildfires/wildfire-smoke-resources-protect-your-health (accessed on 25 October 2023).
78. Azimi, P.; Zhao, D.; Stephens, B. Estimates of HVAC filtration efficiency for fine and ultrafine particles of outdoor origin. *Atmos. Environ.* **2014**, *98*, 337–346. [CrossRef]
79. Stephens, B.; Siegel, J.A. Ultrafine particle removal by residential heating, ventilating, and air-conditioning filters. *Indoor Air* **2013**, *23*, 488–497. [CrossRef] [PubMed]
80. Hecker, R.; Hofacre, K.C.; EPA United States Environmental Protection Agency. Development of Performance Data for Common Building Air Cleaning Devices. 2008. Available online: https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NHSRC&dirEntryID=188373 (accessed on 2 November 2023).

81. Vandergrift, G.; Lata, N.; Mathai, S.; Ijaz, A.; Cheng, Z.; Shrivastava, M.; Zhang, J.; Shawon, A.S.M.; Kulkarni, G.; Mazzoleni, L.; et al. Case study evaluation of size-resolved molecular composition and phase state of carbonaceous particles in wildfire influenced smoke from the Pacific Northwest. *Environ. Sci. Atmos.* **2023**, *3*, 1251–1261. [CrossRef]
82. Kamiński, M.; Gac, J.M.; Sobiech, P.; Kozikowski, P.; Jakubiak, S.; Jankowski, T. Filtration of Submicron Soot Particles, Oil Droplets, and their Mixtures on Single- and Multi-layer Fibrous Filters. *Aerosol Air Qual. Res.* **2022**, *22*, 210258. [CrossRef]
83. Motyl, E. Effect of Air Humidity on Charge Decay and Lifetime of PP Electret Nonwovens. *Fibres Text. East. Eur.* **2006**, *14*, 39–42.
84. Tang, M.; Thompson, D.; Chen, S.-C.; Liang, Y.; Pui, D.Y.H. Evaluation of different discharging methods on HVAC electret filter media. *Build. Environ.* **2018**, *141*, 206–214. [CrossRef]
85. Straube, C.; Meyer, J.; Dittler, A. Identification of Deposited Oil Structures on Thin Porous Oil Mist Filter Media Applying μ-CT Imaging Technique. *Separations* **2021**, *8*, 193. [CrossRef]