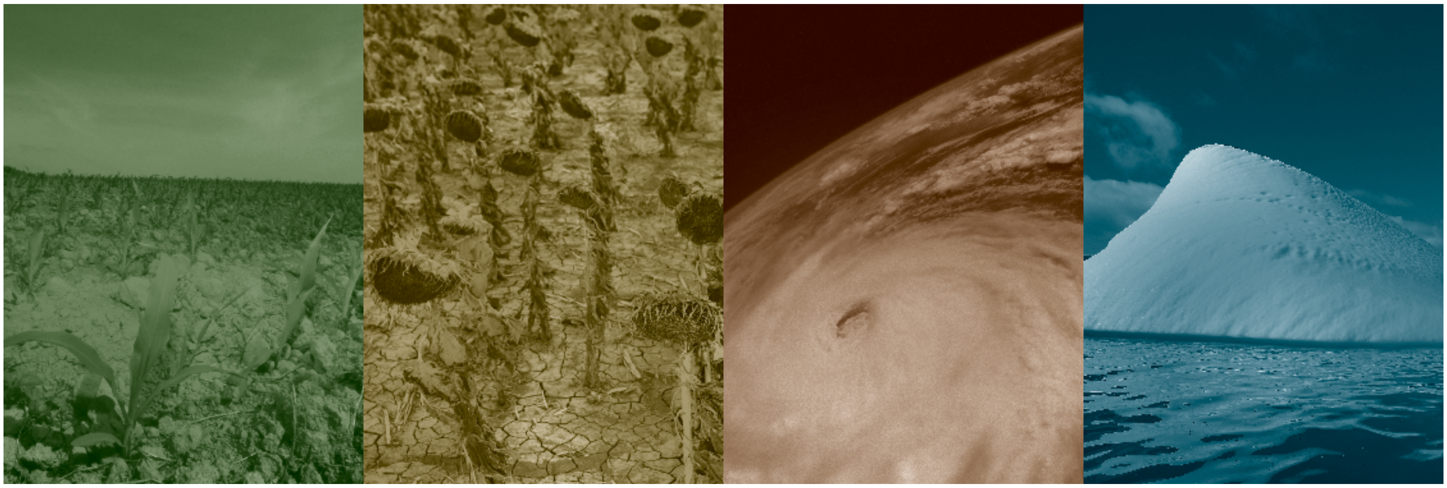
Evidence on the Use of Indoor Air Filtration as an Intervention for Wildfire Smoke Pollutant Exposure

A Summary for Health Departments



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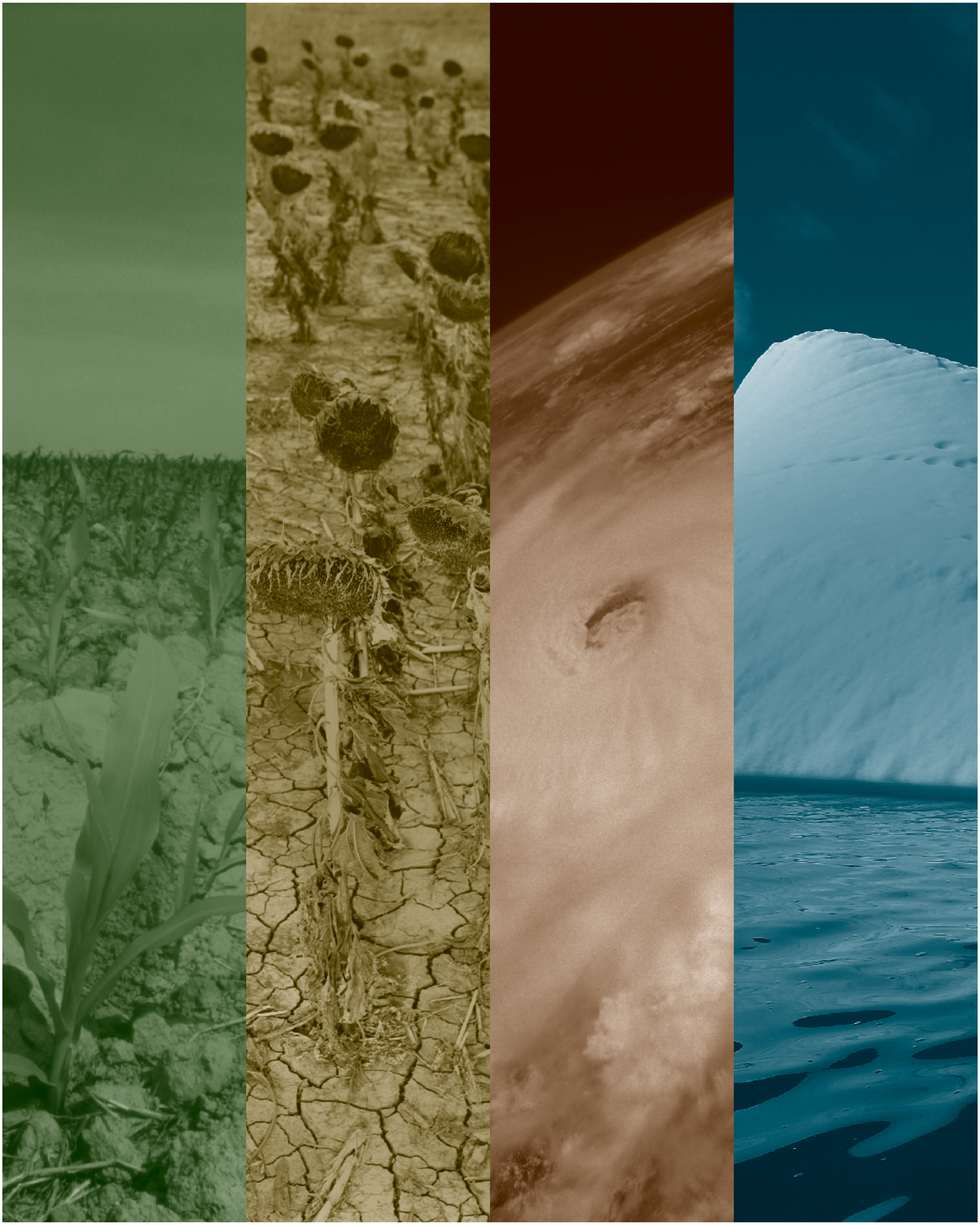

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Executive Summary

Over the last few decades, the United States has experienced an increase in frequency of intense wildfires. Climate change has likely impacted these events through increased summer and spring temperatures, drier vegetation, decreased precipitation in some areas, and an increased probability of lightning storms.[8,14,19] Wildfires have caused billions of dollars in property damage and contributed to an estimated 339,000 premature deaths per year globally.[7,30] Wildfires are also associated with negative health outcomes. The smoke from wildfires contains gaseous pollutants and particulate matter which are associated with multiple respiratory and cardiovascular illnesses.[24] There is evidence that certain populations are more vulnerable to the wildfire smoke exposure than others, including older adults and infants, pregnant women, people with pre-existing medical conditions, and people of lower socio-economic status.[23] Interventions that effectively decrease wildfire smoke exposures can protect these vulnerable populations as well as the health of the general public.

This technical document summarizes the available peer-reviewed literature about the effectiveness of air filtration as an intervention to decrease exposure to wildfire smoke and protect health when sheltering indoors. It describes the different types of air filtering technology and metrics for measuring air quality and summarizes the literature on their effectiveness in protecting against the harmful air pollutants in wildfire smoke. Relevant federal and state resources for local health professionals are listed.

This review illustrates that proper air filtration is an effective method of reducing certain wildfire smoke pollutants indoors and potentially limiting the risk of negative health impacts associated with exposure to wildfire smoke.

Background

Wildfires

Photo of a wildfire.

Over the past three decades, the frequency of wildfires in the United States has increased. In addition, the duration of wildfires and average amount of area burned have increased since 1987.[1,2] "Megafires," which are defined as wildfires that burn over 100,000 hectares (ha), have also significantly increased in frequency, intensity, and duration over the last few decades.[3,4] For instance, in 2018 California experienced one of its largest wildfires on record (Mendocino Complex Fire—459,123 ha) and its deadliest wildfire (Camp Fire—85 fatalities, 18,804 destroyed structures) in state history.[5,6] The United States Forest Service's annual suppression cost has exceeded a billion dollars for 13 of the 18 years between 2000 and 2017;[7] In contrast, annual suppression costs had never exceeded a billion dollars from the years 1985 through 1999.[2] These financial costs of wildfires are damaging, but the personal cost is far greater. People in wildfire proximity have the potential to lose their entire livelihood. Houses, cars, businesses and more are at risk of destruction from these events, displacing thousands of people. Displaced people put additional strain on community resources as some decide to leave their homes, impacting neighboring communities.[2] One of the biggest factors that influences the increase in severity and frequency of wildfires is climate change.[8]

Climate Change Impact on Wildfires

Human behavior has a direct impact on climate change and the recent trends in wildfires.[9,10,11,12] As the earth's climate changes, the effects on the environment and weather patterns create an environment in some regions suitable to create large, sustained wildfires.[9,11,12] The Fourth National Climate Assessment demonstrates that global average temperature measured both on land and in oceans has increased by about 1.8°F from 1901 to 2016. Sixteen of the last 17 years have been the warmest ever recorded by human observation. In the United States, the annual average temperature has increased by 1.2°F for the period 1986–2016 and by 1.8°F relative to the beginning of last century. Researchers project that additional increases in annual average temperatures of about 2.5°F will take place over the next few decades, regardless of any changes in human activity to mitigate the changes in climate. The frequency of cold waves has dramatically decreased, while the frequency of heat waves has increased since the mid-1960s.[8] The increased heat caused by global warming creates drier climates and even prolonged drought, which could make many environments more susceptible to wildfires due to the flammability of fuel sources. Researchers predict that climate change will increase the probability for megadroughts within the United States.[14] The increased temperatures also influence weather patterns. According to the United States Forest Service, 46% of the National Forests and Grassland wildfires were caused by lightning over the last decade.[15] Lightning storms occur more frequently during higher temperatures than when it is cooler.[16] Of all the lightning-caused fires that occurred from 1994–2012, 78% of them occurred during the summer months.[17] Between 1992 and 2015, 70% of the area burned in the western U.S. region was from lightning-ignited wildfires and 27% of the area burned in the Southeastern U.S. resulted from lightning-ignited wildfires.[18] As the average temperature of the globe continues to increase, the frequency of lightning storms will potentially increase as well, which could increase the probability of lightning strikes.19 Lightning is the primary natural wildland fire source, with an average of over 10,000 lightning-caused fires reported each year.[20]

Wildfires Smoke Impacts on Human Health

Photo of wildfire smoke.

Wildfire smoke is a major contributor to air pollution. In 2014, wildfire smoke accounted for approximately 30% of all fine particulate emissions in the United States.[21] The composition of wildfire smoke is largely influenced by the type of vegetation being burned, flame temperature, weather conditions, and moisture content.[22] The key primary emission of public health concern from wildfires is particulate matter (PM). Particulate matter varies in size, but 90% of particulate mass produced by wildfires is fine particulate matter, or $PM_{2.5}$ (particulate matter 2.5μm in aerodynamic diameter or smaller).[23] $PM_{2.5}$ has significant health impacts if inhaled.[23] Wildfires also produce harmful gases such as carbon monoxide (CO), nitrous acid (HNO_2), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), nitrous oxide (N_2O), nitrogen oxides (NO_x), heavy metals, and other air pollutants.[23,24,25] These are just a few of the dangerous pollutants produced, but wildfire smoke can be composed of thousands of different compounds.[23] The smoke from wildfires poses a significant danger to large areas of the country because it can travel long distances under certain weather conditions.[1,27] Because of this, there is potential for smoke exposure even in areas not in direct danger of wildfire.[1,28,29]

There is evidence that suggests exposure to fine particulate matter from wildfire smoke can be associated with premature mortality. Many studies have noted the positive relationship between fine particulate matter exposure and mortality rates across the globe.[30,31,32,33] Wildfire smoke has been estimated to attribute to 339,000 deaths per year globally, making wildfires an important contributor to global mortality.[30] In addition to contributing to mortality rates worldwide, wildfire smoke exposure has also been associated with cardiovascular and respiratory morbidity.[1,8,34] The 2019 EPA Integrated Science Assessment on particulate matter highlights the current science on acute health effects from particulate matter exposure (see Selected Resources).[21]

Epidemiologic studies conducted over the last 50 years have demonstrated a relationship between an increase in respiratory effects and exposure to wildfire smoke pollutants, especially fine particulate matter ($PM_{2.5}$).[4,24,35,36,37,38] $PM_{2.5}$ can potentially contribute to oxidative stress, inflammation, and cell toxicity.[39] Increased exposure to particulate matter has also been associated with a significant decrease in lung functionality.[40,41] During wildfire events, there is evidence of increases in hospital visits pertaining to respiratory illnesses including asthma, bronchitis, and chronic obstructive pulmonary disease (COPD).[26,29,42,43]

Positive associations between wildfire smoke exposure and cardiovascular illness have been reported in multiple studies.[19,42,44] The particulate matter from wildfire smoke has been associated with elevated blood pressure and heart rate along with decreased heart rate variability.[45,46] Recent studies have shown that during wildfire events, emergency department visits for cardiovascular illnesses increase. The risk for out-of-hospital cardiac arrests also increases during wildfire events.[14] Extended exposure to the highly polluted air caused by wildfires can significantly increase the risk of cardiovascular disease-related mortality and nonfatal events.[45]

At-Risk Populations Affected by Wildfire Smoke

Exposure to wildfire smoke poses a significant danger to everyone. However, certain populations may have a higher risk of experiencing negative effects. This section gives a brief overview of evidence of vulnerability.

Photo of a child using an inhahler.

Pregnant Women

Pregnant women may be particularly vulnerable to the health impacts of wildfire smoke exposure.[24,35,47] A study that analyzed the effects of long-range wildfire smoke transport on pregnant women found that exposure to wildfire smoke particulate matter over the full gestation and during the second trimester were positively associated with preterm birthrate. The researchers found that each increase of 1 $\mu g/m^3$ in the trimester-average wildfire smoke $PM_{2.5}$ over the second trimester was associated with 13.2% increase in odds of preterm birth.[35] These results were consistent with the findings of another study conducted in Brazil, which found that the exposure to air pollutants in biomass burning during the second and third trimesters of pregnancy were associated with low birth weight.[33] A systematic review of evidence highlighted that maternal inhalation of certain hydrocarbons found within $PM_{2.5}$ can lead to endocrine disruption, which could result in intrauterine fetal growth retardation.[47] Exposure to CO from biomass burning may result in the formation of carboxyhemoglobin in the mother, which could potentially result in decreased delivery of oxygen to the fetus.

Children

Children are vulnerable to many environmental hazards due to the ongoing development of their respiratory and immune systems.[48] Exposure to pollutants in wildfire smoke can exacerbate respiratory symptoms in children. A study analyzing the effect of the 2003 southern California wildfires on children concluded that in homes that had a "smell of fire smoke indoors" for more than six days, the rates of dry coughs and sneezing increased threefold. The rates of wheezing increased more than threefold and the rates of sore throats, physician visits and missed school increased twofold.[49]

Another study was conducted focusing on the San Diego fires in 2007, where the researchers found that among children (aged 0–4 years) emergency department visits for respiratory related illnesses increased by 70% during the wildfire $PM_{2.5}$ exposure period.[50] These findings were consistent with a study in Chile that found a 40% increase in coughing symptoms among children after exposure to wildfire smoke pollutants.[13]

Older Adults

Older adults are especially vulnerable to $PM_{2.5}$.[51] A study of the health impacts of wildfire smoke pollutant exposure on elderly populations found that hospitalization rates for asthma, bronchitis, and wheezing were positively associated with $PM_{2.5}$ exposure during periods of wildfire smoke and concluded that the pollutants in wildfire smoke can trigger acute respiratory responses.[34] These results were consistent with another study of cardiovascular and respiratory hospital admissions and exposure to fine particulate matter ($PM_{2.5}$) pollution from the California wildfires of 2003. The researchers found a 10.1% increase in hospitalizations for asthma amongst the elderly population per 10 μg/m3 increase of $PM_{2.5}$ concentrations.[36] The vulnerability of older populations to wildfire smoke pollutants may be linked to their immunology. Older people tend to have degraded immune systems, making them more vulnerable to the health impacts of wildfire air pollutants.[52]

Pre-existing Medical Conditions

People with certain illnesses prior to wildfire events have a higher risk of being impacted by the pollutants present in the smoke. Multiple studies have found that people with pre-existing respiratory and cardiovascular conditions have a higher risk of experiencing exacerbated health symptoms during wildfire events.[13,41,53] Studies have found that individuals with certain respiratory conditions such as having small airways[26] and asthma[54] exhibited worse symptoms and higher frequency of hospital visits during wildfires. A study conducted on individuals with asthma during the 2007 San Diego wildfires found that exposure to wildfire air pollution was associated with increased airway inflammation.[55]

Low Socioeconomic Status

Communities of low socioeconomic status (SES) may be particularly vulnerable to the health impacts of wildfire smoke pollutant exposure. People with low SES tend to have a higher prevalence of comorbid cardiovascular and respiratory illnesses that would make them more susceptible to the effects of the smoke pollutants.[56] SES also influences individuals' ability to access resources and adapt to disasters. Low SES households are more likely to have poorer housing quality.[57] The quality of the buildings can play a large factor in the amount of exposure to harmful components of wildfire smoke in indoor air. For instance, a study in Arizona suggested that households with low SES tend to have more difficulty preparing for wildfire disasters and recovering from them than high SES households.[58] People of the lowest SES may not even have structures to protect them from smoke pollutants. People experiencing homelessness are already more susceptible to respiratory and cardiovascular illnesses due to poor nutrition, environmental stressors, and crowding.[59] Lack of suitable clean air structures could make them more vulnerable to high exposure to pollutants, raising their risk of exacerbated symptoms and preexisting health conditions.

Air Filtration: An Intervention for Wildfire Smoke Pollutant Exposure

During wildfires, it is generally advised that people stay inside in order to protect themselves from the heavy air pollution caused by the fires.[23] Air pollution from wildfire smoke still poses a significant danger to individuals that are indoors, as pollutants can infiltrate structures through multiple points of entry. One of the most effective ways to protect individuals from indoor wildfire smoke pollutant exposure and the health impacts associated with it is to ensure that proper air filtration mechanisms are in place during wildfire events.[60] A wide variety of air filtration technologies are available to protect individuals from fine particulate matter and harmful gases indoors. This section will define key terms and summarize the main facts about the filtration technologies (mechanical, electronic, gas), air devices (installed inside Heating, Ventilation, and Air-Conditioning [HVAC] systems and Portable Air Cleaners), and standard measures of performance (Minimum Efficiency Reporting Value [MERV] and Clean Air Delivery Rate [CADR]). It will also provide a summary of evidence on the effectiveness of these technologies in reducing wildfire smoke pollutants and evidence-based complementary actions to aid in reducing pollutants within structures.

HVAC Systems and Portable Air Cleaners

Air filtration technology can be implemented in two ways: portable room air cleaners and inside central Heating, Ventilation, and Conditioning (HVAC) systems. Both can be effective in reducing indoor air pollution when the devices are outfitted with the appropriate air filtration technology. There are significant differences when it comes to functionality, cost, and noise that should be considered when deciding which method to use.[23]

HVAC systems filter air for the entire structure. The filters are typically installed in the return-air ducts in a specific filter rack either at the base of the air-handling unit or upstream in the return grills within the HVAC system. The filters only function when the system is operating. Most HVAC systems can run as long as needed to filter indoor air but are usually only operated when heating and cooling is necessary, which can be less than 25% of the time during heating and cooling seasons in residential structures.[61,84] In order for the system to filter indoor air during a wildfire, the HVAC system would need to run for longer periods (See Complimentary Methods to Improve Air Filtration Section). It can be relatively inexpensive to install a filter within an HVAC system. However, certain structures may need to have an HVAC installed or retrofitted in order to accommodate certain filters, which can be expensive. There is also a difference in price when comparing HVAC filtration technology for a home and a commercial building.[23,63]

Portable air cleaning devices are air filtration units that are designed to be mobile. Unlike HVAC systems, which filter air throughout the whole structure, portable air cleaners are designed to just clean the air in smaller spaces, such as individual rooms. In order to effectively reduce pollutants throughout the entire structure, multiple portable air cleaning devices may be needed due to this limitation. Portable cleaning devices can be activated for as long as necessary to improve the air quality within its vicinity. Portable cleaning devices are relatively cheap to install. Portable air cleaners tend to generate a lot of noise which could be disruptive to some people if they expect to run the device overnight.[23,63]

For these devices to effectively filter particles, it is important to adhere to proper maintenance and filter replacement procedures. Maintenance neglect can inhibit functionality and performance of the devices. Any owner should follow the manufacturer recommendations when operating their air cleaning technology.[63]

Photo of HVAC units.

Photo of a portable air cleaner.

Efficiency and Effectiveness

When referring to air filtration and the use of portable air cleaners and HVAC system filters, it is important to understand the difference between effectiveness and efficiency. These measures are used to compare different technologies under similar conditions.

The EPA defines an air cleaner's efficiency as a fractional measure of its ability to reduce the concentration of pollutants in the air that passes once through the device. Efficiency is usually measured in a laboratory setting, where all variables for testing can be controlled.[63]

The effectiveness of an air cleaning device is a measure of its ability to remove pollutants from the spaces in which it is operated. Effectiveness is used to describe an air cleaners' function in real-world scenarios. Unlike efficiency, which is strictly tested in laboratory settings under highly controlled conditions, the effectiveness of an air cleaning device is dependent on factors such as its location, installation, air flow rate, and hours of operation.[63]

Standard Measures of Performance

Multiple air cleaners are available to the general public, making it difficult to understand which cleaners are most effective in reducing air pollutants within certain structures.[64] Currently, two main standards are used to measure performance for fibrous air cleaners: MERV and CADR. No standards for efficiency currently exist for electronic filters although testing standards are being created. Gas-phase filters are tested using the ANSI/ASHRAE Standard 14.1-2015 and 145.2-2016, but there are no rating metrics from the testing method.

MERV: The Measure for HVAC Fibrous Filters

Multiple measures are used to evaluate the efficiency of particle removal within fibrous filters. The most widely used fibrous media air filter test method for duct-mounted particle filters in the United States is the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 52.2, which is a national consensus standard that evaluates the removal efficiency for particles 0.3 to 10 µm in diameter. Results are reported as a minimum efficiency reporting value (MERV) based on the average removal efficiency across three particle size ranges, which are 0.3–1 µm, 1–3 µm, and 3–10 µm. The higher the MERV rating, the higher particle removal efficiency of the filter. Only MERV 11 filters and above are specifically tested for their ability to remove the smaller (0.3–1 µm) particles. MERV 11 filters must achieve at least 20% efficiency for 0.3–1 µm particles, while MERV 13 and above require at least 50% efficiency for 0.3–1 µm particles.[63]

CADR: Portable Air Cleaner Measure

Portable air cleaners have a metric that evaluates their effectiveness in reducing airborne pollutants from the air. The clean air delivery rate (CADR), which was developed by the Association of Home Appliance Manufacturers (AHAM), is a measure that estimates the filtration effectiveness of reducing particle concentrations in an occupied space, based on the maximum recommended floor area for the rated unit expressed in cubic feet per minute. Similar to the MERV rating, CADRs are calculated for three different size classes of particles: pollen (5 to 11 µm), dust (0.5 to 3 µm) and tobacco smoke (0.09 to 1.0 µm). Typically, a person will want a portable air cleaner that is rated with a tobacco smoke CADR at least 2/3 of the room area in which it will be placed. For example, a unit with a CADR of 200 is appropriate for a room size of 300 ft^2. Many of the portable air cleaners tested by AHAM have moderate to large CADR ratings for small particles. Units tested by AHAM carry a verified label suggesting the appropriate maximum room size for the cleaner.[61,63]

Air Cleaning Technologies

Mechanical Filtration

Fibrous Media Filter

According to ASHRAE, mechanical air filters use media with porous structures that contain fibers or stretched membrane material in a variety of fiber sizes, densities, and media extension configurations to remove particles from airstreams. Air is cleaned when particles enter a filter and attach to the media, removing the particles from the air as it passes through. The effectiveness of these filters in cleaning air is contingent on a multitude of factors (Figure 1). Fibrous air filters can be made from a variety of different materials that influence the effectiveness and efficiency of the filter.[65]

Figure 1: Factors that influence fibrous air filtration

- Particle size
- Filter porosity
- Dust loading conditions
- Filter thickness
- Electrostatic media
- System/device runtime
- Airflow

Fibrous Media Filter Types

MERV Ratings (ASHRAE Standard 52.2)[86]

MERV RATING	PARTICLE SIZE RANGE (μM)	EFFICIENCY	APPLICATION
1–4	3.0–10.0	<20%	Minimum Equipment Protection
5–8	3.0–10.0	≥20% to <85%	Minimum Particulate Protection Residential Homes Commercial Buildings
9–12	3.0–10.0 1.0–3.0	≥85% <50 to ≥80	Improved Particulate Protection Industrial Buildings Commercial Buildings Residential Buildings
13–16	3.0–10.0 1.0–3.0 0.30–1.0	≥90% >90% <70 to ≥95	Superior Particulate Protection Smoke Removal Healthcare Facilities General Surgery

Panel Filters (MERV 1–4)

Flat or panel filters are inexpensive filters consisting of coarse glass fibers, coated animal hair, vegetable fibers, synthetic foams, metallic wools, synthetic fibers, or expanded metals and foils. Panel filters have very low efficiency to remove most particle sizes. These filters are commonly used in residential furnaces and air-conditioning systems. They are also used as pre-filters for more efficient filters. Given its efficiency, these filters are mostly used to protect HVAC equipment from buildup of materials in the machinery than protect occupants from particulate matter.[63]

Pleated, extended surface, and unpleated, pad filter (MERV 5–12)

Compared to panel filters, pleated/unpleated pad filters generally have a higher efficiency for most particle sizes. Pleating the filter increases its surface area and allows for the use of smaller fibers and increased density of the filter fibers without reducing airflow. The media used for pleated filters can be fiber mats, bonded glass fibers, synthetic fibers, cellulose fibers, wool felt, and other cotton-polyester material blends. These filters are more suitable for protecting occupants from certain types of particles like dust and pollen.[63]

High efficiency filters (MERV 13 or higher)

High-efficiency filters will have a higher average airflow resistance than medium-efficiency filters with the same thickness. The EPA recommends high efficiency filters for residential and commercial buildings for their ability to protect occupants from fine particulate matter. High Efficiency Particulate Air (HEPA) filters are categorized as MERV 16 under the ASHRAE Standard 52.2, but undergo more specific testing and are the most effective at removing fine and ultrafine particulate matter than lower rated filters. HEPA filters are better than a standard MERV 16 filter and are generally used in healthcare and industrial settings due to their efficiency in removing particles and more narrowly defined performance characteristics. A HEPA filter is standardized at a minimum 99.97% efficiency rating for removing particles at 0.3µm in diameter. Particles that are larger or smaller than 0.3µm are trapped at even higher efficiencies, which make HEPA filters effective in protecting occupants from particulate matter from smoke.[61,63, 66]

Gas-phase Filtration

Sorption Filters

Gas-phase air filters use a material with a high surface area called sorbent to capture gaseous pollutants. This is done through either adsorption or chemisorption. Adsorption is a process that results from the physical attraction of gas or vapor molecules to a surface. Chemisorption occurs when gas or vapor molecules chemically react with the sorbent material or with reactive agents impregnated into the sorbent.[29] The reaction forms compounds that can be bound to the media or broken down and released into the air. Activated carbon is the most common filter used in HVAC systems and portable cleaners for gaseous pollutant removal. It can potentially remove most hydrocarbons, ozone, aldehydes, and organic acids, but is not effective against oxides like sulfur, nitrogen oxide, and ammonia. Activated carbon filters are rarely found on their own in air cleaners. They are usually used in addition with another air cleaning technology, like a HEPA filter. Gas-phase filters are usually specifically designed to address one or a limited number of gaseous pollutants and need to be replaced frequently due to their limited lifespan. None are expected to remove all the gaseous pollutants present in a typical home.[61,63]

Electronic Filtration

A few electronic air cleaning technologies can be used to filter indoor air pollutants: electrostatic precipitators, ionizers, and ozone generators. Currently there are no widely used standard measurements for the effectiveness of electronic air cleaners.

Electrostatic Precipitators

Electrostatic precipitators (ESPs) are air cleaners that use an electrostatic process to charge particles, which make them become attracted to the oppositely charged plates inside the cleaner. ESPs remove and collect small airborne particles and often have an initial single pass removal efficiency of 60% or more for most particle sizes, depending on the airflow rate. ESPs can have different removal efficiencies for particles with different compositions. This is because different particles have different electrical properties that will affect their ability to hold a charge.[63]

Ion Generator

Ion generators (Ionizers) use a high voltage wire or carbon fiber brush to electrically charge air molecules, which produces negative ions that attach to airborne particles. Ionizers are similar to ESPs but without the added collector, instead dispersing the negatively charged particles in the air. The charged particles can attach to nearby surfaces, like walls and furniture, or to one another and settle faster. Because ionizers don't typically use fans to move air past the cleaner, their CADRs are usually low for most particle sizes. Ionizers can also be installed within HVAC systems.[61,63]

Ozone Generators

Both ESPs and ionizers can potentially produce ozone when operating. Ozone (O_3) is a known pulmonary irritant.[61] Positive associations have been found between ozone exposure and hospital admission visits for conditions such as pneumonia, asthma, chronic obstructive pulmonary disease, and other respiratory illnesses. Increased exposure to ozone has also been correlated with premature mortality.[36] Ozone, through potential secondary chemical reactions, can produce other harmful pollutants like formaldehyde, which has been associated with negative respiratory health effects.[67] The productions of this pollutant directly contrast with the goal of reducing harmful irritants within structures. Ozone generators intentionally produce ozone in order to create a chemical reaction with the harmful VOCs that produce a less harmful substance like carbon dioxide. However, given the potential harm that ozone can cause, ozone generators have not been recommended for use within structures.[63,64,68] The California Air Resources Board (CARB) requires that all air cleaners sold in California be certified to meet electrical safety and ozone emissions standards and has created a list of certified air cleaners for public use (See Selected Resources).[69]

Effectiveness in Reducing Pollutant Concentrations

A literature search was conducted to find relevant studies pertaining to the effectiveness of air cleaning technologies in substantially reducing air pollutants prevalent in wildfire smoke (see Appendix for methodology). The tables below summarize study characteristics and conclusions of highly relevant research. Detailed summaries of each study follow the tables.

Effectiveness of Mechanical Filters on Air Pollution Reduction

Summary of Literature on Pollutant Reductions from Mechanical Filter Use

STUDY	STUDY CHARACTERISTICS	POLLUTANT EXPOSURE VARIABLE IMPACT	MAIN CONCLUSION
Barn et al. (2018)	Randomized control group, 540 pregnant adult women, Residential apartments, portable HEPA filter air cleaner, Secondhand smoke pollution.	$PM_{2.5}$ (29%) ▼	Portable air cleaners substantially reduced indoor $PM_{2.5}$ concentrations and secondhand smoke exposure.
Chuang et al. (2017)	Randomized crossover, 422 adult homeowners, Residential Houses, Mongolia, HVAC with filter, General air pollution	$PM_{2.5}$ (57%) ▼ VOC (33%)[c] ▼	Findings suggest that air conditioning with a HEPA filter can be a simple and useful method to reduce indoor air pollution.
Ward et al. (2017)	Three arm randomized placebo-controlled trial, 98 residential homes, Portable HEPA filter air cleaner, Wood stove smoke pollution.	PM2.5 (68%) ▼	HEPA filter air cleaners were a relatively less expensive and more efficacious intervention than a wood stove changeout intervention for lowering exposure to wood stove pollutants.
Wheeler et al. (2014)[a]	Randomized case-control study, 31 residential homes, Canada, portable HEPA filter air cleaner, wood smoke pollution.	$PM_{2.5}$ (52%) ▼	The use of HEPA air cleaners reduced exposures to indoor $PM_{2.5}$ resulting from both indoor and ambient wood smoke sources.
Allen et al. (2011)[a]	45 healthy adults, Randomized crossover, residential homes, portable HEPA filter air cleaner, wood smoke pollution.	$PM_{2.5}$ (60%) ▼ Levoglucosan (75%) ▼	Proper air filtration (HEPA) can significantly reduce woodsmoke pollutants like $PM_{2.5}$.
Xu et al. (2010)[a]	30 children with asthma, Residential homes, portable HEPA filter air cleaner, general air pollution.	PM_{10} (72%) ▼ VOC (59%)[c] ▼ CO_2 (19%) ▼ CO (30%) ▼	Use of HEPA filter/ventilator proved to be effective in reducing particle and gas concentrations.
Barn et al. (2008)[ab]	38 homes affected by either wood smoke or forest fire smoke, British Columbia, 89% CADR, portable HEPA air cleaner, wildfire & wood smoke pollution.	Avg. Summer Finf (57%) ▼ Avg. Winter Finf (79%) ▼ Avg. Both Finf (75%) ▼	Remaining indoors combined with use of HEPA filter air cleaner can effectively reduce $PM_{2.5}$ exposure during forest fires and residential smoke burning.
Eggleston et al. (2005).	Randomized controlled trial, HEPA air filter, Homes with asthmatic children	PM_{10} (39%) ▼	Environmental treatment reduced indoor airborne particulate matter.

a = (μg/m^3)

b = F_{inf}: PM Indoor infiltration rate

c= Specific filters weren't designed to reduce VOCs, so reasons for VOC reduction are unclear.

Barn et al. (2018)

A study was conducted to determine the effectiveness of portable HEPA filter air cleaners in reducing indoor particulate matter $PM_{2.5}$ and secondhand smoke exposures among non-smoking pregnant women in Ulaanbaatar, Mongolia. 540 participants were randomly assigned to an intervention group which received one or two HEPA filter air cleaners and a control group which received no air cleaners. The researchers monitored 259 intervention and 253 control participants to the end of their pregnancy. Residential indoor and outdoor $PM_{2.5}$ concentrations were measured in early and late pregnancy. The blood samples of 382 participants were collected by a nurse and analyzed for cadmium during late pregnancy. Hair samples were also collected and analyzed for nicotine as an indicator for secondhand smoke exposure. The researchers used a mixed-effects and multiple linear regression models and used stratified models and interaction terms to evaluate potential modifiers of effectiveness. Indoor $PM_{2.5}$ concentrations were 29% lower in the intervention group. Blood cadmium concentrations were 14% lower in intervention group due to reduced pollutant exposure. Researchers concluded that HEPA filter air cleaners can lower indoor PM2.5 concentrations and secondhand smoke exposures in highly polluted settings.[70]

Chuang et al. (2017)

A study was conducted on whether there was an association between air pollution filtration and cardiovascular health. The researchers recruited 200 adult homemakers and randomly assigned 100 of them to either an air filtration intervention or control intervention. The subjects who were assigned to the air filtration group in 2013 were assigned to the control group in 2014, while the people who were assigned to the control group in 2013 were assigned to the filtration group in 2014. Measurements were taken for $PM_{2.5}$ and total VOCs. The blood pressure of the participants was monitored, and blood samples were collected after air pollution monitoring. The researchers used mixed-effects models to investigate the associations among pollution measurements, biological markers, and blood pressures. The participants in the air filtration intervention group experienced less exposure to VOCs and $PM_{2.5}$ and had improved cardiovascular health markers. Researchers concluded that long-term filtration lowered exposure to particulate matter and VOCs and affected cardiovascular health.[71]

Ward et al. (2017)

A study was conducted to assess the efficacy of residential interventions to reduce indoor particulate matter exposure from wood stoves. The researchers enacted a three-arm randomized placebo-controlled trial, with the interventions of air filtration and wood stove changeouts being evaluated. The outcomes variables being monitored were $PM_{2.5}$ concentrations and carbon monoxide. 16 homes received the wood stove changeout, 40 homes received a placebo filter, and 42 homes received the HEPA air cleaner. The variables were collected before and after the interventions and linear mixed models were used to account for the dependence of repeated measures of indoor air quality in the same home and were used to evaluate whether pre- to post intervention changes in indoor air quality concentrations differed significantly by interventions. $PM_{2.5}$ concentrations were reduced by 68% in the filtration intervention group, whereas no significant reductions in $PM_{2.5}$ were observed in the placebo filter intervention group or wood stove changeout group. The researchers concluded that HEPA filter air cleaners were a relatively less expensive and more efficacious intervention for lowering exposure to wood stove pollutants.[72]

Wheeler et al. (2014)

A study was conducted to evaluate the effectiveness of air cleaners in reducing wood smoke associated $PM_{2.5}$. Thirty-one homes were monitored for three consecutive days each, with two homes monitored concurrently per week. Homes were randomly assigned to a filtration intervention group and control group. Homes used their wood burning appliance as usual on day 1. On days 2 and 3, the wood smoke appliance was not operated, and the HEPA filter air cleaner was activated (if assigned to intervention group). The $PM_{2.5}$ concentrations were monitored, along with the infiltration factor. The infiltration factor (F_{inf}) is defined as the fraction of ambient particles that penetrate indoors and remain suspended under steady-state conditions. The researchers found that when the air cleaner was operating, the total indoor $PM_{2.5}$ levels were significantly lower than in the control group, with median reductions of 52%. There was also a reduction in the median $PM_{2.5}$ F_{inf} from .56 to .26, suggesting that the HEPA filter air cleaner was responsible for increased PM deposition during filtration days. The researchers concluded that the use of HEPA air cleaners reduced exposures to indoor $PM_{2.5}$ resulting from both indoor and ambient wood smoke sources.[73]

Allen et al. (2011)

A study was conducted to assess a HEPA portable air filter's effectiveness in lowering indoor pollutants from wood smoke and improving cardiovascular health outcomes. The researchers recruited 45 healthy adults and conducted a randomized crossover intervention study that exposed them to consecutive 7-day periods of filtered and nonfiltered air. $PM_{2.5}$ was monitored for the indoor air pollutant measure. The researchers used mixed models to account for measurements clustered within individuals and individuals clustered within homes. They explored effect modification by filtration/placebo order, age, sex, overweight, time spent indoors at home, and wood stove use. Averages of indoor infiltration factor (F_{inf}) for $PM_{2.5}$ were significantly lower during HEPA filtration, with nearly 60% reductions in average concentrations. The HEPA filters reduced indoor $PM_{2.5}$ in 24 of 25 homes and were associated with positive increases in selected cardiovascular health markers. The researchers concluded that proper air filtration can significantly reduce woodsmoke pollutants like $PM_{2.5}$, which can favorably influence cardiovascular morbidity.[74]

Xu et al. (2010)

A study was conducted to monitor how a HEPA air cleaner/ventilator would improve respiratory health of children with asthma. Thirty children with asthma were recruited and randomly assigned to a control group and a filtration group. For the first six weeks the filtration group had air cleaning/ventilation units running in their bedrooms and the control group did not. During the second six weeks, both groups had air cleaning/

ventilation units running. The parameters of indoor air quality were temperature, VOC, CO, CO_2, and PM_{10} concentrations. The researchers monitored exhaled breath condensate (EBC) for nitrate and pH to measure pulmonary inflammation and peak expiratory flow (PEF). They also measured peak expiratory flow. ANOVA was performed on the raw health marker data to test the treatment levels for the different HEPA status (on/off). The researchers found that there were average reductions in the pollutants of PM_{10}, VOCs, CO, and CO2 by 72%, 59%, 30%, and 19% respectively when the air cleaner was operating. There was also less pulmonary inflammation and an increase in PEF in the children who had an air cleaner/ventilator operating in the room. These results indicate that air cleaning in combination with ventilation can effectively reduce symptoms for asthma sufferers.[75]

Barn et al. (2008)

A study was conducted to address the effectiveness of HEPA filter air cleaners on indoor pollutants from forest fires. The researchers collected valid indoor/outdoor 1-minute $PM_{2.5}$ averages and 48-hour outdoor $PM_{2.5}$ samples for 19 winter and 13 summer homes impacted by wood burning and forest fire smoke respectively during 2004–2005. Portable HEPA filter air cleaners were operated indoors with the filter removed for one of two sampling days. The researchers conducted modeling in order to measure the indoor filtration factor (Finf) of $PM_{2.5}$ from forest fires/wood smoke. Particle F_{inf} and air cleaner effectiveness (ACE) were calculated for each home with a recursive model. The researchers found significantly lower Finf values in the homes when the air cleaner was run with the HEPA filter. $PM_{2.5}$ was decreased with air cleaner use for 9 out of 10 homes sampled in the summer and 14 out of 16 houses sampled in the winter. The researchers concluded that remaining indoors combined with use of a HEPA filter air cleaner can effectively reduce $PM_{2.5}$ exposure during forest fires and residential smoke burning.[76]

Eggleston et al. (2005)

A study was conducted to monitor if reducing airborne pollutants inside homes would reduce asthma morbidity in children. An initial evaluation that included interviews, allergen tests, home inspections, and pollutant measurements was implemented to locate suitable candidates for the study. 100 asthmatic children were randomized to a treatment group, which were households that were provided with pest and mice extermination services, HEPA filters, and allergen-free mattress and pillow casings, and a control group, which received no interventions until after the 1 year period. The outcome variables monitored were particulate matter concentration, allergens, and asthma symptoms. The researchers evaluated the differences in outcomes between the two groups at 6 and 12 months. Within the treatment group, the PM_{10} concentrations decreased 30% at 6 months and 39% at 12 months in comparison to the respective 8% and 5% increases in concentrations within control group. There were reductions in indoor allergen levels in the intervention group, as well. Daytime symptoms significantly decreased under the intervention group. Researchers concluded that a tailored, multifaceted environmental treatment reduced airborne particulate matter and indoor allergen levels in inner-city homes, which, in turn, had a modest effect on morbidity.[77]

Effectiveness of Electrostatic Precipitators (ESP) on Air Pollutant Reduction

Summary of Literature on Pollutant Reduction from ESP Use

STUDY	STUDY CHARACTERISTICS	POLLUTANT EXPOSURE VARIABLE IMPACT	MAIN CONCLUSION
Chen et al. (2015)[a]	Randomized, double blind crossover trial, 35 nonsmoking college students, Shanghai college dormitories, portable ESP air cleaner, general air pollution.	$PM_{2.5}$ (57%) ▼	The intervention of air purification demonstrated clear cardio-pulmonary benefits among healthy adults in a Chinese city with severe ambient particulate air pollution.
Weichenthal et al. (2013)[ab]	Crossover study, 37 Canadian residents (20 homes), portable ESP air cleaner, general air pollution.	Avg. PM_{10} (38%) ▼ Avg. $PM_{2.5}$ (37%) ▼ Avg. PM_1 (34%) ▼ BTEX (7%) ▼	Portable indoor air filters may offer substantial reductions in indoor particulate matter, and such reductions may be associated with improved lung function.
Hart et al. (2011)[ac]	Crossover study, two residential homes, portable ESP air cleaner, wood stove smoke pollution.	PM_{10} (61%, 78%) ▼ PM_5 (63%, 81%) ▼ $PM_{2.5}$ (61%,84%) ▼ PM_1 (63%, 85%) ▼ $PM_{0.5}$ (66%, 83%) ▼ $PM_{.0.3}$ (65%, 82%) ▼	A portable air cleaner may effectively reduce indoor particulate matter concentrations associated with wood combustion during home heating.
Henderson et al. (2005)[a]	Randomized controlled trial, two residential homes, portable ESP air cleaner, wildfire smoke pollution.	$PM_{2.5}$ (63-88%) ▼ O_3 (2-4ppm) ▲	Indoor air filtration in combination with closed windows is effective in reducing harmful wildfire smoke pollutant exposure.

a = (µg/m3)

b = BTEX: sum of benzene, toluene, ethylbenzene, xylenes

c = (Home A, Home B)

Chen et al. (2015)

A study was conducted to evaluate the effectiveness of ESP air cleaners in improving cardiopulmonary health in China. The researchers enacted a randomized, double-blind crossover trial among 35 healthy, nonsmoker college students in Shanghai. The students lived in 10 dormitory rooms that were randomly assigned into two groups of five. The groups alternated between using a real ESP air cleaner and a placebo cleaner for 48 hours with a two-week washout period (where no cleaner was being operated). The researchers monitored health impacts by measuring 14 markers for inflammation, coagulation, vasoconstriction, lung function, and blood pressure.

The researchers applied linear mixed-effect models to evaluate the effect of the air cleaners on health outcome variables. Air purification resulted in an average 57% reduction in $PM_{2.5}$ concentration within hours of operation. Purification was also significantly associated with decreases in geometric means of multiple inflammatory and thrombogenic markers. The researchers concluded that the intervention of air purification demonstrated clear cardio-pulmonary benefits among healthy adults in a Chinese city with severe ambient particulate air pollution.[78]

Weichenthal et al. (2013)

A case-crossover study was conducted to examine how indoor air quality impacts cardiorespiratory health within First Nation communities. The researchers recruited 37 residents within 20 homes. Each home was monitored over a three-week period and was provided an electrostatic precipitator air cleaner for 1 week, a placebo air filter for one week, and no filter (washout period) for one week. Pollution was measured by monitoring the weekly average particulate matter concentrations (PM_1, PM_{10}, $PM_{2.5}$), VOCs concentrations, NO_2 samples, and CO_2 samples. Heath markers monitored were blood pressure, reactive hyperemia index (RHI) and forced expiratory flow. The researchers used linear model-effects models to examine the impact of indoor air filter use on weekly changes in clinical measures (excluding washout period) adjusted for potential time-varying factors. Indoor $PM_{2.5}$, PM_1, and PM_{10} decreased substantially during air filter weeks relative to placebo. Filtration had little impact on the other exposure pollutants monitored. The researchers concluded that portable indoor air filters may offer substantial reductions in indoor particulate matter, and that such reductions may be associated with improved lung function.[79]

Hart et al. (2011)

A study was conducted to evaluate the effectiveness of an electrostatic filter portable air cleaner in reducing the particulate matter (PM_{10}, $PM_{2.5}$, PM_1) within homes where a wood stove is the sole heat source. The study was conducted in two homes in Montana that contained wood burning stoves. Sampling of $PM_{2.5}$ counts and mass concentrations were conducted in each home for ten 24-hour periods. In each of the 24-hour periods, an ESP air cleaner was operated on high for 12 hours (half of the period duration). The remaining sample duration was conducted with the cleaner turned off. Occupants were told to record any activities conducted inside the houses that could potentially create more particulate matter. The researchers conducted multiple regression tests to analyze the data. Home A's mean 12-hour particle count and particle mass concentrations were consistently lower when the air cleaner was on versus when it was off. The effectiveness of the ESP filter was demonstrated in all particle sizes, ranging from 61% to 68% reductions. House B's mean 12-hour particle count and particle mass concentrations were also significantly reduced when the ESP air cleaner was operated. There were significant decreases in all particle sizes, ranging from 78% to 85% reductions. Findings suggest that an ESP portable air cleaner may effectively reduce indoor particulate matter concentrations associated with wood combustion during home heating.[80]

Henderson et al. (2005)

A study was conducted to understand the impacts of mitigation strategies for residences impacted by scheduled prescribed burns and wildfires. Indoor and outdoor

$PM_{2.5}$ concentrations from pairs of residences were monitored during one prescribed burn and three wildfires during the 2002 fire season. The effect of ESP cleaners on indoor $PM_{2.5}$ concentrations was investigated, with a cleaner being given to one of the houses in each pair. All occupants in the residences were told to keep all windows closed and to record all activities that may be a source of particulate matter (like cooking or cleaning). The researchers found that the homes that used the ESP cleaner had reduced concentrations of $PM_{2.5}$ by a range of 63–88%. The researchers concluded that air filtration in combination with closed windows is an effective intervention for reducing exposure to the harmful pollutants of wildfire smoke and prescribed burns.[81]

Summary of Evidence

Several studies found beneficial impacts of implementing HEPA filter air cleaners in order to reduce air pollutants prevalent in wildfire smoke. Most studies reported a statistically significant reduction in particulate matter and a few studies have reported reductions in other gaseous pollutants, such as VOCs and CO. In some cases, researchers also found modest improvements in cardiorespiratory function when implementing HEPA filter air cleaners. Based on the evidence, HEPA filter implementation can potentially reduce exposure to wildfire smoke pollutants and could mitigate negative health impacts.

A moderate amount of literature supports the effectiveness of ESP air cleaners in reducing harmful air pollutants that are prevalent in wildfire smoke. Most studies found a significant reduction in particulate matter and certain VOCs when operating an ESP cleaner indoors. Henderson et al. (2005) cited noticeable ozone increases when operating the ESP cleaner. Even though the evidence suggests that ESP filters will reduce PM and pollutants in wildfire settings, the potential ozone production from some of the devices can be dangerous to residents and should be considered.[67] Referring to the CARB certified list of air cleaners when purchasing electronic air cleaners could potentially mitigate dangerous ozone production within structures.[69]

There is little evidence on gas-phase filters reducing wildfire smoke pollutants. Newer air cleaning devices usually have sorbent filters in a addition to HEPA filters. Gas phase air cleaners are not generally used by the general public and there are not any widely used standardized measures for performance for gas filters in structures. An evaluation of air cleaner effectiveness in reducing VOCs illustrated the efficiency of gas filters to reduce the concentration of VOCs was inconsistent even when using the same model. More research needs to be done on the effectiveness of gas filters in reducing harmful gaseous pollutants.[64,82]

Overall, HEPA filter and electrostatic precipitators seem to be effective in reducing exposure to air pollutants produced by wildfires and can potentially limit the negative health impacts from exposure as well. These findings are consistent with an evidence review conducted by Barn et al. (2016), who also found a significant amount of evidence to state that air filtration is an intervention that should be utilized during wildfires.[60]

Complementary Methods to Improve Air Filtration

In addition to using effective air filtration technology to reduce pollutants within structures, there are other methods that will aid in reducing exposure to harmful wildfire smoke. Listed in the figure below are methods that will help filter the air and create a "clean room" environment.

Figure 2: Methods to help improve air quality in combination with air filtration23

- Stay indoors
- Keep windows and doors closed
- Make sure air is not recycled from outsidea
  - If you have an HVAC system with a fresh air intake, set the system to recirculate mode, or close the outdoor intake damper.81
  - If you have a window air conditioner, close the outdoor air damper. If you cannot close the damper, do not use the window air conditioner. (Make sure that the seal between the air conditioner and the window is as tight as possible).81
  - If you have an HVAC system which has a filter, you can set the fan to continuous operation to pull indoor air through the filter, even when the HVAC system is not actively heating or cooling or when the heat/cool is intermittent.61,84
  - If you have a portable air conditioner with a single hose, typically vented out of a window, do not use it in smoky conditions. If you have a portable air conditioner with two hoses, make sure that the seal between the window vent kit and the window is as tight as possible.81
- Reduce activities that might increase pollutants (smoking, wood smoke, cooking, lighting candles)
- Do not vacuum anywhere in the house unless using a HEPA-filter equipped vacuum
- Keep the room clean (use a damp cloth or mop)
- Ventilate the room once outside air quality is improved

a = Please refer to manufacturer for information on your specific air conditioning unit.

These methods highlighted in Figure 2 in combination with using air filtration technology will reduce harmful exposure to wildfire smoke pollutants and potentially improve health outcomes. In addition, there may be cases to where the air quality is so bad to where it is a direct harm to stay in certain structures, even with the appropriate measures. If that happens, it is more advantageous to relocate to a safer area with cleaner air.[23]

Selected Resources

Wildfire Smoke: A Guide for Public Health Officials—EPA:[30]
https://www.airnow.gov/sites/default/files/2020-06/wildfire-smoke-guide-revised-2019.pdf

Residential Air Cleaners Technical Summary—U.S. Environmental Protection Agency:[63]
https://www.epa.gov/sites/production/files/2018-07/documents/residential_air_cleaners_-_a_technical_summary_3rd_edition.pdf

Guide to Air Cleaners in the Home—U.S. Environmental Protection Agency:[61]
https://www.epa.gov/sites/production/files/2014-07/documents/aircleaners.pdf

Integrated Science Assessment for Particulate Matter—U.S. Environmental Protection Agency:[21]
https://www.epa.gov/isa/integrated-science-assessment-isa-particulate-matter

Air Cleaning Devices for the Home—California Air Resource Board:[84]
https://ww3.arb.ca.gov/research/indoor/acdsumm.pdf

Residential Air Cleaner Evidence Review—National Collaborating Centre for Environmental Health:[63]
http://www.ncceh.ca/sites/default/files/Air_Cleaners_Oct_2010.pdf

California Certified Air Cleaners – California Air Resource Board:[69]
https://ww2.arb.ca.gov/our-work/programs/air-cleaners-ozone-products/california-certified-air-cleaning-devices

Filtration in Institutional Settings during Wildfire smoke events—British Columbia Centre for Disease Control:[85]
http://www.bccdc.ca/resource-gallery/Documents/Guidelines%20and%20Forms/Guidelines%20and%20Manuals/Health-Environment/WFSG_EvidenceReview_FiltrationinInstitutions_FINAL_v3_edstrs.pdf

New Guidance of Residential Air Cleaners—ASHRAE:[66]
https://www.epa.gov/sites/production/files/2019-09/documents/harriman_stephens_brennan_-_new_guidance_for_residential_air_cleaners_-_ashrae_journal_sept-2019._web_version.pdf

Appendix

Methodology

An initial peer-reviewed and grey literature search was conducted in the winter of 2019-2020, utilizing Google Scholar. Additional subject matter expert input was received from internal CDC staff, and EPA staff. The literature search focused on finding relevant resources pertaining to climate change effects on wildfires, wildfire smoke exposure effects on human health, and literature focusing on the effectiveness of certain air cleaning technology and devices for reducing pollutants prevalent in wildfire smoke. Based on initial search and discussion with internal and external partners, a more comprehensive narrative review was conducted with the assistance of the CDC Library using CAB Abstracts, Embase, Medline, and Scopus. The Library found 1486 sources using the designated search terms (Figure 3). All sources were reviewed, and the most relevant literature was compiled into a separate database which was used for the document. The database contained 200 articles. Additional articles were identified through snowball searching by examining citations and "cited by" references. Additional citations and resources were recommended by CDC staff, the author team, reviewers, and subject matter experts.

Figure 3: Literature Search Terms

- Air cleaner
- Air filter
- Air purifier
- Air quality
- Asthma
- Cardiovascular
- Children
- Climate change
- Electrostatic precipitator
- Elderly
- Fine particulate matter
- Health effects
- HEPA
- High-efficiency
- Houses
- HVAC
- Industrial
- Intervention
- Ionizer
- PAC
- Portable air cleaner
- Respiratory
- Schools
- Wildfire smoke

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