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Improving the Indoor Air Quality of Residential Buildings during Bushfire Smoke Events

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Abstract: Exposure to bushfire smoke is associated with acute and chronic health effects such as respiratory and cardiovascular disease. Residential buildings are important places of refuge from bushfire smoke, however the air quality within these locations can become heavily polluted by smoke infiltration. Consequently, some residential buildings may offer limited protection from exposure to poor air quality, especially during extended smoke events. This paper evaluates the impact of bushfire smoke on indoor air quality within residential buildings and proposes strategies and guidance to reduce indoor levels of particulates and other pollutants. The paper explores the different monitoring techniques used to measure air pollutants and assesses the influence of the building envelope, filtration technologies, and portable air cleaners used to improve indoor air quality. The evaluation found that bushfire smoke can substantially increase the levels of pollutants within residential buildings. Notably, some studies reported indoor levels of PM_{2.5} of approximately 500 µg/m³ during bushfire smoke events. Many Australian homes are very leaky (i.e., >15 ACH) compared to those in countries such as the USA. Strategies such as improving the building envelope will help reduce smoke infiltration, however even in airtight homes pollutant levels will eventually increase over time. Therefore, the appropriate design, selection, and operation of household ventilation systems that include particle filtration will be critical to reduce indoor exposures during prolonged smoke events. Future studies of bushfire smoke intrusion in residences could also focus on filtration technologies that can remove gaseous pollutants.

Keywords: bushfire smoke; indoor air quality; filtration; building envelope; energy



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1. Introduction

Indoor air quality (IAQ) may be defined as the air quality within buildings that can impact occupant comfort, health and wellbeing [1]. In most developed countries people spend the majority of their time indoors, and in particular, within residential buildings [2]. Residential indoor environments can be important places of exposure to air pollution, including hazardous air pollutants [3]. Common sources of indoor pollutants include emissions from building and furnishing materials, fragranced consumer products, and occupant activities such as cooking and cleaning [3–5]. In addition, when ambient air becomes heavily polluted, such during bushfires, concentrations of indoor pollutants can increase substantially, resulting in poor IAQ. During bushfire smoke events, the levels of indoor pollutants may initially be lower than outdoors, however, as smoke persists for days (or weeks), the levels indoors and outdoors can be similar. Due to the long periods of time spent at home and the relative scarcity of residences equipped with air filtration technologies capable of removing pollutants, exposure to bushfire smoke in residences may be considerable. One important recommendation given by authorities to residents affected by bushfire smoke is to stay indoors. Doing so can provide a level of protection from exposure to smoke, however the degree of protection will depend on factors such as the duration of the smoke event [6], the design of the building envelope, occupant activities,

and type of ventilation system (if any). The effectiveness of homes in protecting occupants from poor air quality is not very well understood.

This paper evaluates the impact of bushfire smoke on the air quality within residential buildings. It focuses on (i) the indoor levels of pollutants (e.g., particles, gases) within residences during bushfire smoke events, (ii) recent advancements in the methods of monitoring pollutants (e.g., low-cost sensors), and (iii) strategies to improve IAQ, such as building envelope design, ventilation air filtration, and use of portable air cleaners. There are many different terms used to describe bushfires. These include wildfires, forest fires, vegetation fires, and landscape fires [7,8]. Barn et al. [9] proposed a definition of uncontrolled fires as "wildfires" and controlled fires as "landscape fires," although this terminology will differ between countries. In this paper we will report the terminology used in the cited article, including "bushfire," "wildfire," "forest fire," and "landscape fire".

2. Impacts of Bushfire Smoke

Smoke from bushfires can be a significant risk to health. Exposure to bushfire smoke has been associated with increased morbidity [10] and mortality [11]. Smoke from landscape fires has been attributed to an estimated 340,000 deaths every year [8]. Vulnerable members of the population are particularly at risk from health complications associated with exposure to bushfire smoke. For instance, children, the elderly, and individuals with respiratory and heart disease are at a greater risk of harm from exposure to bushfire and wildfire smoke [12,13]. Also, the association between maternal exposure to wildfire smoke and reduced birthweight is evident [14].

Under most climate change scenarios, the frequency and severity of bushfires are predicted to increase [15,16]. The main drivers include increased occurrences and durations of droughts as well as higher ambient temperatures. Modelling estimates of wildfire activity in the western United States suggest an increase of up to 54% in the areas burned by 2050 (compared to 2009), coupled with an approximate doubling of carbonaceous aerosol emissions [17]. Recent fires in California and other parts of the world have reinforced these concerns. In Australia, bushfires have always been a feature of the natural environment, however their impact has increased over the years with fire seasons extending for a longer time and extreme weather becoming more severe [18]. Climate change, smoke and other emissions from bushfires may also influence urban microclimates and exacerbate phenomena such as the urban heat island effect. A recent study conducted in Sydney, Australia [19] compared urban heat island intensity during the 2019/2020 bushfire season to historic meteorological data from the previous 20 years and found an exacerbation of urban heat island events compared to median levels. Analysis of the combined effects of extreme pollution, heat waves, and droughts demonstrated dependencies between environmental factors such as air temperature, relative humidity, particle concentration, wind speed, and rain, and anomalies in the intensity of the urban heat island in comparison to historical trends. The 2019–20 bushfires in Australia caused significant damage to natural and built environments in many states and exposed millions of people to extreme levels of air pollution. During these "Black Summer" fires, more than 15,300 bushfires burned an area of 18,983,588 hectares, destroyed 3113 houses, and took 33 lives. An estimated 1 billion vertebrate animals were lost, and the economic impact has been estimated to be in the order of AUD \$40 billion [20]. Approximately 80% of the population was impacted by bushfire smoke for prolonged periods of time (i.e., weeks) [21]. An analysis of global data for the remotely sensed burned areas of all major forest biomes over the past 20 years found that this massive bushfires in Australia burnt 21% of the total temperate broadleaf and mixed biome, pointing to the likelihood that the projected "flammable future" has arrived earlier than anticipated [22].

The predicted increases in the levels of outdoor pollutants from sources such as bushfires may result in higher indoor pollutant concentrations and increased exposures [23]. Fisk [24] reviewed the potential health consequences of climate change on indoor environments. Projected effects during wildfires include twice the number of heat-related deaths,

increased hospitalizations due to asthma, pneumonia, and cardiovascular effects, and increased mortality and hospitalizations linked to ozone. The authors make the compelling point that a significant proportion of these adverse exposures are likely to occur indoors. Highlighting the challenges that the protracted occurrence of bushfire smoke creates, Vardoulakis et al. [25] called for "more nuanced health advice to protect populations and individuals from exposure to bushfire smoke." For example, the authors suggest the need for additional methods to communicate air quality information, and for an evaluation of the current health protection advice so that it can be adapted for longer periods of smoke exposure.

In summary, the frequency and severity of bushfires are likely to increase in the future. Smoke from bushfires can have a substantial impact on the levels of pollutants within residences and other indoor environments. Therefore, the extent to which people are exposed to pollutants is also likely to increase, and strategies to minimize exposure and health risks are needed. Some of these will be explored in the following sections of this article.

3. General Guidelines and Occupant Behaviour

Key factors that impact health-related symptoms are the concentrations of pollutants in the smoke, the duration of exposure, level of protection that can be utilised, and the underlying health status of those exposed [26]. Government agencies typically use an air quality index (AQI) to communicate the air pollution level to the public. Different countries have specific AQIs that correspond to relevant national air quality standards and use a combination of pollutants including PM_{2.5}, PM₁₀, ozone, sulphur dioxide and nitrogen dioxide. WHO [27] advises maximum levels of 10 µg/m³ per year and 25 µg/m³ per 24-h period for PM_{2.5} levels. In Australia, the ambient PM_{2.5} guideline is 8 µg/m³ averaged over one year and 25 µg/m³ averaged over one day [28]. As per the United States National ambient air quality standards [29], the one-year PM_{2.5} standards for primary and secondary are 12 µg/m³, and 15 µg/m³, respectively, and the standard for 24 h is 35 µg/m³. Primary standards are for protecting the health of sensitive populations and secondary standards provide protection against decreased visibility and damage to buildings, animals and vegetation. During recent bushfires in Australia, the concentrations of PM_{2.5} measured in major cities were as high as 500 µg/m³, more than 20 times the ambient air quality guidelines [30,31].

Advice for reducing exposure to bushfire smoke at home includes publicly available websites and factsheets (e.g., [32,33]) and academic literature [9]. The recommendations include staying indoors with windows and doors closed, reducing strenuous physical exercise (outdoors), going to an airconditioned facility or public building (e.g., shopping centre or library), attending a clean air shelter (if available), using a portable air cleaner, and using well fitted P2 facemasks (e.g., [32,33]). For vulnerable individuals such as asthmatics, the California Department of Public Health [32] suggest that residents consider temporarily evacuating their homes until air quality conditions improve. Some agencies also stress the importance of removing residual smoke that has adsorbed and deposited on surfaces [33]. However, cleaning activities such as vacuuming can increase particle levels in homes and should be avoided when a wildfire smoke is present [34].

Occupant behaviour during wildfires can strongly influence indoor levels of pollutants and occupant comfort. For instance, occupant movement has been associated with high indoor levels of PM_{2.5} [35], therefore minimising the resuspension of indoor pollutants is an important strategy for preventing further exposure [36]. Using computational fluid dynamics to explore indoor exposure risks, Luo et al. [37] found that indoor airflow patterns and pollutant concentrations were significantly impacted by occupant behaviour. The use of air conditioning, operation of doors and windows, use of products, and movement were all important factors that impact indoor air quality during smoke events. Monitoring studies also found that indoor activities such as smoking, cooking, and burning incense or candles can significantly contribute to indoor levels of PM_{2.5} [38]. Reducing or discontinuing the

use of fragranced consumer products, scented candles, and air fresheners has been shown to improve indoor air quality, therefore the use of these products should be minimized, especially when wildfire smoke is present [32,39].

4. Monitoring Studies

Bushfire smoke contains a complex mix of particles and gases including PM₁₀, PM_{2.5}, carbon dioxide, carbon monoxide, sulphur dioxide, nitrogen dioxide, benzene, acetaldehyde, formaldehyde, polycyclic aromatic hydrocarbons, and ozone [40–42]. Experimental and monitoring studies of bushfire smoke in homes have predominantly focused on indoor PM_{2.5} due to well documented health effects of exposure to fine particulate matter [7,8], and existence of health base exposure guidelines such as the National Environment Protection (Ambient Air Quality) Measure e.g., [32]. The relative availability of particle sensors to take measurements during a fire may also have contributed to the research focus on PM_{2.5}. The levels of PM_{2.5} during bushfires can be many of times higher than guideline values. For instance, during the 2019–20 bushfires in Australia, average 24-h PM_{2.5} concentrations in Sydney exceeded 100 µg/m³ and peaked at approximately 500 µg/m³ [30].

Pantelic et al. [43] monitored PM_{2.5} generated during the Chico forest fire in California with the use of a combination of sensor networks outdoors and inside buildings. The study focused on two buildings with different modes of ventilation (i.e., mechanical, natural), in an urban area. The results showed that a mechanically ventilated building was more resilient to outdoor pollution with lower indoor-outdoor concentration ratios and lower indoor PM_{2.5} levels. A study conducted in Denver (CO, USA) during the 2016/2017 wildfires season used laser-based optical particle counters (Dylos-1700) to evaluate levels of particulate matter within 28 low-income homes [44]. The study found median indoor levels of PM_{2.5} were 4.6 times higher than outdoors. Homes that used mechanical ventilation systems with low efficiency filters had indoor-outdoor ratios that were 18% higher for PM_{2.5} than those that did not [44], indicating that the outdoor pollutants are brought indoors through ventilation supply air even when filters were in place. This study also evaluated levels of black carbon (BC), CO, and NO₂ and found that indoor levels of BC during wildfires were about twice the levels recorded when no wildfire smoke was present. In addition, the levels of BC, CO, and NO₂ were consistently higher in homes closer to roads compared to those further away (i.e., >200 m), reflecting the importance of traffic emissions on air quality. Furthermore, activities such as opening a window increased levels of BC, however decreased CO concentrations, suggesting an internal source of CO emissions (such as a gas pilot light) [44]. These studies highlight the variability of PM_{2.5} levels in buildings with mechanical and natural ventilation systems. The studies also highlight the importance of occupant behaviour and proximity to background pollution sources in preventing indoor exposure to air pollutants.

Sapkota et al. [45] investigated transport of particles generated in forest fires using a range of measurement techniques (i.e., laser, time of flight aerosol spectrometers, oscillating microbalances). Three ambient sites and four indoor sites were monitored. PM_{2.5} concentration averaged over 24 h reached 86 µg/m³ during the event and the peak level PM_{2.5} reached a maximum concentration of 199 µg/m³, which is eight times above background levels. With median 0.91 indoor-outdoor ratio, indoor and outdoor concentration levels were found to be similar [45]. In Australia, Reisen et al. [46] evaluated levels of PM_{2.5} within homes impacted by smoke from the prescribed burning of biomass. Four homes were monitored in the town of Ovens, located in the alpine region of north eastern Victoria. The study also monitored outdoor levels of PM_{2.5} and ozone in the same region and at another rural location in Western Australia. For particle concentrations two different instrumental approaches were used: continuous PM_{2.5} measurements were taken at 1-minute intervals using light scattering techniques (DustTrak, TSI Incorporated, Shoreview, MN, USA); and gravimetric mass measurements (MicroVol-1100, Ecotech Pty Ltd, Knoxfield, Australia) were made at weekly intervals to provide reference data and to calibrate the DustTraks. Ozone was measured using a photometric analyser (Model 49 UV, TECO). In

two of the four residences, indoor $PM_{2.5}$ levels exceeded $25 \mu\text{g}/\text{m}^3$, and maximum daily concentrations peaked at $89 \mu\text{g}/\text{m}^3$. Air infiltration rates were also measured in this study using a carbon dioxide tracer gas method. The reported air exchange rates ranged between 0.29 and 0.9 air changes per hour, suggesting that these homes were well sealed. The indoor levels of $PM_{2.5}$ depended on the duration of the smoke event and the ventilation rate of the houses. Household activities were found to be key influencers of indoor pollutant levels when smoke events were short; and external conditions and household ventilation critical during more persistent smoke events.

Other studies have monitored pollutants including air toxics and polycyclic aromatic hydrocarbons (PAHs). A study of the indoor and outdoor levels of 63 PAHs (24 h) found that during wildfire events, the levels of indoor gas phase PAHs were consistently equal to or higher than outdoor levels, thus suggesting the importance of these compounds in evaluation of air pollution risk assessment [47]. Another study of gaseous emissions from bushfire and wildfire smoke compared the trace gas emissions factors of the smoke from Australian and North American research [48]. The study found that approximately 20% of the gases identified had similar emission factors including hydrogen cyanide, ethene, methanol, formaldehyde, and 1,3-butadiene, and others such as acetic acid, ethanol, monoterpenes, ammonia, acetonitrile, and pyrrole differed by a factor of two or more.

Ozone is an important secondary pollutant that can be detrimental to the health and the environment. It is formed by the interaction of nitrogen oxides (NO_x) and non-methane organic carbon molecules (e.g., VOCs) in the presence of sunlight. Exposure to high levels of ozone has been linked to a range of adverse health effects including increased short-term mortality [49]. Wildfires produce approximately 170 Tg of ozone globally every year [40], and levels of ozone increase significantly in smoke plumes and can disperse over large regions [50]. For instance, wildfires in northern Quebec resulted in a 10ppbv increase in downwind ozone concentrations [50]. In addition, ozone can react with anthropogenic sources of volatile organic compounds (e.g., from consumer products) and generate hazardous air pollutants such as formaldehyde and ultrafine particles [51,52], further contributing to levels of hazardous air pollutants in urban areas.

Sensor Technology for Monitoring

Real time information relating to the severity and location of bushfire smoke can help reduce exposure and prevent adverse health effects. Air quality sensors that meet international standards are mostly located at fixed site locations. These sparsely distributed sensors are capable of fulfilling the regulatory needs and providing the public with access to air quality data. However, they have limitations as they can only provide data for a relatively local area. Also, due to the small number of sensors, detailed information about the spatial distribution of pollutants may not be available, making it difficult to identify hotspots [53]. In addition, fixed air quality sensors are characterized by relatively high purchase costs, regular maintenance, and the need for support infrastructure such as enclosures and a reliable power supply. A high spatial scale is important as the levels of air pollutants are extremely location dependent and the nearest fixed station may not be representative of the local pollution concentrations due to geographical and topographical differences.

Low-cost sensors (e.g., $PM_{2.5}$) are widely being used by researchers, private organisations and the general public to monitor air quality. Low-cost particle sensors typically use light scattering techniques to count and determine particle size. However, there is inadequate information about the accuracy of low-cost sensors, particularly on how they perform under conditions of heavy smoke [54]. Furthermore, limited performance information is provided by the manufacturers of the sensors. Field calibration under similar conditions to the actual measurement environment is crucial for obtaining accurate measurements from low cost sensors. Many particle sensors have high correlation (i.e., moderate to high R^2 values) with research-grade calibrated reference instruments, however sensor response has been found to decline at particle concentrations above $50\text{--}100 \mu\text{g}/\text{m}^3$ [55]. In an evaluation of two types of low-cost particle sensors (i.e., PMS 1003s and PMS 5003s, Plantower, Shunyi

District, Beijing, China), Sayahi et al. [56] observed that $PM_{2.5}$ concentrations were typically 0.3–1.25 times the concentration of the reference sensors concentrations and over 1.5 times the reference values during wildfire smoke events. However, this study was limited as the hourly smoke concentrations only reached $\sim 60 \mu\text{g}/\text{m}^3$. Delp and singer [57] note that adjustment factors specific to bushfire smoke are needed for low cost monitors as the optical sensors used varied with aerosol properties. The four low-cost particle sensors assessed, i.e., AirVisual Pro (IQAir, Goldach, Switzerland), PurpleAir (PurpleAir, Draper, UT, USA), Air Quality Egg (Wicked Device LLC, Ithaca, NY, USA), and the Indoor Air Quality Pro Station (eLichens, Grenoble, France), showed accurate data with correction factors ranging between 0.48 to 0.60 compared to a reference instrument, a tapered element oscillating microbalance (i.e., TEOM-FDMS, Thermo Scientific, Waltham, MA, USA). This study was conducted during wildfire season when smoke concentrations were as high as $150 \mu\text{g}/\text{m}^3$. The authors conclude that even though the adjustment factor can vary according to location and over time during a fire event, a global adjustment factor can reduce bias significantly. Holder et al. [54] collated three types of low-cost fine $PM_{2.5}$ sensors with reference instruments during a number of fire events and found moderate to strong correlation with reference instruments, however the sensors overpredicted $PM_{2.5}$ concentrations (with normalized root mean square errors = 80–167%). The authors developed different correction equations for each sensor. Field calibration, under similar environmental and measurement conditions is critical to obtain more accurate measurements from low-cost PM sensors [55,58]. Mehadi et al. [59] assessed seven instruments including two low cost sensors (Dylos, Riverside, CA, USA and PurpleAir, Draper, UT, USA) and found that the ratio of the median Purple Air $PM_{2.5}$ sensor concentrations to reference sensor concentrations varied from about 1.5 to 2 when the smoke intensity increased whereas the same for Dylos was around 25%. Many low-cost sensors have been found to perform better under stable laboratory conditions compared with field conditions [55]. Key factors that influence this variability are the changing particle compositions, sizes, and environmental factors. Therefore, site specific calibration rather than laboratory calibration may be necessary for low-cost sensors. It was also found that sensor performance was sensitive to the composition of smoke. Holder et al. [54] noted that further monitoring and comparison studies focusing on higher particle concentrations are required as optical-based sensors can saturate when the concentrations are very high.

Digital technologies such as smartphone apps that access real-time data are becoming more prevalent, and popular with users. For instance, a near real time smartphone app "AirRater" has been developed by Australian researchers to provide air quality information to vulnerable individuals such as asthmatics and the general public [21]. The app can track user symptoms, monitor air quality conditions, and help reduce personal exposure to air pollution, including smoke from bushfires [21]. An evaluation of the technology during smoke events revealed that the app helped users avoid exposure and effects of smoke by advising them on precautionary measures, such as (i) staying inside, (ii) rescheduling or planning outdoor activities, (iii) changing locations to less affected areas, and (iv) informing decisions on medication use [21].

5. Factors Influencing IAQ

5.1. Building Envelope

The integrity of the residential building envelope is critical for preventing smoke and other pollutants from infiltrating into the building. A tighter building envelope will be less leaky and will reduce the rate of infiltration through cracks, gaps and openings (provided windows and doors remain closed). Therefore, tighter buildings may perform better during smoke events. Attention to detail during design and construction is critical for creating tight building envelope. A more airtight envelope is achieved through the use of air barriers inside and outside and careful sealing of every construction joint in the building envelope such as around windows and doors, wall to roof and wall to floor junctions, and sealing of all service penetrations such as electrical fixtures, wiring plumbing and ducts. The leakiness

of a building can be tested by measuring the number of air changes per hour (ACH). For instance, in the US, ASHRAE 62.1 recommends that to achieve acceptable indoor air quality in buildings, the ACH should be above 0.35 air changes per hour. Increases in ambient temperatures due climate change are expected to affect the ACH in buildings. In some US locations, increased infiltration has been predicted to increase by up to 30% in summer months. Consequently, patterns of exposures to both indoor and outdoor pollutants will likely occur [60]. In residential buildings that rely on fresh air for ventilation, the levels of particles from outdoor sources are often more pronounced, especially when outdoor air quality is poor.

A recent study of Australian homes found that the level of protection offered from peak outdoor PM_{2.5} levels during controlled burning ranged from 12–76% [38]. The authors found that PM_{2.5} infiltration was significantly influenced by the age of the house and ventilation behaviour (e.g., windows open/closed). Australian homes are generally considered leaky compared to homes in other countries, and older Australian homes are often much leakier than those built more recently [61]. In a study of air tightness in new Australian homes (i.e., <3 years old) the average ACH ranged between 7.9–28.5 @ 50 Pa, depending on state or territory. Among the leakiest homes were in Melbourne and Sydney, notably, these cities were severely impacted by smoke during the summer of 2019–2020 bushfires. By contrast, Canberra homes were found to have ACH slightly below the national average of 15.5 ACH @ 50 Pa [61].

In a more recent study in Melbourne during the 2019–20 bushfire season, Munro and Seagren [62] found that the PM_{2.5} levels in a conventional leaky building were under 500 µg/m³ when outdoor levels were close to 600 µg/m³, while the levels in air tight homes reached peak of 320 to 380 µg/m³ which is 30% lower. A centralised mechanical ventilation with an F7-grade filter was used in the airtight home that had air permeability of 0.93 m³/m²h at 50 Pa. The authors also monitored two identical airtight homes that use mechanical ventilation: one with a standard F7 filter and the other with a HEPA filter and found that the home with the HEPA filter achieved lower PM_{2.5} concentrations, that are within recommended guidelines. In summary, even though an airtight building alone is unlikely to keep particles within threshold concentrations, more airtight construction provides an opportunity to better control indoor air quality.

5.2. Filter Technology and Portable Air Cleaners

Air filtration and purification technologies can improve indoor air quality during bushfire smoke. Fisk and Chan [63] found that using air filters during wildfires can substantially reduce hospitalisations and deaths from exposure to wildfire smoke. They also found that the greatest benefits will be realised by focusing on the homes of individuals who experience the most severe health effects such as the elderly. The authors state that the economic benefits of air filtration (particles) in buildings exceed the costs of installation and operation by more than a factor of ten. Common filters used in residential air conditioning such as G4 (~MERV 7–8) will only capture a small percentage of the smoke particles, say around 10%; and a finer F6 (~MERV 10–11) filter may capture around half of these particles. As discussed in the previous section, air filters may not be effective if houses are excessively leaky, therefore, the use of personal respirators independent of the mechanical ventilation system could be explored [6]. Studies have shown that portable air cleaners can reduce indoor levels of fine particles in office environments [64] and residential environments [65,66]. A Canadian study of 31 homes found that using portable air cleaners (Filtrete Ultra Clean Air Purifier model series FAP02-R, 3M, London, ON, Canada) equipped with a patented air filter can reduce indoor levels of PM_{2.5} by a median of 52% [65]. An earlier Canadian study found that using portable air cleaners (with HEPA filters) can reduce PM_{2.5} indoor levels of residential wood smoke in winter and forest fire smoke in summer [67]. In both Canadian studies, air filters were operated without filters (“placebo mode”) and with filters during the smoke events to ascertain differences. In a randomised cross over intervention study conducted in Taipei, Chuang et al. [68]

examined the effect of long-term indoor air conditioner filtration on the link between cardiovascular health and air pollution. The results showed that increased levels of PM_{2.5} was associated with cardiovascular health of adults. A review by Barn et al. [9] found that portable air filters can reduce indoor PM_{2.5} concentrations by 32–88% with important factors of variation being study design and airflow into the room. The review found that high efficiency particulate air (HEPA) filters and electrostatic precipitators can reduce indoor PM_{2.5} concentrations and respiratory and cardiovascular health effects.

Gaseous pollutants from wildfires are not generally the focus of studies as the main pollutant of concern is considered to be PM_{2.5}. However, air toxics such as benzene [69] and PAH's [47] are also present in smoke. The WHO [70] reports that there is no safe level of exposure to benzene as it is carcinogenic to humans. In Australia, the National Environmental Protection (Air Toxics) Measure specifies the national limits for outdoor air pollutants, including formaldehyde, benzene, and polycyclic aromatic hydrocarbons [71]. Therefore, strategies that minimise exposure during bushfires are also needed. Filtration technologies that remove other pollutants such as air toxics (in addition to PM_{2.5}) may provide further benefits in terms of acute and chronic health effects than technologies that exclusively remove particles. Laboratory studies have found activated carbon effective at reducing indoor concentrations of VOCs including benzene and formaldehyde [72], and toluene, cyclohexane, and ethyl acetate [73]. However, there is little or no research to demonstrate the effectiveness of gas-phase filtration systems in actual buildings [63, 72]. If a residential building has a heating ventilation and air conditioning (HVAC) system, it is likely to be less standardised by comparison to those installed in commercial buildings [74] and this can impact the effectiveness of the system.

Impact on Energy

The particle removal efficiency and energy consumption of an air filtration system is influenced by many factors including the system design and the type of installed filter. For instance, high efficiency particulate air filters (such as HEPA) can stop a large proportion of smoke particles. However, the air handling system must be capable of running the additional power load due to resistance to airflow created by the HEPA filter [75]. Also, switching to a higher rated filter has a consequence on energy consumption. Increased pressure drop across the filters will increase fan power consumption. Alavy and Seigel [74] note that the particle removal efficiency of filters can impact three energy related parameters: airflow rate, fan motor energy, and system energy. Prediction of long-term filtration is challenging because particle removal depends on many parameters related to buildings and associated systems such as airflow rate, runtime and particle loading in filters [74]. Using a filter with a higher minimum efficiency reporting value (MERV) causes a higher filter pressure drop and a reduced airflow rate and this will reduce fan energy use. However, the cooling energy will increase because the compressor will have to operate for longer periods of time. For a system with speed control, the fan speed will adjust to maintain the airflow and the total system energy use will remain approximately unchanged. For a system with no speed control, the energy will increase with increasing MERV. Alavy and Seigel [74] summarize that the major factor that determines the energy impact of higher efficiency filters is the increased system runtime due to reduced airflow. This is particularly important in systems without fan control. In summary, there are many factors affecting the relationship between energy use and filter efficiency and these are beyond the scope of the current paper.

A theoretical analysis by Stephens et al. [76] showed that the extent of energy impacts in relation to high-efficiency filters are likely to be small. They also measured results in a test system and confirmed that there was no difference in energy consumption with the use of high-efficiency filters in comparison to low-efficiency filters. Similarly, Walker et al. [77] measured energy usage and filter pressure drop in ten California homes for a year. When low MERV filters are replaced with MERV 10-13 filters, the effects on blower energy use are either negligible or moderate but MERV 16 filters introduced about 20% blower power

increases. They found that climates with more cooling had bigger impacts with a change to higher MERV filtration. The authors suggested that requiring filter manufacturers to label filters with static pressure drop would allow contractors and consumers to make filter replacement decisions based on air flow resistance. However, others caution that modification of HVAC systems, such as by inclusion of additional or higher rated filters, needs to be done carefully in order to avoid "unintended effects" such as reduced airflow, reduced heating/cooling capacity, filter bypass, life-cycle costs, and infiltration of the building envelope [75].

6. Discussion

Access to clean, fresh air is an enduring environmental and public health challenge. The need for fresh air is even more pronounced during bushfire smoke events when levels of air pollutants (e.g., $PM_{2.5}$) can be many times the levels specified in national ambient air quality guidelines. Bushfire smoke can persist for many weeks and can substantially impact air quality in local communities as well as those that are hundreds of kilometres away from the fire front [45], including densely populated urban areas. In a measurement study that included ground-based air quality measurements, aircraft air quality measurements, and computer modelling, Wotawa and Trainer [78] found that wildfires in Canada contributed to elevated levels of carbon monoxide, VOCs, and ozone in the southeastern United States—approximately 3500 km away.

Therefore, strategies and guidance to reduce indoor levels of particulates and other pollutants from bushfires are needed. Vulnerable members of the population could be provided with timely advice on how to avoid smoke exposure. For example, schools and childcare centres could provide warnings to limit outside activities on these days [79]. Aged care homes could be equipped with a 'smoke plan' where appropriate preventative measures based on the concentration of smoke can be detailed. Awareness of, and access to, localised, reliable, real time, user-friendly data is important for residents so that they can minimise their personal exposure to air pollution. The inclusion of air quality, health and activity advice in smart phone apps such as "Air Rater" is an innovation that has been shown to help vulnerable members of the community such as asthmatics.

Very fine smoke particles can penetrate through filtered ventilation systems. The design of ventilation system is critical during persistent smoke events. Ventilation system using efficient filters such as HEPA filters can be effective only if the building construction is relatively airtight (i.e., low ACH). It may not be possible to improve the efficiency of a filtration system simply by replacing a low efficiency filter with a high efficiency filter due to the pressure drop and limited capacity of the air handling system. Additionally, there is cost associated with the use of HEPA filters due to the pressure drop and increased cooling energy. In order to conserve energy, it may be necessary to only apply additional filtration (e.g., HEPA) in response to smoke events, provided filters can be easily retrofitted.

Low-cost particle sensors have been investigated by many researchers. With the advancements in sensor technology and with an increasing number of low-cost sensors available in the market, there is a need for additional studies of sensor performance focused on monitoring particle levels in bushfire smoke. The sensors tested in studies should be compared to reference instruments under the same conditions and in same locations and calibration factors applied that relate to the individual sensor tested as each sensor will have a unique response to smoke. Appropriate correction factors must be applied to ensure data reliability if low cost sensors are used.

Due to the potential adverse health effects of exposure to gaseous pollutants such as benzene and formaldehyde and the lack of studies investigating removal of these pollutants from bushfire smoke future studies should also focus on the benefits of filtration systems for removal of gaseous pollutants from indoor air in addition to particulate matter. However, monitoring individual organic pollutants (e.g., formaldehyde, benzene) at low levels can be difficult and expensive. The development of low-cost sensors capable of detecting individual organic compounds (e.g., formaldehyde) in real time at ppb levels is

another area for exploration [80]. Figure 1 shows the summary of findings from this study highlighting areas of future studies.

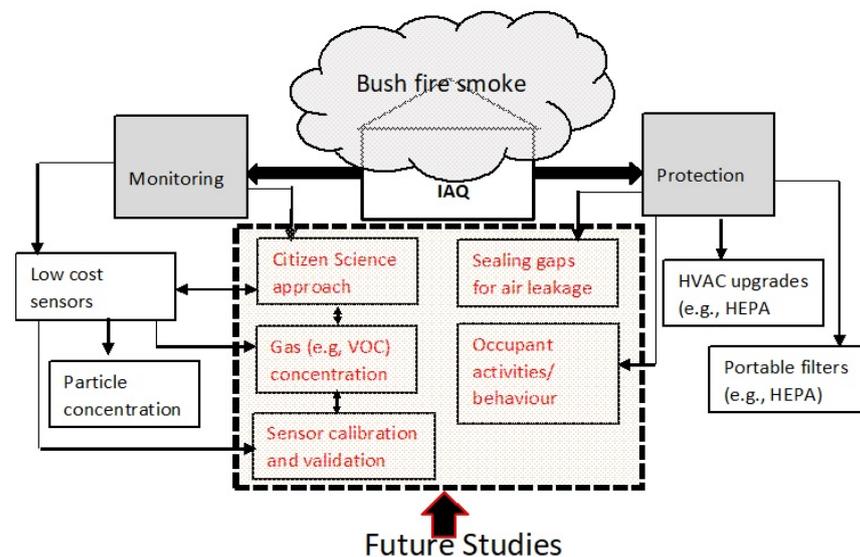


Figure 1. Summary of findings.

Even though it is advised that residential buildings should be constructed to provide an airtight envelope to reduce smoke infiltration, it can be expensive to renovate an entire leaky building to achieve an airtight envelope. Instead of renovating the whole house, the possibility of creating a dedicated indoor "clean air" space (e.g., bedroom) that is protected from smoke intrusion could be explored. This room could include a portable air filter with HEPA filters to remove particles and activated carbon filters for reduction of gaseous pollutants. Citizen science approaches can provide important insights into the effectiveness of low-cost interventions to reduce smoke infiltration into homes. It may be helpful for vulnerable members of the community, such as asthmatics, the elderly, and pregnant women to have access to portable respirators, clean air shelters, and opportunities for temporary relocation.

Studies also demonstrated the importance of reducing smoke pollution from other sources and highlight the need for technologies to improve IAQ even when bushfire smoke is not a threat. For example, Desservettaz et al. [81] compared the atmospheric composition of smoke from domestic wood heaters and hazard reduction burns. The study found no significant differences in the composition but concluded that despite the higher peak pollution levels of hazard reduction, the overall exposure of air toxins was greater from domestic wood smoke due to the greater frequency and total duration of use.

7. Conclusions

This study found that bushfire smoke can substantially degrade residential indoor air quality. While many studies have investigated the use of filtration systems in controlling particle levels, such studies concerning gaseous pollutants are limited. The study revealed that air filtration technologies can be effective at reducing indoor particle levels, although the effectiveness of these depends on many factors, and in particular the leakiness of the building envelope. Many residential buildings in Australia are very leaky (i.e., >15.5 ACH). This is of particular concern as many of these residences are located in densely populated urban areas that can be severely impacted by bushfire smoke. Strategies such as improving the building envelope (e.g., sealing gaps), modifying occupant behavior (e.g., minimizing indoor sources), and increasing awareness of resources (e.g., smartphone apps) can help protect occupants from exposure to bushfire smoke. Areas for future research include evaluations of air filtration technologies focused on the removal of gaseous pollutants within buildings, and calibration and validation of low-cost sensors for monitoring elevated

levels of PM_{2.5} and other pollutants. Also there are limited studies where lay people participate in monitoring and apply various intervention strategies in their home. The use of low-cost sensors by homeowners and participants of citizen science programs will help to deliver real time information to occupants.

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