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# The Connection between Indoor Air Quality and Mental Health Outcomes

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**THE CONNECTION BETWEEN INDOOR AIR QUALITY AND MENTAL HEALTH OUTCOMES**

THESIS

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## Abstract

Mental health among United States citizens, military members, and veterans warrant research into factors not fully considered for their effects on mental health. The built environment is increasingly recognized as a potential influence on the mental health of occupants. Specifically, indoor air quality is theorized to contribute to mental illness. Through the development of a literature review, specific air pollutants common in the built environment were identified, and the mechanisms behind their affect on mental health were explored. A model framework is outlined, estimating the number of cases of major depressive disorder attributable to indoor exposure to particulate matter. The model also performs a benefit-cost analysis of different residential filters, outlining which filter is the most financially efficient for the purposes of reducing major depressive disorder outcomes. Finally, a discussion of particulate matter is elaborated, outlining ways in which engineers and architects, as well as homeowners, can decrease particulate matter concentrations indoors.

**Acknowledgements**

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# THE CONNECTION BETWEEN INDOOR AIR QUALITY AND MENTAL HEALTH OUTCOMES

## I. Introduction

### Background

An alarming global trend is the growing problem of mental health, which impacted over 1 billion people in 2016, and led to 7% of all disability adjusted life years [1]. In the United States, mental health disorders cause the highest medical burden of disease, costing $201 billion in 2013 [2]. United States military members and veterans are victims of mental illness at an even higher rate than their civilian counterparts, committing suicide at 2.1 times the national average, after age adjustments [3]. Amplifying trends in urbanization have resulted in United States citizens spending an average of 93% of their time indoors [4], leading researchers to study factors of the built environment that could be influencing mental health outcomes [5], including indoor air quality [6]. More traditionally thought of as a factor of low self-esteem, physical ailments, and socioeconomic status, among others [7], increasing literature suggests that depression and other mental illnesses could be influenced by environmental factors [8], [9]. Outdoor air quality is already established as a contributor to the physical burden of disease [10], and an expanding amount of research indicates that air pollution has an influence upon mental health outcomes as well [11], [12]. Outdoor air penetrates indoors [13], leading to the possibility that health effects from harmful outdoor air pollutants continue within the confines of the built environment. Evidence exists to suggest that the mental health status of built environment occupants may be influenced by indoor air quality.

**Problem Statement**

Awareness of mental health conditions and causes continue to rise within the United States population, warranting an exploration into indoor air quality as a potential contributor to mental illness. Currently, only a limited amount of research exists or is being conducted that includes indoor air quality as a contributor to mental illness. The extent to which indoor air quality affects the mental health outcomes of building occupants is unclear. Standards for physical health and safety exist for the built environment but fail to include the impacts that indoor air quality has upon the mental health of the occupants. This lack of knowledge justifies research into the role that indoor air quality may play in mental illness.

**Research Objectives**

With the understanding that the purpose of this thesis is to determine indoor air pollutants and their propensity to influence mental health, the research objectives for this paper are as follows:

1. Comprehend common indoor air pollutants and the mechanisms behind their effects on mental illness.
2. Synthesize a framework model that is used to estimate the prevalence to which a specific pollutant impacts mental health on a national scale, and perform a cost benefit analysis of filtration methods for preventing mental health outcomes from said pollutant.

3. Evaluate information found from the first two objectives for applicability to military specific populations.

**The Way Ahead**

This thesis will follow a scholarly format, in order to cover a wide range of research objectives. In Chapter 2, “Indoor Air Quality and Mental Health Outcomes,” a thorough review of current academic research outlines three common pollutants present in indoor air quality. Sources and composition of each pollutant are outlined, and literature is discussed of each pollutant’s influence on physical health, cognitive function, and mental health. Additionally, theorized biological mechanisms behind the pollutants relationship with mental health effects are explored. Chapter 2 concludes with recommendations for further research in this topic. The target journal for this article is Building and Environment.

In Chapter 3, “A Framework for Estimating the US Mental Health Burden Attributable to Indoor Fine Particulate Matter Exposure,” a novel method is introduced that estimates cases of depression expected for specific built environment parameters. The model simulates indoor residential particulate matter concentrations through the utilization of Monte Carlo methods. Furthermore, the simulated concentrations are used as inputs in an epidemiological exposure-response function, estimating the number of cases of depression expected at the given concentration. Lastly, the model compares the cost of different residential filters with the avoidance of mental health effects due to indoor particulate matter exposure, generating benefit-to-cost ratio values for different scenarios. A discussion follows, outlining which scenarios show to be favorable to consider the purchase of a higher quality filter, or to utilize a different means of reducing particulate matter indoors. The target journal for this paper is Indoor Air.

Chapter 4, “The Triple Threat of Particulate Matter in the Built Environment,” is written to an intended audience of military engineers and building professionals, with the goal of synthesizing the information contained within Chapters 2 and 3 into an abbreviated format. Providing the knowledge learned from this thesis is intended to highlight the impacts indoor air quality may have upon mental health. The target journal for this paper is The Military Engineer. Lastly, Chapter 5 presents conclusions and future work.

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## II. Literature Review of Indoor Air Quality and Mental Health Outcomes

### Chapter Overview

The purpose of this chapter is to provide a thorough summary of academic literature pertaining to indoor air quality and mental health. The target audience is building scientists. The article discusses a brief history of indoor air quality, before leading into the main body discussing three common indoor air pollutants: particulate matter, volatile organic compounds, and mold. Each pollutant's impact on physical health, cognitive function, and mental health is summarized, with an exploration into theorized biological mechanisms behind their impact on mental health. The article concludes with recommendations for continuing research on this topic. This chapter provides the bedrock knowledge behind Chapters 3 and 4, establishing the health impacts that are discussed therein.

### Publication Intention

**Title**: Indoor Air Quality and Mental Health Outcomes

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# Indoor Air Quality and Mental Health Outcomes

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**Abstract**

In the United States, nearly one in five adults live with a mental illness, and 44,000 individuals committed suicide in 2016. Neuropsychiatric disorders trail only cancer and cardiovascular diseases as the highest cause of disability adjusted life years in Europe. Such profound health outcomes drive a need for greater understanding of mechanisms that might influence mental health, including possibly the built environment. Particulate matter is generated by common household activities like smoking, cooking, and burning candles or incense. Studies of outdoor particulates have shown that individuals have an increased risk of suicide when exposed to increased levels of particulate matter. This opens the possibility that indoor-generated particulate matter could have an affect on mental health outcomes as well. Additionally, the location of a residence can strongly influence particulate matter concentrations within the home, with homes within 100 meters of a busy roadway having increased concentrations. Volatile organic compounds are emitted by many sources within the built environment, and can affect physical, cognitive, and mental health outcomes. Finally, biological contaminants resulting from water damage in a residence can also have harmful health repercussions. Oxidative stress is hypothesized as the mechanism behind exposure to these contaminants and their affect on mental health, and will be explored in this review. The literature surrounding the physical health effects of indoor air quality is thorough and well studied, yet the connection to mental health is lacking. Future studies of indoor air quality should seek to identify factors that have a direct impact on mental health.

**Introduction**

In the United States, nearly one in five adults live with a mental illness [1]. Individuals with a mental illness have higher odds of committing suicide [2], with 47,173 individuals committing suicide in 2017 [3]. The World Health Organization estimates that 13.6% of disability adjusted life years in the United States are caused by mental illness [4]. Commonly cited influences of mental illnesses include: genetics, brain injury, prenatal damage, substance abuse, trauma, and social problems [5]. One factor not normally considered is the built environment's potential influence. The built environment is the physical aspects of where human beings live, work, and perform activities on a daily basis [6]. North Americans spend approximately 93% of their time indoors [7]. Such a large quantity of time spent in the built environment may influence mental health outcomes as well as physical health and cognitive function. As outlined by Beemer et al. (2019), specific factors of the built environment theorized to impact occupant mental health include personal control, lighting, and indoor air quality [8]. However, due to more research on outdoor air quality than indoor air quality, a review on that literature is warranted.

Previous research concerning outdoor and indoor air quality focused more on physical health impacts rather than mental health impacts. Most air quality research prior to the 18th century was backed by incomplete scientific reasoning that did not understand at that time what different forms of pollutants were [9]. But in 1781, Antoine Lavoisier discovered the role of oxygen to the human body, helping researchers understand that air was composed of multiple substances, and not all of them were necessary for life [9]. A century later, Elias Heyman, a Swedish professor in hygiene, performed ventilation experiments, arriving at the opinion that ventilation was a necessary feature in buildings in order for occupants to remain healthy [9]. Concerns regarding outdoor air pollution began rising in the mid 1900s, prompting Congress to enact the Air Pollution Control Act in 1955, which provided money for research in air pollution [10]. The Clean Air Act in 1963 added more money for research, but more specifically into ways to monitor and control air pollution. The 1970 Clean Air Act allowed the enforcement of new air quality standards, through a new arm of the government, the Environmental Protection Agency (EPA) [10]. As knowledge about outdoor air increases, the EPA updates its standards [10]. However, the EPA has not set standards for indoor air quality.

The sources of indoor air pollutants [11]–[13] depend on the individual characteristics of the building as well as the occupants' habits. Preliminary results from Beemer et al (2019) highlighted potential pollutants that may affect mental health: particulate matter (PM), common volatile organic compounds (VOCs), and biological pollutants due to water damage (i.e. mold) [14]. Each of these pollutants may have an effect on mental health through a direct effect as result of exposure. Two theorized mechanisms behind the effect on mental health are oxidative stress and chronic inflammation [15]. Oxidative stress is an imbalance of free radicals within the human body, and air pollutants can contribute to that imbalance [16]. Oxidative stress has been linked to depression [17]. Chronic inflammation can be exacerbated by air pollution [18], [19], and inflammation is a known contributor to depression and other mental health outcomes [20]. Additionally, PM, VOCs, and mold may have an indirect effect on mental health through poor physical condition induced by the pollutants, and reduced cognitive state induced by the pollutants. Although the focus of this paper is mental health, poor physical health is an established contributor to depression [21] and anxiety [22], and reduced cognitive state is a known contributor to depression and other mental health outcomes [23]. The purpose of this paper is to summarize the literature surrounding indoor air quality and how it relates to mental health.

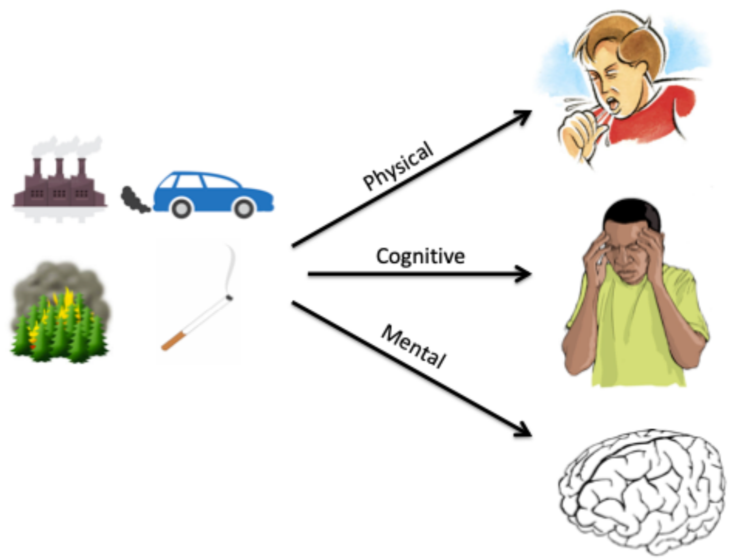


**Figure 1 – Indoor air quality pathways leading to mental health effects**

**1. Particulate Matter**

Outdoor particulate matter (PM) is one of the EPA's six criteria pollutants, meaning it is regulated as a National Ambient Air Quality Standards (NAAQS) from the Clean Air Act. The EPA distinguishes PM in two categories based upon nominal size, $PM_{10}$ and $PM_{2.5}$. $PM_{10}$ includes all particles under 10 micrometers in diameter, while $PM_{2.5}$ contains particles under 2.5 micrometers in diameter [24]. A third size range not recognized by the EPA, but widely cited in scientific literature, is ultrafine particulate matter ($PM_{0.1}$) consisting of all particles with a diameter of 0.1 micrometers or smaller [25].

The physical constituents contained in particulate matter are a function of the particle sizes and source. For particle size, researchers have characterized based on the three particle groups listed above. For example, $PM_{10}$ contains smoke, soil, dust, sea spray, combustion generated, pollen, mold, and spores [26]; $PM_{2.5}$ mostly contains particles generated by combustion [26]; and $PM_{0.1}$ mainly consists of sulphates, nitrates, organic carbons, and elemental carbons [26]. PM composition by emission can vary over time [27]. Indeed, a research team identified soil, sea, traffic, heavy oil combustion, and secondary particles as sources of ambient PM generation in Genoa, Italy, with concentrations varying depending on sample location [27]. Both composition and concentration of the sampled PM varied over time, PM composition and concentration variances were similarly observed in Beijing and Granada, with results specific to location. These studies highlight how PM composition and concentration can differ, based on sources as well as the time of day that sampling occurred [28], [29].

**Proximity to Roads & Greenspace**

Urban and suburban residents may be exposed to higher concentrations of PM due to their residence location, primarily due to the increased amounts of vehicular traffic [30]. For example, wind speed and direction are highly influential on $PM_{0.1}$ concentration at specific sampling locations [31] and vehicular exhaust is the largest contributor to $PM_{0.1}$ concentration near major highways, decaying exponentially with distance away from the road [30]. This is consistent with a study comparing high schools in urban and suburban neighborhoods, in which outdoor $PM_{2.5}$ concentrations were found to be significantly higher in the urban schools due to nearby vehicular traffic levels. Additionally, the outdoor $PM_{2.5}$ concentrations were significantly correlated with the numbers of trucks and buses per hour that drove past the schools, showing again that vehicular exhaust is a major contributor to PM concentrations [32]. PM concentrations can be lowered through the implementation of green space within cities, as a result of PM depositing on trees and foliage. Amount of pollution removed is dependent on the vegetation structure and composition of the green space [33]. While green space is shown to be correlated with reduced mortality rates [34], that result is likely confounded by socioeconomic factors. Research has shown that green space removes approximately 7-10% of air pollution [35], [36], suggesting a positive impact on air quality and related health of nearby residents.

**Relationship between Indoor/Outdoor (I/O) Particle Concentrations**

Previous studies on mental health outcomes in relation to particulates measured outdoor pollutant concentrations. Outdoor particulate monitoring stations provide a regional input on concentrations. Although accurate for those areas measured, outdoor monitors neglects the possibility that the study population may be subject to different concentrations within the built environment. Factors affecting the I/O ratio include building height, floor height, building width and geometric configuration [37], as well as temperature and humidity [38]. A meta analysis of 38 indoor air studies observed the I/O ratio of $PM_{2.5}$ was greater than 1.0. This suggests that airborne particles may be more concentrated within the built environment, which could be resulting in more adverse health effects than are currently estimated [39].

While more efficient filters can reduce the amount of PM entering the indoors via the HVAC system [40], PM concentrations are still increased through common household activities like cooking, smoking, cleaning, and general activity [41]. Smoking is especially impactful, even for residents who are not the actual smoker. Smoking indoors can raise $PM_{2.5}$ levels to more than three times higher than the World Health Organization's recommended limit of 10 micrograms per cubic meter [42].

**Health Effects of Particulate Matter**

Different sizes of PM will accumulate in separate areas of the human body. $PM_{0.1}$ penetrates into the alveoli and terminal bronchioles and can cross the air-blood barrier. $PM_{2.5}$ also penetrates into the alveoli and terminal bronchioles, but does not cross the air-blood barrier. $PM_{10}$ primarily deposits into the primary bronchi. Particles larger than $PM_{10}$ will deposit into the nasopharynx [26]. PM can accumulate in the brain, but the research discussing the health effects it may have from as a result of that accumulation is limited [43]–[45].

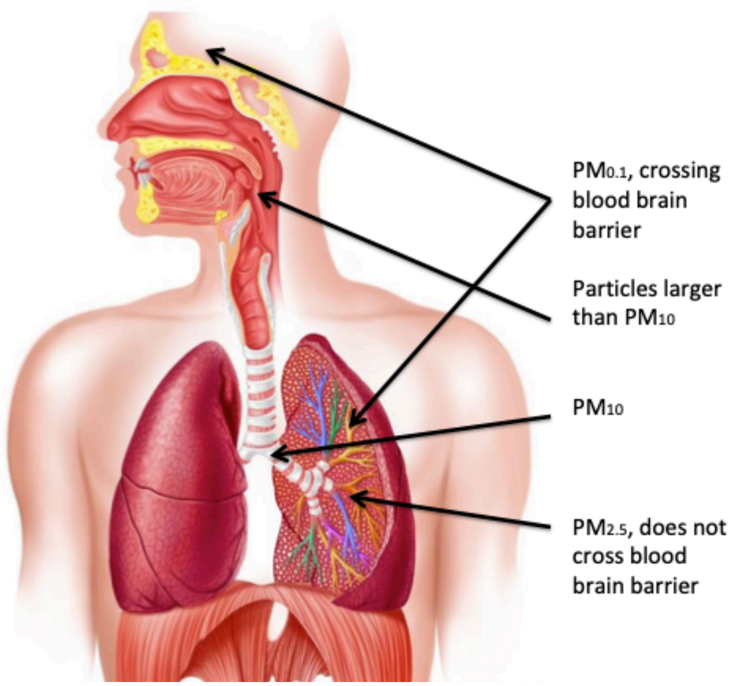


**Figure 2 – Particulate Matter deposition locations within human body**

Credit: Leon Calvetti, Getty Images

PM exposure can lead to physical, cognitive, and mental health effects. While the relationship between indoor air quality and mental health is the focus of this paper, the physical and cognitive effects of poor indoor air quality can subsequently lead to mental health effects.

A growing body of research connects PM exposure to negative mental health outcomes. Kim et al. (2010) showed that increases in outdoor $PM_{2.5}$ and $PM_{10}$ concentrations increased risk of suicide completion by 9% and 10.1%, respectively [46]. Bakian et al. (2015) observed evidence of increased suicide risk due to short-term PM exposure, with interquartile range increases in $PM_{2.5}$ increasing risk of suicide by 5% [47]. PM exposure was also correlated with depression, particularly in individuals already suffering from a chronic illness, such as cardiovascular disease or diabetes [48]–[52]. Increased PM concentrations are theorized to aggravate chronic diseases and inflammation, as well as increase oxidative stress, leading to heightened depression and suicide risk [46], [53]. As part of the Nurses Health Study, researchers studied the effect that PM levels have upon anxiety. Nurses reported increased levels of anxiety in accordance with increased levels of PM exposure [15]. Results from the Nurses Health Study was consistent with results from Pun et al. (2017), who found that anxiety symptoms were a significant outcome among individuals exposed to higher levels of PM, specifically those of low socioeconomic status or suffering from a chronic illness [53].

PM has been more linked in previous research to physical health effects, mainly respiratory issues. Although the focus of this paper is mental health, poor physical health is an established contributor to depression [21] and anxiety [22]. Comprehensive view of physical illnesses due to PM exposure has been previously summarized [25], including specific impacts to asthma [54], [55].

PM exposure can also have negative cognitive health outcomes, and contribute to mental health outcomes [23]. By aiding in the development of cognitive health effects, PM exposure is indirectly affecting mental health. For information regarding PM exposure related to reduced cognitive functions has been reviewed by others [56]–[59]. Specifically, the relationship between PM exposure and Alzheimer's disease has been thoroughly reviewed [60].

**2. Volatile Organic Compounds**

Volatile Organic Compounds (VOC) are chemical substances, which can evaporate under normal indoor atmospheric pressure and temperature due to their low boiling points [61]. VOCs are prevalent throughout the indoor and outdoor environment, since they are components in products, and are produced by combustion and other manufacturing processes [62], [63]. Ambient outdoor levels of VOCs are higher than recommended EPA standards in certain cities, posing health threats to individuals [64], [65].

In 1990, the EPA made amendments to the Clean Air Act [66], which aided in decreasing specific VOC concentrations outdoors, and as such decreasing concentrations indoors [67]. The implementation of the 1990 amendment decreased concentrations of select VOCs to half of 1987 concentrations observed in the EPA TEAM study [68]. Although VOC concentrations can be as much as 10 times higher indoors than outdoors [68], the CDC reports smoking trends in the United States are down to 14.0% of adults in 2017, from 20.9% in 2005 [69]. This suggests a possible decline in indoor VOC concentrations associated with smoking due to an overall reduction in the smoking population. However, E-cigarette use has sharply risen in the past decade [70], and studies show that they too can expose the user to hazardous levels of VOCs [71]–[73]. Cleaning products can also be a source of VOCs. While the total volume of contaminants given off may be low, cleaning products are harmful specifically due to the concentration in which users inhale them, since they are largely used indoors and in close proximity. Cleaning products ingredients may also react with ozone or other contaminants in the ambient air to create secondary pollutants [74].

**Health Effects of Volatile Organic Compounds**

VOCs do not accumulate within the human body due to their typically short half lives [75]. VOCs are instead theorized to cause negative health effects through oxidative stress, as reported in a South Korean study that confirmed higher levels of oxidative stress markers in individuals exposed to VOCs [76]. The following section of this paper will discuss the known mental, physical, and cognitive health effects that VOCs may cause in humans.

Only a few studies have connected VOC exposure directly to mental health outcomes. An animal study showed VOCs correlating with behavioral impairment [77], which is consistent with the limited human studies performed [78], [79]. These studies assessed the toxicity of common indoor VOCs, with behavioral impairment and anxiety being side effects, hypothesized to be caused by oxidative stress [78], [79]. Additionally, VOCs emissions from commercial swine operations have been shown to significantly correlate with increased tension, anger, and depression in individuals residing near the site of operations [80]. Increased VOC concentrations after an office renovation caused panic attacks in one office worker [81]. Workers exposed to VOCs in the form of solvents had a 71% chance of testing for a psychiatric disorder, compared to 10% of those not exposed [82].

VOCs have been more researched in relation to physical health effects, mainly respiratory issues.  By causing negative physical health outcomes, respiratory and other physical illnesses from VOC may be indirectly affecting mental health [21], [22]. Comprehensive discussions have been conducted previously on the connection between physical health and VOCs, namely, respiratory illnesses [83]–[85] and fetal development [86].

Specific VOCs have been studied to assess their affect on cognitive performance. For example, long-term exposure to formaldehyde and benzene decreased cognitive test scores in elderly adults [87], as well as animals [88]–[90].  Additionally, a study involving histology technicians revealed formaldehyde exposure corresponded to reduced memory function and reaction times, with the effects persisting for days after exposure [91].  Chronic petrol sniffing has been shown to expose individuals to high levels of VOCs, including benzene.  Individuals engaging in this activity showed worse visual attention, recognition, memory, and learning measures [92].  Mechanistically, animals exposed to benzene showed inhibition of a specific enzyme in the brain; interestingly, the same enzyme has been associated with Alzheimer's disease [93].

**3. Mold**

Mold is a type of fungus, of which there are 300 known pathogens to humans [94].  The most common varieties found indoors and that may result in health effects of building occupants include Alternaria, Aspergillus, Cladosporium, Penicillium, and

Stachybotrys [95]–[98]. This section will refer to all molds collectively as a potential hazard to human health but recognizes that many varieties are harmless.

Sources

Mold exists as spores, present in the ambient air, but only begins to grow when exposed to adequate amounts of water [99]. Increased water levels occur after natural disasters like hurricane or flooding events, giving the mold adequate moisture to grow in the built environment. Infections or other health effects due to mold also may increase after disasters like tornados or earthquakes, or even routine construction. These events may cause mold spores to be displaced from the location from which they had minimal effect on humans, becoming airborne, where they may be inhaled by those individuals in close proximity [100]. For example, mold sampling efforts two months after Hurricane Katrina in New Orleans revealed that mold concentrations in flooded areas were double those of non-flooded areas of the city. Furthermore, mold concentrations were highest indoors, up to 645,000 spores/m3 [101], and an estimated 46% of the homes in New Orleans had some mold growth after the hurricane [102].

**Health Effects of Mold**

Mold has been reported to affect human health in two ways: causing either an under reaction to exposure, or an over reaction to exposure. An under reaction to mold exposure will result in the immune system failing to recognize the harm mold can cause, allowing sufficient quantities of the mold to enter the body and cause an infection. Contrarily, an over reaction to exposure will result in an inflammatory response, leading to inflammatory diseases [103]. Mold is most dangerous to immunocompromised individuals, such as children, elderly, or those with pre-existing respiratory issues [104].

Mold exposure may also cause oxidative stress in exposed individuals [105]. The following section of this paper will discuss the known mental, physical, and cognitive health effects that mold may cause in humans.

Similar to VOCs, only a small amount of research has connected mold directly to mental health outcomes. There is some evidence that mold directly impacts mental health, independent of physical illness or loss of control [106]. Additional research found the effects of mold exposure similar to those of individuals with mild traumatic brain injuries, with most of the patients exhibiting acute or post traumatic stress symptoms, as well as moderate to severe depression [107], [108].

Mold has a well-established relationship with respiratory diseases, especially asthma. Although the focus of this paper is mental health, poor physical health is an established contributor to depression [21] and anxiety [22]. By causing negative physical health outcomes, respiratory and other physical illnesses from mold exposure are indirectly affecting mental health. Comprehensive views of physical illnesses due to mold exposure have been summarized by others in relation to asthma [109]–[112] and skin inflammation [113], [114].

While not as thoroughly established as the relationship between mold and physical health, a growing body of research is connecting mold to negative cognitive outcomes. By aiding in the development of cognitive health effects, mold exposure is indirectly affecting mental health. For information regarding mold exposure related to reduced cognitive functions, please reference the following studies [107], [115]–[118].

**Conclusion**

The literature references highlighted in this paper highlight the argument that indoor air quality has a significant impact upon mental health outcomes, through three possible channels: indoor air quality's direct effect on mental health, indoor air quality's indirect effect on mental health through poor physical condition, and indoor air quality's indirect effect on mental health through reduced cognitive state. Continued research should focus on which aspects of the built environment affect indoor air quality the most and how engineers and architects can change existing design guides to promote positive mental health outcomes. Future work needs to be done collaboratively across engineering, psychology, and medicine disciplines to bring awareness to the effects that indoor air quality has on mental health, and how certain lifestyle changes can improve those outcomes. Presenting a large enough amount of evidence to federal authorities may encourage the implementation of indoor air quality standards, improving mental health outcomes across all populations.

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# III. A Framework for Estimating the US Mental Health Burden Attributable to Indoor Fine Particulate Matter Exposure

## Chapter Overview

The purpose of this chapter is to detail a model that can be used to estimate the number of cases of major depressive disorder resulting from fine particulate matter exposure in the United States. The model combines indoor particulate matter concentration simulations with an epidemiological exposure-response function, approximating a number of depressive outcomes for the stated input parameters. The values approximated are used in a benefit-cost analysis to determine an optimal economic strategy for the reduction of particulate matter indoors. At the time of this writing, no other model estimates mental health disorders due to indoor particulate matter exposure.

## Publication Intention

**Title**: A Framework for Estimating the US Mental Health Burden Attributable to Indoor Fine Particulate Matter Exposure

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# A framework for estimating the United States depression burden attributable to indoor fine particulate matter exposure

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**Abstract**

Recently published exploratory studies based on outdoor $PM_{2.5}$ indicate that the pollutant may play a role in mental health conditions, such as major depressive disorder. This paper details a model that estimates the United States (US) major depressive disorder burden attributable to indoor $PM_{2.5}$ exposure, locally modifiable through input parameter calibrations. By utilizing concentration values in an exposure-response function, along with relative risk values derived from epidemiological studies, the model estimated the prevalence of expected cases of major depressive disorder in multiple scenarios. Model results show that exposure to indoor $PM_{2.5}$ might contribute to 440,000 cases of major depressive disorder in the US, approximately 2.3% of the total number of cases reported annually. Increasing HVAC filter efficiency in a residential dwelling results in minor reductions in depressive disorders in rural or urban locations in the US. Nevertheless, a MERV 13 filter does have a benefit/cost ratio at or near one when indoor emissions are present, e.g., smoking; during wildfires; or in locations with elevated outdoor $PM_{2.5}$ concentrations. The approach undertaken herein could provide a transparent strategy for investment into the built environment to improve the mental health of the occupants.

## Introduction

The field of mental health research is expanding,[1] with good reason, as one in five Americans adults have a mental illness.[2] One mental illness, major depressive disorder, impacted 17.7 million Americans in 2018[3] and globally was the third leading cause of disability  in 2017.[4] Previous research has focused on risk factors for mental health disorders to include genetics,[5] environment factors,[6] and social determinants.[7] However, another potential contributor to negative mental health outcomes might be found in the built environment.[8] Risk of a negative health outcome is often a function of exposure time, and in the case of the built environment, Americans spend 93% of their time indoors[9] and 70% of the time in their residence.[10]

Major depressive disorder, also called clinical depression, is characterized by a wide variety of symptoms that cause significant distress or impairment that affects individuals for at least two weeks.[11] Symptoms may consist of a persistent sad mood, loss of pleasure derived from or interest in hobbies or routinely pleasurable activities, a poor evaluation of the past, present, future and of oneself, decreased energy, appetite or weight changes, and reduced functioning.[11] Though not as prevalent as major depressive disorder, other unique forms of depression exist, such as persistent depressive disorder, which refers to cases of depression lasting longer than two years, with depressed mood present on more days than not,[11] and seasonal affective disorder (SAD) , which occurs seasonally, with spontaneous remission at the end of the season of vulnerability. The most common one, SAD with a winter pattern, is precipitated by short days and decreased environmental light exposure.[12] Depression frequently co-occurs with other mental health conditions/symptoms, including anxiety and posttraumatic stress disorder.[22,23] Depressed individuals have higher odds of dying by suicide as compared to non-depressed individuals.[24] Risk factors that increase the chance of depression include, but are not limited to, substance abuse, physical ailments, history of depression, and low self-esteem.[25] There is also research showing environmental factors may moderate depressive outcomes, as evident from research in monozygotic twins with non-similar incidences of depression.[26,27]

Exposure particulates that are under 2.5 microns nominal diameter (fine particulate matter or $PM_{2.5}$), are a general health concern, providing the largest contributions to global mortality and morbidity due to air pollution.[28,29] $PM_{2.5}$ is theorized to influence depression and other mental health outcomes through two biological mechanisms, chronic inflammation and oxidative stress.[30] Chronic inflammation is an established contributor to mental health disorders,[31–35] and $PM_{2.5}$ is associated with aggravation of chronic inflammation.[36,37] Inflammatory cytokines and other biological indicators of depression are more prevalent in individuals living in proximity to higher outdoor $PM_{2.5}$ concentrations.[36,37] Oxidative stress is an imbalance of oxygen free radicals within the body. Air pollutants such as $PM_{2.5}$ can increase oxidative stress.[38,39] Specifically, the free radicals are highly reactive, producing harmful by-products and tissue damage.[40] Oxidative stress has previously been connected to mental health outcomes, including depression.[41]

Recent epidemiological studies have estimated the mortality and morbidity associated with outdoor $PM_{2.5}$ exposure.[42–48] Illnesses that may contribute to the burden of disease from $PM_{2.5}$ exposure include respiratory infections, lung cancer, ischemic heart disease, and chronic obstructive pulmonary disorder.[48] Although less studied, exploratory correlations between outdoor $PM_{2.5}$ concentrations and mental health outcomes, including depression, have been noted.[30,49–54] Specifically, long-term exposure to elevated $PM_{2.5}$ concentrations outdoors may increase the risk of depression by approximately 25%[53] and cause an acute depressive response in select individuals.[50]

Outdoor particles enter into the built environment and become indoor $PM_{2.5}$,[55–58] a principle that has been applied in previous prospective studies that have correlated depression with outdoor concentrations of $PM_{2.5}$ measured at central outdoor monitoring stations.[53] However, central monitoring stations in the United States (US) are not ideal for measuring exposure to indoor $PM_{2.5}$ concentrations. To our knowledge, no previous study has modeled indoor concentrations of $PM_{2.5}$ to predict any mental health outcome. In this study, we propose use of an indoor concentration model to assess the impact of HVAC filtration on major depressive disorder, through a reduction in $PM_{2.5}$ exposure. Central filtration systems can abate indoor $PM_{2.5}$ concentrations,[59–64] resulting in disease-related treatment cost avoidance.[65–67] The purpose of this paper was to develop an epidemiological model, using a mass-balance approach for $PM_{2.5}$ concentrations, that estimates the number of major depressive disorder cases attributable to indoor fine particulate matter exposure. This is the first known use of an exposure-response model to estimate cases of depression resulting from indoor $PM_{2.5}$ exposure. Eight case studies were conducted, for varying ambient concentrations and indoor emissions, to explore the influence of $PM_{2.5}$ on major depressive disorder outcomes. The locations used for outdoor particulate matter concentrations were selected to provide a range of potential possibilities and all factors were kept the same, based on US data.

## Methodology

This paper combines an epidemiological exposure-response function and indoor mass balance models to estimate the potential major depressive disorder impacts of indoor $PM_{2.5}$ exposure within a residential setting. To account for spatial variability of model input parameters in the US, Monte Carlo simulation was used to sample from known distributions of residential housing characteristics. Calculated indoor concentrations inform an exposure-response model to estimate the number of cases of major depressive disorder. Furthermore, an economic analysis is performed to identify the tradeoffs between the cost of various minimum efficiency reporting value (MERV) filter technologies, and major depressive disorder treatment cost avoidance. A summary schematic of the process used in the present paper is shown in Figure 1. The modeling process includes eight different scenarios, representative of a range of outdoor $PM_{2.5}$ concentrations and indoor emissions: (1) US average; (2) New York City; (3) Cincinnati; (4) Sacramento; (5) homes with indoor smokers; (6) homes near wildfires; (7) Delhi; (8) Beijing. No parameters were changed between model runs, other than the outdoor $PM_{2.5}$ concentrations and the indoor emissions in the smoking scenario. That is, all other model parameters are characteristic of nationally averaged US housing parameters. Therefore, these different scenarios represent the estimated depressive outcomes to occur if those conditions were present in the US.

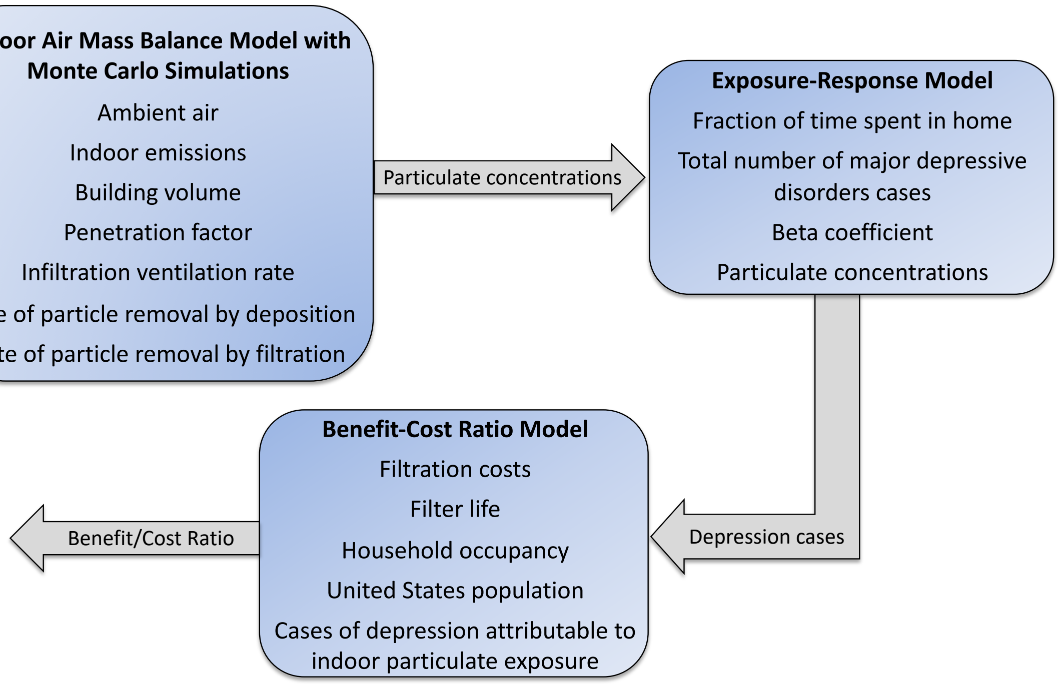


Figure 1 – Description of modeling process with input and output parameters. Blue boxes are for each major calculation, gray arrows are primary outputs.

## Indoor Air Modeling

A mass balance approach was utilized to calculate the concentration of $PM_{2.5}$ within a typical US residence,[65] as shown in Equations 1 and 2. Air within the homes was assumed to be well-mixed, and $PM_{2.5}$ concentrations were assumed to be steady state. All homes were assumed to utilize a forced-air HVAC system, as this is currently the most widely used system in the US.[68]

$$C = C_o \frac{P\,\lambda_V}{\lambda_V+\lambda_D+\lambda_F} + \frac{E}{(\lambda_D+\lambda_F)V} \qquad (1)$$

Where:

$C$ = resulting concentration of $PM_{2.5}$ $(\mu g/m^3)$

$C_o$ = the ambient air concentration of $PM_{2.5}$ $(\mu g/m^3)$

$P$ = penetration factor (unitless)

$\lambda_V$ = infiltration ventilation rate ($h^{-1}$)

$\lambda_D$ = rate of particle removal by deposition ($h^{-1}$)

$\lambda_F$ = rate of particle removal by filtration ($h^{-1}$)

$E$ = total emissions of $PM_{2.5}$ from indoor sources ($\mu g/h$)

$V$ = building volume ($m^3$)

Discrete values for the factors in Equations 1 and 2 are summarized in Table 1. Ambient air concentrations were fit to lognormal distributions, calculated from mean and percentile values from 2018.[69] Cooking was the only source of indoor emissions considered in the analysis. Cooking emissions were averaged over the course of a day in a normal distribution.[70] Home volume was assumed to be normally distributed.[65] Infiltration ventilation rate was fit to a lognormal distribution.[71] Penetration factor and rate of particle removal by deposition were determined from residential studies.[70,72] Penetration factor was determined using a cropped normal distribution, with an upper bound of one. The rate of particle removal by deposition was assumed to be normally distributed.

The rate of particle removal by filtration ($\lambda_F$) in the HVAC system was calculated using Equation 2.[65] Duty cycle was a cropped normal distribution, with a minimum bound of zero.[73] The flow rate through the residential HVAC system was represented by a lognormal distribution, with distribution parameters obtained from two studies of residential housing characteristics.[74,75] Filter particle removal efficiency was assumed constant for each MERV rating,[59] ignoring efficiency changes with increased dust buildup over time.[76]

$$\lambda_F = DH\varepsilon_L \quad (2)$$

Where:

$D$ = duty cycle (unitless)

$H$ = airflow rate through HVAC system, divided by indoor volume ($h^{-1}$)

$\varepsilon_L$ = particle removal efficiency of filter in use (unitless)

Monte Carlo simulation methods were utilized to calculate concentration values and account for variability in the parameters used in Equations 1 and 2. First, distributions were created from the mean and standard deviation values for each parameter. Next, 100,000 concentrations were calculated using Equations 1 and 2, with random values selected from the distributions of each variable. Finally, the calculated concentrations were used to estimate major depressive disorder outcomes in the exposure-response function, detailed below. This process was replicated for each filtration system and each scenario, to understand the influence that filtration has on the estimated prevalence of major depressive disorders.

**Exposure-Response Model**

To quantify the number of major depressive disorder cases that can be attributed to indoor $PM_{2.5}$ exposure, an exposure-response function was utilized, Equation 3.[77]

$$\Delta y = F\, m_o\, (1 - e^{(-\beta * \Delta x)}) \quad (3)$$

Where:

$\Delta y$ = number of adults diagnosed with a major depressive disorder as a result of indoor $PM_{2.5}$ exposure (incidences $year^{-1}$)

$F$ = average percent of day that the population spends in a residence (unitless)

$m_0$ = the number of adults diagnosed with major depressive disorder (incidences year$^{-1}$)

$\beta$ = coefficient of exposure-response function, selected from different epidemiology study results. $\beta = log(RR_{10})/10$, with $RR_{10}$ describing the relative risk for an increase of $10\ \mu g/m^3$ in $PM_{2.5}$ concentration (unitless)

$\Delta x$ = the median $PM_{2.5}$ concentration of the residence, calculated using the results of Equations 1 and 2 ($\mu g/m^3$)

It was assumed that US adults spend 70% of their day within their residence.[10] The number of episodes of depression in the US was based on reports for adults (over 18 years old) in 2018.[78] Beta values were converted from odds ratio values developed from epidemiological studies, summarized in a meta-analysis,[53] which included long-term odds ratio of 1.25 for depression cases associated with $PM_{2.5}$, with a 95% confidence interval of 1.07 – 1.45. Many applications of an exposure-response function utilize a relative risk instead of an odds ratio. Herein the relative risk and odds ratio can be considered equivalent here since the baseline prevalence for depression is low.[53,79] The median $PM_{2.5}$ concentrations were calculated based on Equations 1 and 2. Some exposure-response studies utilize a baseline exposure value in this term, assuming that no adverse health effects occur below a select concentration.[48,77] However, the present analysis assumes a baseline exposure value of zero, practically meaning that any concentration could have an adverse health effect.[42–44]

**Economic Analysis**

To determine the value of indoor air filtration as a method to remove $PM_{2.5}$ for a health benefit, major depressive disorder treatment cost avoidance was estimated.

Downscaling the estimated cost of depressive disorders in the US to individual cases resulted in an average annual cost of $14,926 (2017 dollars) per incidence of major depressive disorder.[80] This cost includes (1) direct costs, such as prescription drugs; (2) indirect costs, such as the value of reduced productivity while at work; (3) and suicide-related costs, including future earnings potential. Multiplying the per-case cost by the estimated number of cases for each scenario yielded a total scenario cost. To determine the value of filtration, particulate matter filtration costs for successively efficient filters were compared to the potential cost avoidance of the reduced numbers of major depressive disorders, using Equation 4. Hereafter, cost avoidance is referred to as benefits, to conform with benefit-to-cost ratio (BCR) methodology, and to avoid confusion between costs of filtration and cost avoidance.

$$FC = \frac{F_i}{S} \quad (4)$$

Where:

$FC$ = annual cost of filter implementation (dollars/capita)

$F_i$ = annual operating cost of filter (dollars)

$S$ = average household occupancy (1.98 people over 18 years old/household)[81]

The total cost of filtration assumes every house in the US has the same filter. Filter operating costs are shown in Supplemental Table 3.[59] The treatment cost avoidance was calculated with Equation 5.

$$B = \frac{(\$MDD - \$MDD_i)}{N} \quad (5)$$

Where:

$B$ = benefit of filtration implementation, per person

$\$MDD$ = baseline cost of major depressive disorder attributable to indoor $PM_{2.5}$ exposure

$\$MDD_i$ = cost of major depressive disorder attributable to indoor $PM_{2.5}$ exposure with different filtration implementations

$N$ = US population over 18 years old (255,190,602)

Calculating both costs and benefits of filtration allows a BCR to be calculated. The baseline cost of major depressive disorder attributable to indoor $PM_{2.5}$ exposure ($\$MDD$) assumes that the home has no filter on the HVAC system, allowing any $PM_{2.5}$ to recirculate within the home without reduction. The baseline cost value is calculated using Equations 1 and 2, with the particle removal efficiency ($\varepsilon_L$) is set to zero. The resulting concentration is entered into Equation 3 to estimate the number of major depressive disorder cases, and then multiplied by the cost of each case of depression ($14,926), ultimately representing the baseline cost of major depressive disorder attributable to indoor $PM_{2.5}$ exposure ($\$MDD$). Repeating this process for each individual MERV rating resulted in the cost of major depressive disorder attributable to indoor $PM_{2.5}$ exposure with different filtration implementations ($\$MDD_i$). The difference between each value and the baseline value, divided by the adult US population ($N$), results in a benefit value per person. All analysis was conducted in R (version 3.6.0)[82] and visualization was completed with the ggplot2 package.[83] R code used for the models and figures is provided in the supplemental information.

**Table 1** – Input parameter values and reference sources for Equations 1, 2, and 3

| **Parameter (variable, units)** | **Values (mean, SD)** | **Source** |
|---|---|---|
| Outdoor air ($C_o$, μg/m$^3$) | Varies by scenario | 84–87 |
| Emissions (E, μg/m$^3$) | 2.62, 1.11 | 70 |
| Building volume (V, m$^3$) | 482, 28.68 | 65 |
| Penetration Factor (P, unitless) | 0.97, 0.06 ‡ | 70,72 |
| Infiltration ventilation rate ($\lambda_V$, hr$^{-1}$) | 0.53, 2.3 † | 71 |
| Rate of particle removal by deposition ($\lambda_D$, hr$^{-1}$) | 0.39, 0.08 | 70,72 |
| Rate of particle removal by filtration ($\lambda_F$, hr$^{-1}$) | Variable | 65 |
| Duty cycle (D, unitless) | 0.153, 0.051§ | 73 |
| Airflow through residential HVAC system (Q, m$^3$/s) | 4.36, 1.44 † | 74,75 |
| Particle removal efficiency of filter in use ($\varepsilon_L$, unitless) | Variable | 59 |
| Percent of day spent within residence ($F$, unitless) | 0.70 | 10 |
| Annual number of major depressive disorder cases ($m_0$) | 17,700,000 | 3 |
| Coefficient of exposure-response function ($\beta$, unitless) | 0.009691 | 53 |
| Median $PM_{2.5}$ concentration of residence ($\Delta x$, μg/m$^3$) | Varied by scenario | Equation 1 |

† - Geometric mean and standard deviation, ‡ - maximum of 1, § - minimum of 0

**Results**

The modeled residential $PM_{2.5}$ concentrations were calculated using Equations 1 and 2, in scenarios of different MERV filter use across the US and in specific US cities (Figure 2A). Resulting concentrations (see Supplemental Figures 1-8) and the median levels in the present model were lower than estimated values in other studies modeling indoor $PM_{2.5}$,[65,88] and measured concentrations in US residential environments.[56,89]

The modeled concentrations for alternate scenarios (indoor smoking, wildfires, and non-US cities) of different MERV filters are shown in Figure 2B. The scenarios of Bejing and Delhi use actual concentrations but are hypothetical since the building and major depressive disorder parameters are based on a US population to enable direct comparisons to US cities. The wildfire scenario shows the highest indoor concentrations of any scenario. Measurements of $PM_{2.5}$ emissions from wildfires vary,[85,90,91], and, notably, the selected concentrations are high. Wildfires aside from the incident modeled in this analysis may not have the same concentration levels and impact on indoor $PM_{2.5}$, and subsequently, health effects. The Delhi and Beijing scenarios, as expected, show modeled indoor concentrations substantially higher than any of the US scenarios. The results from this analysis were not expected to closely resemble indoor concentrations of $PM_{2.5}$ in Delhi or Beijing, since the residential housing parameters used were representative of US homes. Indeed, the calculated median indoor concentration with no filter present (mean ± SD, 41.3 ± 176.5 $\mu g/m^3$) had a lower mean than one study's measurement of $PM_{2.5}$ levels in Delhi homes of (mean ± SD, 57.7 ± 40.8 $\mu g/m^3$).[92] Studies of residential housing in Beijing also showed higher $PM_{2.5}$ concentrations than in the model.[93,94]

The use of HVAC filters reduced the indoor concentrations of $PM_{2.5}$ in the US city scenarios from a no-filter condition by an average of approximately 8%, 18%, 24%, 31%, and 34%, for MERV 7, MERV 8A, MERV 8B, MERV 12, and MERV 13, respectively (Figure 2A). Similar results were observed in the alternate scenarios; namely, filters reduced the modeled concentrations of $PM_{2.5}$ in alternate scenarios by an average of approximately 9%, 18%, 22%, 26%, and 32%, for MERV 7, MERV 8A, MERV 8B, MERV 12, and MERV 13, respectively (Figure 2B). Other studies of filtration efficiency vary in estimates $PM_{2.5}$ removed when passing through the filter of the HVAC system,[64,95] but they are consistent in the determination that increasing MERV ratings lowers indoor concentrations of $PM_{2.5}$.

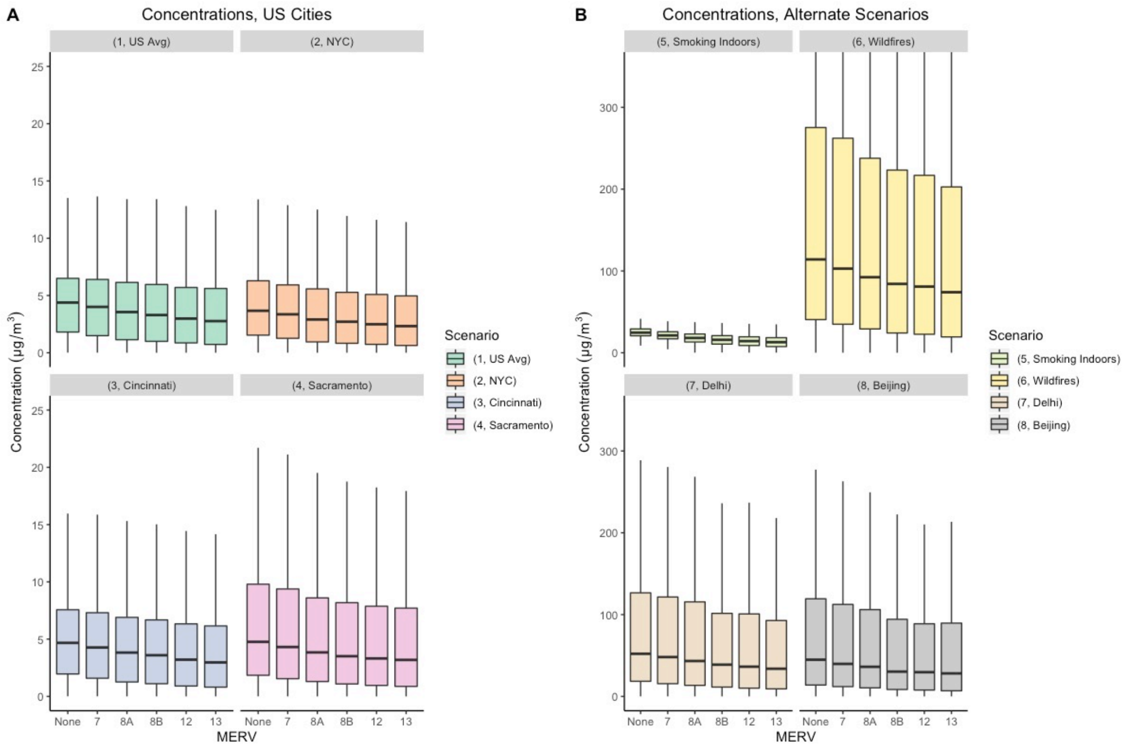


Figure 2 – Modeled indoor $PM_{2.5}$ concentrations across filters for A) United States cities and B) indoor smoking, wildfires, and non US Cities.

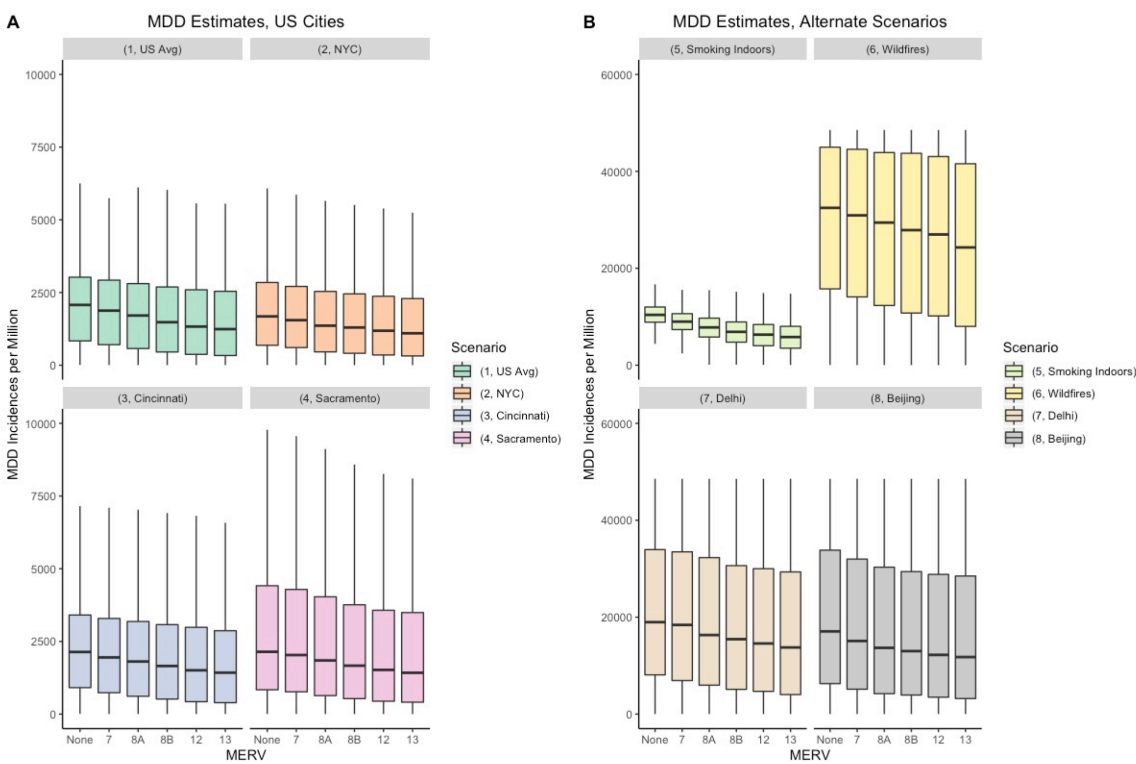

Figure 3 – Incidences per million people of major depressive disorder attributable to indoor $PM_{2.5}$ exposure across filter systems for A) United States cities and B) alternate scenarios.

Figures 3A and 3B display the estimated incidences of major depressive disorder per million people, attributable to residential $PM_{2.5}$ exposure. The estimated cases of major depressive disorder in the model of the US average scenario is approximately 2.3% of the total number of major depressive disorder cases in the US, annually. Figure 4 highlights the results of BCR calculations for implementation of different filtration systems in each scenario. BCR was generally higher in scenarios with higher indoor $PM_{2.5}$ values. Moreover, the filter with MERV rating 8B had the highest BCR among all scenarios, due to the balance of low price and relatively high removal efficiency.

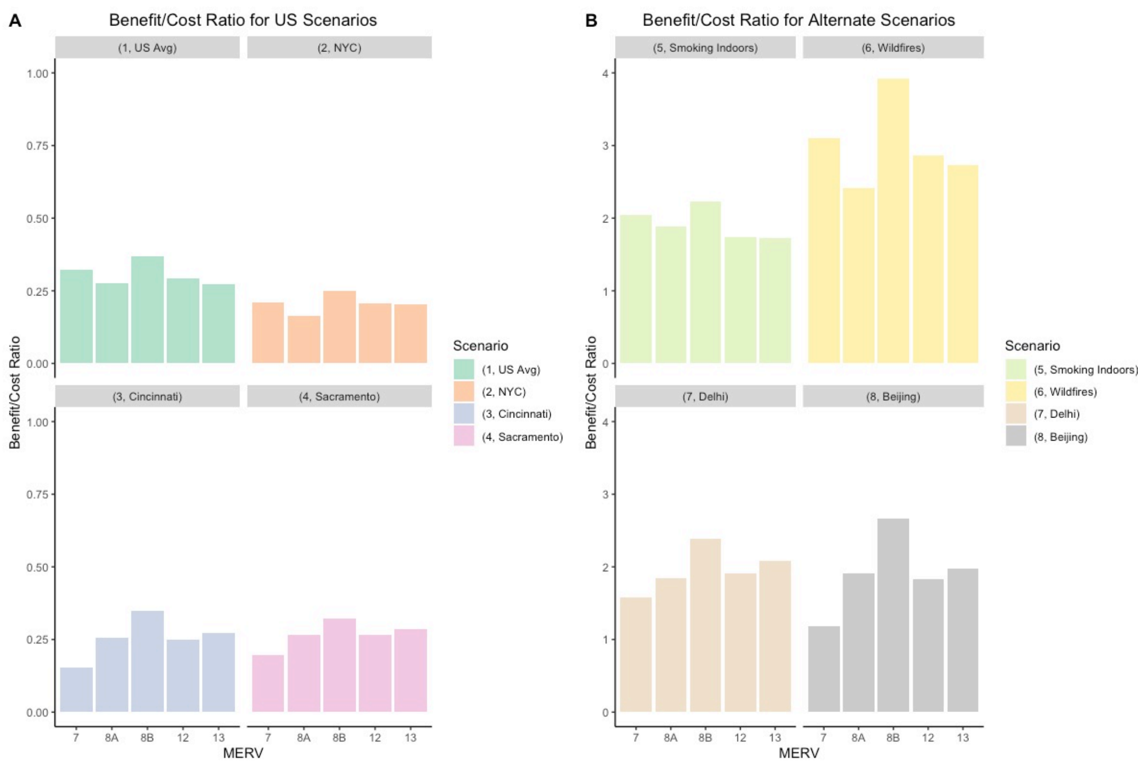


Figure 4 – Benefit/cost ratios (BCRs) for filter implementation in each scenario.

For a direct comparison of the use of filters to impact the incidence of major depressive disorder, the same model parameters were used for each scenario. A comparison was made on the percent reduction in estimated incidence of major depressive disorder between no filter to MERV 7 in US (Figure 5A), and alternate scenarios (Figure 5C), and then again from MERV 7 to MERV 13 in US (Figure 5B), and alternate scenarios (Figure 5D). The percent reduction in US cities scenario from zero filtration to a MERV 7 was independent on the outdoor concentration and the 90$^{th}$ quartile was at 25.5% reduction in cases of major depressive disorder. In contrast, reduction from MERV 7 to MERV 13 in US scenarios has more distribution in the percent reduction, with the 90$^{th}$ quartile at 67.8% reduction in cases of major depressive disorder. The alternate scenario with elevated outdoor $PM_{2.3}$ concentrations did have some differences due to outdoor concentration levels.

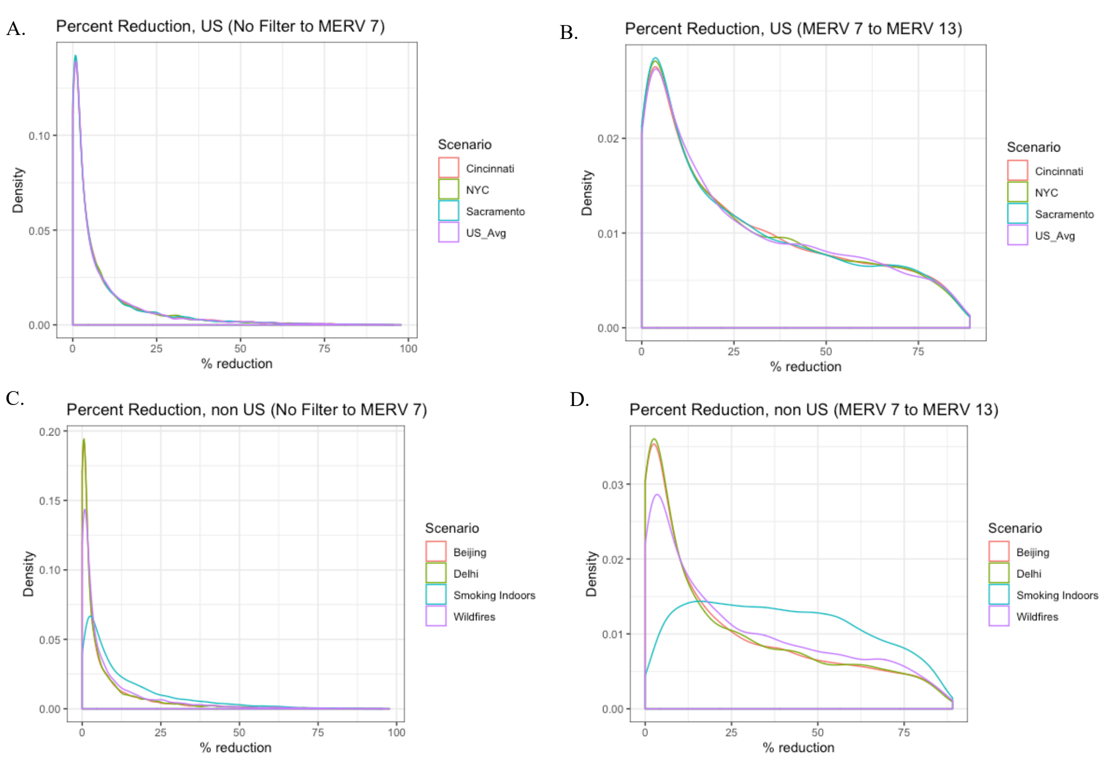

Figure 5 – Percent reduction in estimated incidence of major depressive disorder due to $PM_{2.5}$ in A) US cities, based on concentration levels from no filter to MERV 7, B) US cities, based on concentration levels from MERV 7 to MERV 13, C) alternate scenarios based on concentrations levels from no filter to MERV 7, D) alternate scenarios based on concentrations levels from MERV 7 to MERV 13.

**Discussion**

Indoor $PM_{2.5}$ concentrations were estimated using a mass balance approach, varying building parameters with Monte Carlo simulations. The resultant concentrations then provided an estimate of expected cases of major depressive disorder in an epidemiological exposure-response function. The BCR was based on a comparison of expected treatment costs avoided and the cost of residential filters, in order to determine which filter provided the best return on investment. Finally, the percent reduction in major depressive disorder was estimated based on increased filter efficiency. The analysis provides a framework for researchers to include major depressive disorder and other mental illnesses in burden of disease studies.

The model estimates for concentrations of indoor $PM_{2.5}$ might be lower then previously reported, providing a conservative estimate for major depressive disorders due to indoor pollutants in the present study. For example, the model estimates for the US average scenario with a MERV 7 filter calculated an indoor to outdoor (I/O) ratio of 0.51. This was lower than values reported in a meta-analysis of IO ratios[96] (mean 0.92). The smoking scenario with a MERV 7 filter installed resulted in a median $PM_{2.5}$ concentration of 21.1μg/m$^3$. Two studies measuring indoor $PM_{2.5}$ concentrations in smoking households found median concentrations of 31 μg/m$^3$ [97] and 27.7 μg/m$^3$.[98] However, the outdoor concentration levels of $PM_{2.5}$ have been declining which might have some influence in the comparisons.[84] The calculated median indoor concentration with no filter present (mean ± SD, 41.3 ± 176.5 μg/m$^3$) had a lower mean than one study's measurement of $PM_{2.5}$ levels in Delhi homes of (mean ± SD, 57.7 ± 40.8 μg/m$^3$).[92] Studies of residential housing in Beijing also showed higher $PM_{2.5}$ concentrations than in the model.[93,94] Aside from the higher outdoor $PM_{2.5}$ concentrations in both of these cities, another large contributing factor to the measured high indoor concentrations could be the emissions from the burning of biomass and solid fuel, which is a primary source of residential heating and cooking fuel in both cities.[99,100]

A lowering of major depressive disorders and impacts on filter efficiency was correlated to indoor emissions. It was observed that increases in filter efficiency had a higher impact on $PM_{2.5}$ concentrations in the smoking scenario compared to other scenarios, due to the emission of indoor $PM_{2.5}$ as opposed to outside contamination that is reduced by the build envelope. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) recommends at least a MERV 7 filter in residential buildings.[101] However, in 2015 ASHRAE published new recommendations for residential units to install MERV 13 filters or higher in guideline 24-2015. The model estimates presented here reinforce that guidance, suggesting a change from a MERV 7 to a MERV 13 filter could create a meaningful difference in reducing major depressive disorder cases due to $PM_{2.5}$ levels.

While it does not appear there are any other studies estimating the impact that indoor $PM_{2.5}$ has upon depressive outcomes, comparisons to morbidity and mortality studies show similar trends to what was observed in this study. Specifically, a positive relationship exists between $PM_{2.5}$ concentrations and health outcomes.[48] A recently published meta-analysis of $PM_{2.5}$ exposure and mental illness[79] included a population attributable fraction (PAF) model. The model estimated that the United Kingdom's rate of depression could be reduced by 2.5%, if the ambient $PM_{2.5}$ concentration dropped from 12.8 $\mu g/m^3$ to the World Health Organization's recommended limit of 10 $\mu g/m^3$.[102] However, the PAF model does not account for the lower levels of $PM_{2.5}$ concentrations experienced in indoor environments, as shown in this analysis, suggesting that the 2.5% reduction could be an overestimate. The caveat to that statement is when indoor emissions of $PM_{2.5}$ is present at meaningful levels (e.g. smoking).

Although the BCRs are below 1.0 for all of the US city scenarios, this analysis does not include the benefit of filtration for the purposes of avoiding any physical diseases associated with $PM_{2.5}$, such as asthma,[59] lung cancer,[66] or chronic obstructive pulmonary disease,[103] suggesting that these are again conservative estimates. Since these BCRs are calculated based on median concentration values, variation in actual scenarios exist, with higher BCRs in some homes, and lower BCRs in others. For sensitive individuals, alternative means of filtration, used in addition to HVAC filters, may be an effective solution. Alternative means of filtration include portable air cleaners,[62,104,105] activated carbon filters,[106,107] or even green walls.[108,109] An economic analysis of filtration methods for reducing $PM_{2.5}$ found that portable air filters had a mean BCR between 7.7 and 13, and provided more of a reduction in expected mortality rates than just HVAC filters alone.[110]

Chronic inflammation and oxidative stress are both thought to contribute to depression and other mental health outcomes, and air pollutants other than $PM_{2.5}$, such as volatile organic compounds and mold, are associated with both of these mechanisms.[111–114] $PM_{2.5}$ is also shown to influence gut microbiome profiles,[115] which some literature proposes are connected to mental health outcomes.[116,117] This introduces the possibility that poor indoor air quality could be contributing to more cases of depression than were estimated with this model. Although $PM_{2.5}$ comprises the bulk of disease due to poor air quality,[29] it cannot be ruled out that other pollutants may increase the burden of disease. Future models estimating depressive risk due to indoor pollutants should seek to include other pollutants in addition to $PM_{2.5}$.

Sensitivity analysis was performed on the odds ratio, the variable parameter in the model that was not considered in the Monte Carlo simulations. Maintaining the other parameters in the exposure-response function constant, the odds ratio has a strong influence on the predicted incidence of major depressive disorder in the model. The confidence interval bounds from the odds ratio (1.07, 1.45) in the average US concentrations with a MERV 7 filter produced an estimated number of major depressive disorder cases of 158,439 and 845,484, respectively. A difference of that magnitude in the model estimates highlights the urgent need to refine the relationship between $PM_{2.5}$ and depression in large population studies.

The model described in this paper was created to be adaptable to estimate major depressive disorder outcomes within other populations. To be as accurate as possible, mass balance input parameter distributions would need to be created for the population set to be analyzed. That is, estimates would need to be considered on parameters in Table 1 that are specific to the population of interest. Additionally, the total number of major depressive disorder cases within the region would replace the value used in this paper (17,700,000), and the population of the region would replace the value used in this paper (255,190,602). Finally, costs of residential air filters could be sourced for the area in order to create accurate BCR results.

**Limitations**

As this is the first known epidemiological model connecting indoor $PM_{2.5}$ concentrations and depression, we acknowledge there are several limitations in the present study. First, the relationship between $PM_{2.5}$ exposure and depressive outcomes is not clearly defined yet. A limited number of meta analyses of the relationship between $PM_{2.5}$ and depression are currently published, and they differ in their results of pooling odds ratios from the available epidemiological studies, with values of 1.10,[79] 1.12,[118] and 1.25.[53] In comparison, statistics from the more well-researched relationship between $PM_{2.5}$ and lung cancer mortality are more precise, with values of 1.11 (RR),[119] 1.11 (RR),[120] 1.14 (OR),[121] and 1.14 (RR).[46]

While the relationship between $PM_{2.5}$ and major depressive disorder may not be as robust as that between $PM_{2.5}$ and physical health, it is becoming increasingly clear there exists a relationship between the two variables. Establishing a causal relationship between $PM_{2.5}$ exposure and depressive outcomes via an exposure-response function can be accomplished through additional epidemiological studies. All $PM_{2.5}$ exposure was assumed to result in the same magnitude of depressive outcomes, regardless of source specific $PM_{2.5}$ and evidence exists to suggest that this is a reasonable assumption.[48]

$PM_{2.5}$ levels were assumed as a snapshot in time, but it is acknowledged that while $PM_{2.5}$ concentrations have been decreasing across the US, they are increasing worldwide,[122] and may remain elevated in the US due to scenarios such as proximity to wildfires or environmental regulation changes. In addition, other models of indoor air quality calculate duty cycle based on site location and typical heating and cooling loads.

This analysis forgoes this method and represents the variability in duty cycle values with the Monte Carlo sampling. Due to the analysis being applied to an annual period, the duty cycle was more accurately represented as a distribution. Cooking and smoking were the only sources of indoor $PM_{2.5}$ considered in this analysis, due to their well-documented emission values.[70,97,98,123] Other activities may also contribute to indoor $PM_{2.5}$ concentrations, such as cleaning or occupant movement.[124] However, these activities were considered too variable to include in this analysis. As a result, the calculated $PM_{2.5}$ concentrations and major depressive disorder estimates may be a conservative estimate, and not representative of all $PM_{2.5}$ sources potentially present in the indoor environment.

$PM_{2.5}$ composition may vary based on source apportionment,[125–127], and estimates of morbidity and mortality assume that all $PM_{2.5}$ provides the same level of toxicity.[48] Current literature suggests that there is no relationship between $PM_{2.5}$ composition and toxicity,[128] and that magnitude of exposure is the sole predictor for health effects. However, it is possible that composition of $PM_{2.5}$ may affect major depressive disorder outcomes in a manner different from physical mortality and morbidity, changing the estimation of major depressive disorder provided described within this analysis. Microbial components and endotoxins are present in some sources of $PM_{2.5}$,[129] potentially another source of influence on major depressive disorder outcomes[130] through inflammatory mechanisms.[131,132]

Finally, indoor $PM_{2.5}$ concentrations were assumed to occur in a well-mixed environment. In reality, residential homes can be poorly mixed, and some areas of the home will experience higher concentrations of $PM_{2.5}$, while others will have lower concentrations. This variability is accounted for in the Monte Carlo simulations, via random sampling of the distributed parameters. However, select indoor activities may cause a spike in $PM_{2.5}$ concentrations and exposure, such as cooking or resuspension of $PM_{2.5}$ due to cleaning. These spikes in $PM_{2.5}$ concentration may increase risk of acute depressive symptoms, but the epidemiological data does not exist to accurately model that impact. Specifically, the model described in this paper was not applied to analyze acute depressive symptoms due to indoor $PM_{2.5}$ exposure, but evidence exists to suggest that some effect occurs.[53,79,118]

**Conclusions**

The results of this analysis highlight the role that $PM_{2.5}$ has upon depressive outcomes. An estimated 2.3% of all depressive cases represents a small, yet important proportion, in that the outcome is controllable, lowered through the reduction of outdoor and indoor $PM_{2.5}$ concentrations. The model described herein could be used to estimate the influence that $PM_{2.5}$ exposure has upon other mental illnesses, provided those illnesses have established relationships (ORs or RRs) with $PM_{2.5}$. These results raise the question of how impactful other indoor air pollutants are on mental health outcomes. While $PM_{2.5}$ has the highest contribution to mortality estimates of air quality,[28,29] other pollutants may have a higher degree of impact on mental health outcomes. This model can be utilized to estimate mental health outcomes resulting from other indoor air pollutant exposure as well, furthering understanding of the effects of indoor air quality on mental illness.

Future research may want to include socioeconomic status, as it may represent a potential confounding factor in linking analysis of particulate matter with major depressive disorder. For example, people of lower socioeconomic status are more likely to live in areas of higher air pollution,[133] have poor quality homes that potentially lead to higher rates of pollutant exposure,[134] and higher rates of depression.[135] Moreover, smoking is a more popular activity among less affluent groups,[136] and is associated with depression.[137–139] Additionally, socioeconomic status has an established relationship with physical morbidity,[140–142] itself a risk factor for mental illness.[143] Yet not all confounders are negative. For instance, household size is larger in areas of lower socioeconomic status,[144] which would result in shared benefit of a higher quality filter for additional people at reduced per-capita cost.

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## Supplemental Information

### Scenario Differences

The methods described are used to generate estimates of the number of cases of major depressive disorder in the US that would occur if the listed ambient air and indoor emission values were present across the entire country. The different scenarios and their respective ambient air and indoor emission values are listed in Supplemental Table 1.

Supplemental Table 1 – Scenario specific values

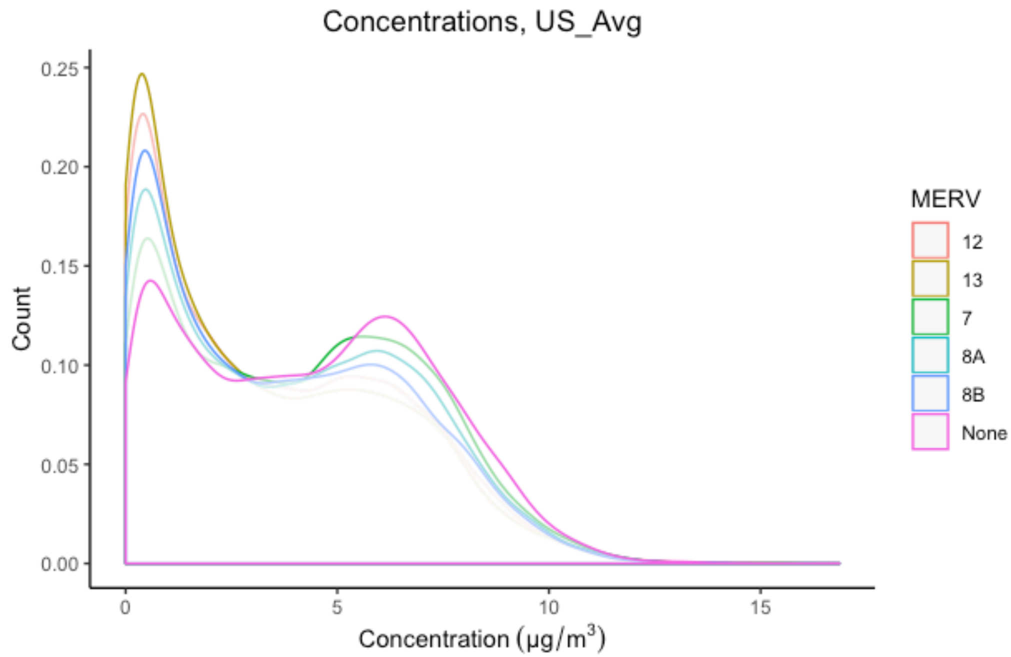
| Scenario | **Outdoor Ambient Air** ($\mu g * m^{-3}$) (mean, 98$^{th}$ percentile) | **Indoor Emissions** ($\mu g * h^{-1}$) (mean, SD) |
|---|---|---|
| United States Average | 8.159, 10.47† | 2.62, 1.11 |
| New York City | 7.4, 19 | 2.62, 1.11 |
| Cincinnati | 9.3, 20 | 2.62, 1.11 |
| Sacramento | 10.8, 53 | 2.62, 1.11 |
| Smoking Indoors | 8.159, 10.47† | 3784.38, 539.58‡ |
| Homes Near Wildfires | 37.5, 2.1 | 2.62, 1.11 |
| Delhi, India | 125.5, 77.2 [86] | 2.62, 1.11 |
| Beijing, China | 107.4, 84.4 [87] | 2.62, 1.11 |

† - 90$^{th}$ percentile
‡ - Assumes one individual smokes 14 cigarettes per day [145], for an average of 5 minutes per cigarette [146]

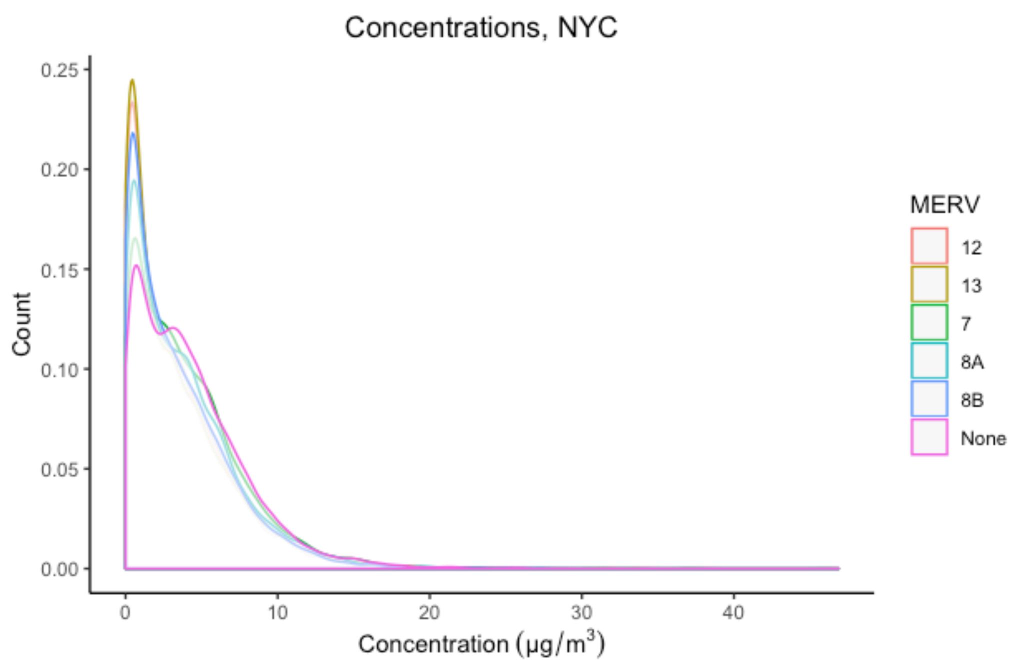
Supplemental Table 2 – Individual Filter Information

| Filter | Annual Operating Costs ($) | Particle Removal Efficiency (unitless) |
|---|---|---|
| No filter | 0 | 0.00 |
| MERV 7 | 20 | 0.07 |
| MERV 8 (A) | 40 | 0.20 |
| MERV 8 (B) | 45 | 0.35 |
| MERV 12 | 70 | 0.50 |
| MERV 13 | 80 | 0.65 |

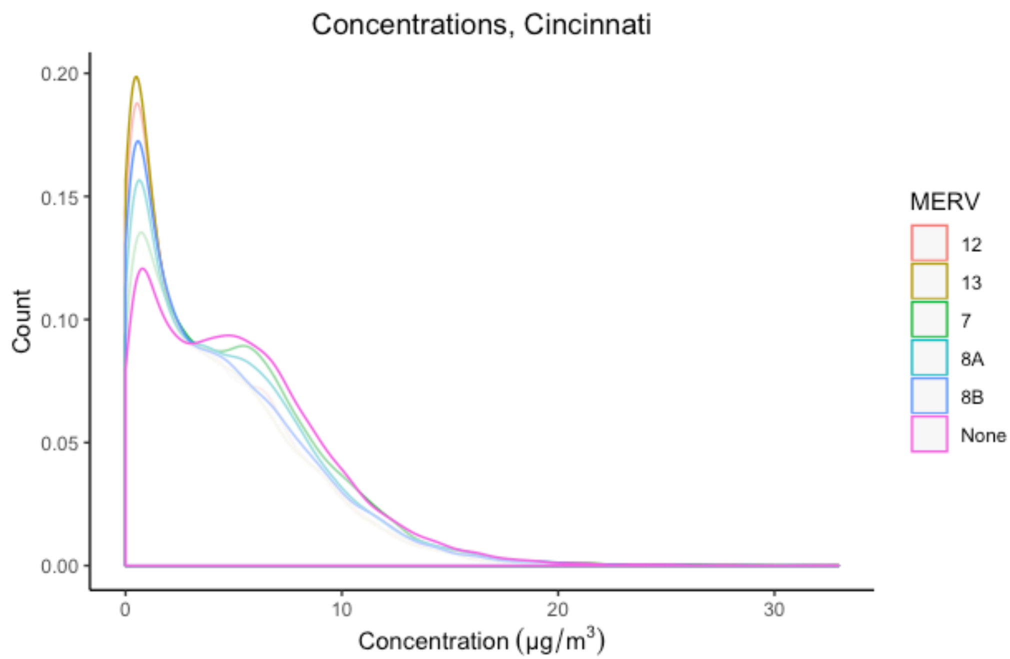
**Concentration Distributions**



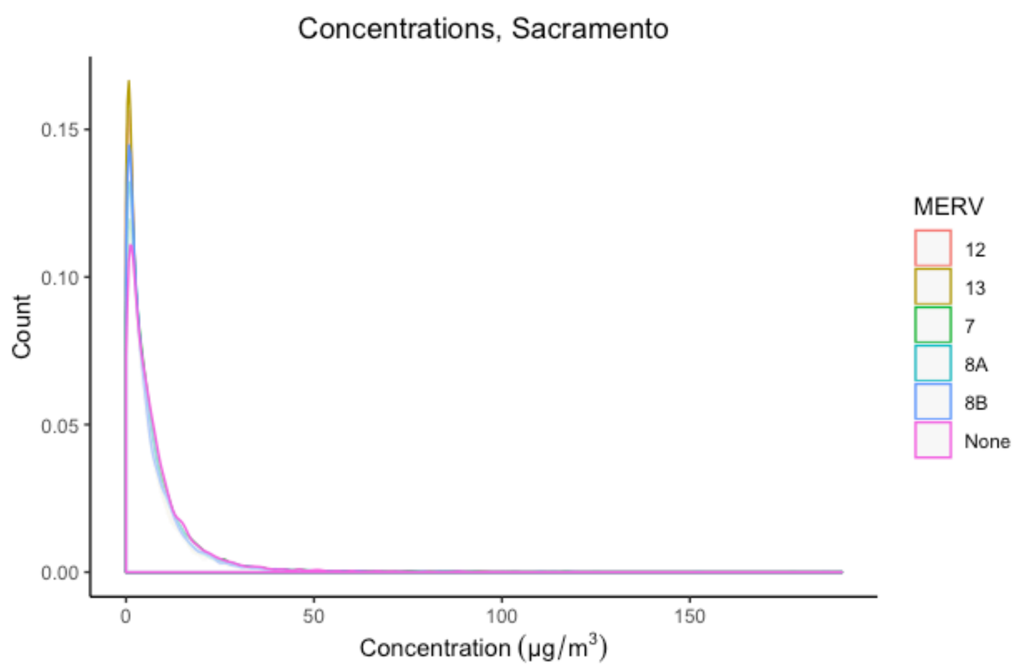

Supplemental Figure 1 – Density plot of calculated $PM_{2.5}$ concentrations for US Average Scenario



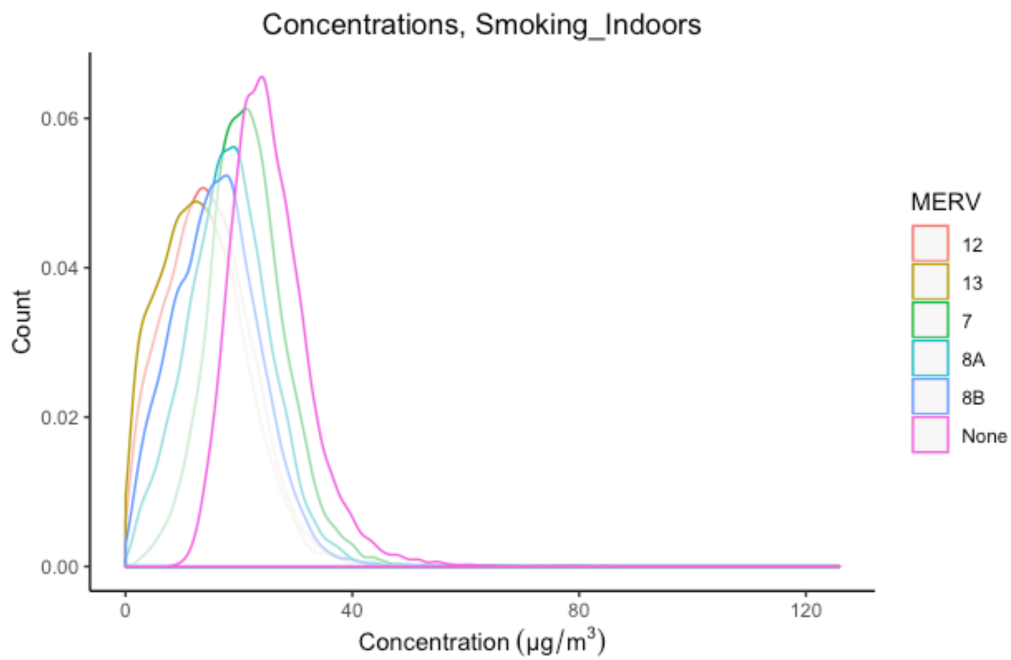

Supplemental Figure 2 – Density plot of calculated $PM_{2.5}$ concentrations for NYC Scenario



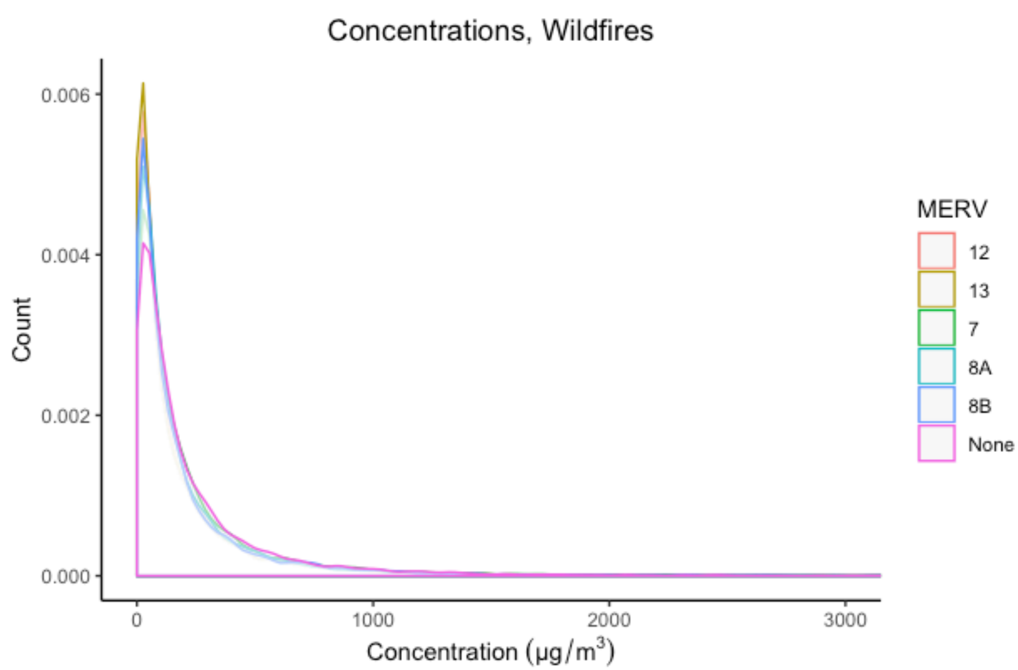

Supplemental Figure 3 – Density plot of calculated $PM_{2.5}$ concentrations for Cincinnati Scenario



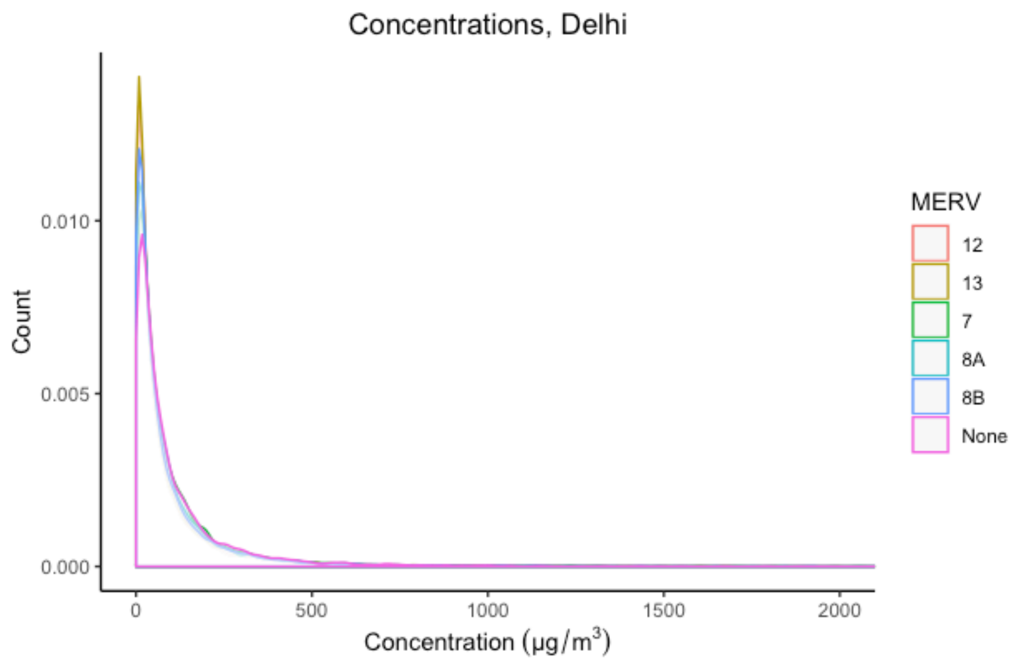

Supplemental Figure 4 – Density plot of calculated $PM_{2.5}$ concentrations for Sacramento Scenario



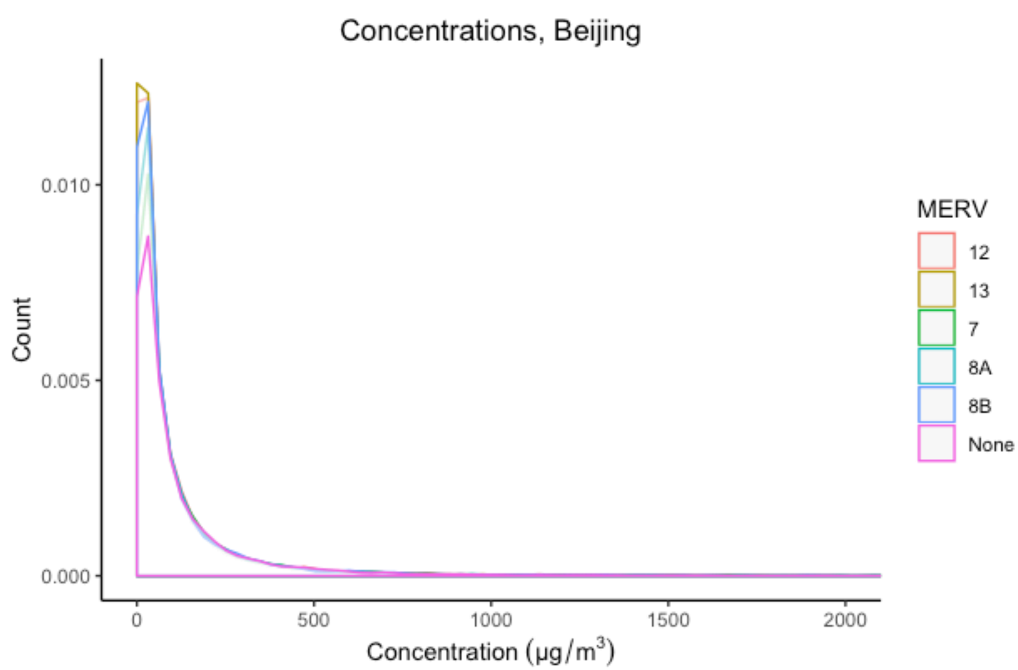

Supplemental Figure 5 – Density plot of calculated $PM_{2.5}$ concentrations for Smoking Indoors Scenario




Supplemental Figure 6 – Density plot of calculated $PM_{2.5}$ concentrations for Wildfires Scenario




Supplemental Figure 7 – Density plot of calculated $PM_{2.5}$ concentrations for Delhi Scenario




Supplemental Figure 8 – Density plot of calculated $PM_{2.5}$ concentrations for Beijing Scenario

**R code used for model and figures**

```
library(lognorm)

N=100

MDDdata <- NULL



#--------------------------------------------------------------

#Ambient Air information for each scenario

A_name <- c("(1, US Avg)","(2, NYC)","(3, Cincinnati)","(4, Sacramento)","(5,
Smoking Indoors)","(6, Wildfires)","(7, Delhi)","(8, Beijing)")

A_median_log <- c(8.159, 7.4, 9.3, 10.8, 8.159, 273.6, 125.5, 107.4) #mean from data

A_value_at_percentile <- c(10.47, 19, 20, 53, 10.47, 440, 202.7, 191.8) #Upper bound

A_percentile <- c(0.90, 0.98, 0.98, 0.98, 0.90, 0.68, 0.68, 0.68) #note fraction

Ambient_Air <- data.frame(A_name, A_median_log, A_value_at_percentile,
A_percentile) #place all the values into a dataframe


S <- getParmsLognormForMedianAndUpper(A_median_log, A_value_at_percentile,
sigmaFac = qnorm(A_percentile)) #converts to a lognormal dist from info given

Log_df<- data.frame(S) #placed into dataframe


log_dist <- rlnorm(100000,Log_df[6,1],Log_df[6,2]) #test

qplot(log_dist, bins = 100) #visual check
```

```
#-------------------------------------------------------------

#Emissions information for each scenario

E_name <- c("US_Avg","NYC","Cincinnati","Sacramento","Smoking
Indoors","Wildfires","Delhi","Beijing")

E_mean <- c(2.62, 2.62, 2.62, 2.62, 3784.38, 2.62, 2.62, 2.62)

E_SD <- c(1.11, 1.11, 1.11, 1.11, 539.38, 1.11, 1.11, 1.11)

Emissions_df <- data.frame(E_name, E_mean, E_SD)

#-------------------------------------------------------------

#MERV Ratings information

filter <- c("None", "7", "8A", "8B", "12", "13")

eff <- c(0,0.07,0.20,0.35,0.50,0.65)

MERVRatings_df <- data.frame(filter, eff)

#-------------------------------------------------------------

#Exposure Response Information

F <- 0.70 #fraction of day spent in residence

mo <- 17700000 #annual number of MDD cases in US (2018)

B <- 0.009691 #converted OR

#-------------------------------------------------------------

#Monte Carlo

for (X in 1:8){ #cycling through the different scenario information, ambient air and
emissions

  for (n in 1:6){ #cycling through the different MERV ratings

    for (i in 1:N){ #monte carlo sampling
```

```
    Co <- rlnorm(N,Log_df[X,1],Log_df[X,2]) #lognormal dist ambient air
    E <- rnorm(N,Emissions_df[X,2],Emissions_df[X,3]) #Emissions
    E <- ifelse(E<0,0,E) #crop to minimum of 0
    V <- rnorm(N,482,28.68) #building volume
    P <- rnorm(N, 0.97,0.06) #penetration
    P <- ifelse(P > 1,1,P) #crop to maximum of 1
    I <- rlnorm(N, meanlog = log(0.53), sdlog = (2.3)) #uses geometric mean and geoSD
to create lnorm dist
    Q <- rlnorm(N, meanlog = log(4.36), sdlog = (1.44)) #HVAC flow rate, also
lognormal
    Dep <- rnorm(N,0.39,0.08) #deposition
    Efficiency <- MERVRatings_df[n,2]
    D <- rnorm(N,0.153,0.05) #duty cycle
    D <- ifelse(D<0,0,D) #crop to minimum of 0
    Concentration <-
Co*((P*I)/(I+Dep+D*Q*Efficiency))+E/((Dep+D*Q*Efficiency)*V)
    MDD_cases <- F*mo*(1-exp(-B*Concentration))
    MERV <- (MERVRatings_df[n,1])
    Scenario <- (Ambient_Air[X,1])
    MDDdata <- rbind(MDDdata, data.frame(MDD_cases, MERV, Scenario))
   }
  print(Efficiency)
 }
```

```
}
US_adults <- 255190602 #number of people 18 and older
#figure displaying incidences per million people, in US cities
US_cities_MDD_df <- subset(MDDdata, Scenario =="(1, US Avg)" | Scenario =="(2,
NYC)" | Scenario == "(3, Cincinnati)" | Scenario == "(4, Sacramento)")
US_cities_MDD_df$MDD_cases <-
US_cities_MDD_df$MDD_cases/US_adults*1000000


colors <- c("(1, US Avg)" = "#B3E2CD", "(2, NYC)" = "#FDCDAC", "(3, Cincinnati)" =
"#CBD5E8", "(4, Sacramento)" = "#F4CAE4")
Fig2a <- ggplot(US_cities_MDD_df, aes(x=MERV, y=MDD_cases, fill=Scenario))+
  geom_boxplot(outlier.size = -1) +
  ggtitle("MDD Estimates, US Cities") +
  coord_cartesian(ylim=c(0,10000)) +
  scale_fill_manual(values =colors) +
  scale_x_discrete(limits=c("None","7","8A","8B","12","13")) +
  facet_wrap(~ Scenario, ncol = 2) +
  theme(plot.title = element_text(hjust = 0.5), panel.grid.major = element_blank(),
panel.grid.minor = element_blank(), panel.background = element_blank(), axis.line =
element_line(colour = "black"))+
  labs(x = "MERV", y = "MDD Incidences per Million")
Fig2a
#figure displaying incidences per million people, in non US cities
```

```
colors1 <- c("(5, Smoking Indoors)" = "#E6F5C9", "(6, Wildfires)" = "#FFF2AE", "(7,
Delhi)" = "#F1E2CC", "(8, Beijing)" = "#CCCCCC")
non_US_cities_MDD_df <- subset(MDDdata, Scenario == "(5, Smoking Indoors)" |
Scenario =="(6, Wildfires)" | Scenario =="(7, Delhi)" | Scenario =="(8, Beijing)")
non_US_cities_MDD_df$MDD_cases <-
non_US_cities_MDD_df$MDD_cases/US_adults*1000000

Fig2b <-ggplot(non_US_cities_MDD_df, aes(x=MERV, y=MDD_cases, fill=Scenario))+
  geom_boxplot(outlier.size = -1) +
  ggtitle("MDD Estimates, Alternate Scenarios") +
  coord_cartesian(ylim=c(0,60000)) +
  scale_fill_manual(values =colors1) +
  scale_x_discrete(limits=c("None","7","8A","8B","12","13")) +
  facet_wrap(~ Scenario, ncol = 2) +
  theme(plot.title = element_text(hjust = 0.5), panel.grid.major = element_blank(),
panel.grid.minor = element_blank(), panel.background = element_blank(), axis.line =
element_line(colour = "black"))+
  labs(x = "MERV", y = "MDD Incidences per Million")
Fig2b

plot_grid(Fig2a, Fig2b, labels = "AUTO")
```

# IV. The Triple Threat of Particulate Matter in the Built Environment

## Chapter Overview

The purpose of this chapter is to promote awareness of the mental health effects that indoor air quality, specifically particulate matter, may have upon building occupants. Traditionally, building standards have only considered occupant physical health in design and construction. Discussing the factors that influence particulate matter concentrations within the built environment is key to informing engineers and architects of their role in addressing the mental health crisis within the military. This chapter is written with a target audience of civilian and military engineering personnel.

## Publication Intention

**Title**: The Triple Threat of Particulate Matter in the Built Environment

**Publication**: The Military Engineer

## The triple threat of particulate matter in the built environment

**William Taylor, Capt, USAF; Lisa A Brenner, Department of Veteran Affairs; Andrew Hoisington, Lt Col, USAF**

*Captain William Taylor is an Air Force Civil Engineering Officer currently pursuing his master's degree in engineering management at the Air Force Institute of Technology (AFIT). Capt Taylor is researching mental health and air quality under the tutelage of AFIT assistant professor Lt Col Andrew Hoisington. Dr. Lisa Brenner and her team at the Department of Veteran Affairs Rocky Mountain Mental Illness Research Education Clinical Center (MIRECC) provided crucial guidance and assistance for this research.*

Air quality is a broad term that is often referenced as having health implications, yet many people may not understand the mechanisms behind those health effects. Atmospheric air is naturally composed of a handful of elements, including nitrogen, oxygen, argon, carbon dioxide, and trace amounts of other gases. Over time, anthropogenic activities have increased a few of these other gases to potentially harmful levels. In the mid 20th century, scientists and healthcare researchers began to recognize the effects that some of these gases were having on humans. As a result, the Clean Air Act of 1963 was passed, eventually to fall under the authority of the Environmental Protection Agency (EPA) established seven years later. The EPA identified six criteria pollutants to regulate, including sulfur dioxide, carbon monoxide, ozone, nitrogen dioxide, lead, and particulate matter. Of these, particulate matter current shows the most consistent relationship with health effects.

Particulate matter (PM) is small particles of solid or liquid matter prevalent in the air. PM consists of a wide variety of types of material, such as dust, bacteria, smoke, ash, smog, and heavy metals, and can originate naturally or be produced from anthropogenic sources. Common sources of PM include wildfires, dust storms, industrial activities, construction or demolition, and the burning of fossil fuels. PM is categorized into three groups: $PM_{10}$ consists of particles smaller than 10 micrometers, $PM_{2.5}$ consists of particles smaller than 2.5 micrometers, and $PM_{0.1}$ consists of particles smaller than 0.1 micrometers. PM may contribute to impairments to physical health, cognitive function, or mental health, as outlined in proceeding paragraphs.

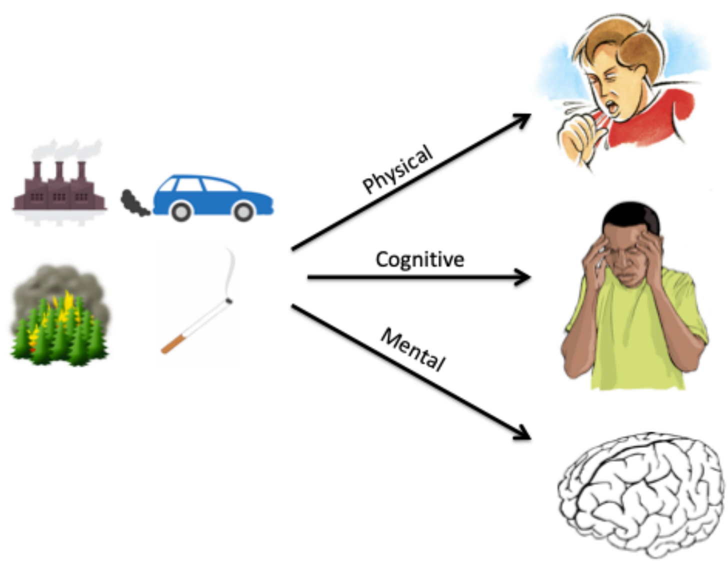



**Figure 1 – The triple threat of air pollution: physical, cognitive, and mental health**

Researchers estimate that $PM_{2.5}$ caused 4.2 million deaths worldwide in 2015, making it the fifth highest mortality risk factor. The resultant loss of life is primarily through damages to physical health. In particular, there is a connection between $PM_{2.5}$

exposure and cardiovascular or respiratory diseases, such as lower respiratory infection, lung cancer, ischemic heart disease, cerebrovascular disease, and chronic obstructive pulmonary disorder. Additionally, $PM_{2.5}$ can exacerbate asthma conditions and contribute to the onset of bronchitis. Chronic $PM_{2.5}$ accumulation can cause result in the aforementioned health effects through a variety of biological mechanisms, by penetrating into the lungs and depositing into the alveoli and bronchioles, or entering into the bloodstream.

Academic research has also shown that $PM_{2.5}$ is associated with reduction in cognitive function. When PM deposits within the body, it can lead to chronic inflammation, which is associated with cognitive decline. A study of elderly adults showed that general cognition, attention, and memory scores declined at faster rates where PM concentrations were higher. Some preliminary studies have even linked $PM_{2.5}$ exposure as a risk factor for Alzheimer's disease. Autopsies of deceased individuals living in cities with high $PM_{2.5}$ concentrations showed biologically relevant inflammatory markers regularly associated with Alzheimer's disease. The mechanism behind this relationship is unclear, but one theory suggests that chronic inflammation of the respiratory tract alters the levels of certain proteins within the bloodstream. These proteins cause the brain to develop chronic inflammation, leading to Alzheimer's.

A growing body of research is also working to connect $PM_{2.5}$ exposure to mental illnesses. Anxiety, depression, and suicide all have population level studies that show their association with $PM_{2.5}$ exposure, with both impacts being acute and chronic exposure. Researchers can utilize Geographical Information Systems to measure and model concentrations in specific areas, and compare the PM levels found with the mental health records of patients residing in area. This helps them to identify trends and explore the potential effects that PM may influence. For example, a study of over 70,000 women found that symptoms of anxiety were higher in women who lived in areas of higher $PM_{2.5}$ concentration. Research in South Korea identified long-term $PM_{2.5}$ exposure as a risk factor for depression, as well as suicide. Large spikes in the study's measured $PM_{2.5}$ concentrations increased the risk of suicide by 9% within the next two days, especially among individuals already suffering from a cardiovascular disease. Commonly cited theories for the biological connection between mental health and $PM_{2.5}$ include chronic inflammation and oxidative stress, which is an imbalance of certain chemicals within the body. Oxidative stress and chronic inflammation have been shown to correlate with depression and other mental health outcomes.

Even though most of the $PM_{2.5}$ that is harmful to humans is generated by outdoor sources and processes, the majority of our exposure comes through our time within buildings. $PM_{2.5}$ penetrates through leaks in the building envelope, and is recirculated indoors by the HVAC system. There are some common indoor activities that can generate $PM_{2.5}$ as well, such as smoking, cooking, and cleaning. Although engineers and architects have little to no control over the outdoor concentrations of $PM_{2.5}$, design and construction decisions can be made that promote the reduction of this harmful pollutant within the confines of the built environment.

While $PM_{2.5}$ enters buildings through leaks in the building envelope, higher Minimum Efficiency Reporting Value (MERV) filters can reduce the amount that circulates through the HVAC system. Higher MERV filters are more expensive than the minimum MERV 6 filter that ASHRAE recommends, but benefit/cost analysis studies show that the increase in price is warranted by the reduction in costs due to health effects. Installing these filters is an important first step in eliminating a large portion of indoor $PM_{2.5}$. We modeled indoor $PM_{2.5}$ concentrations for a research project and found that upgrading from a MERV 6 to a MERV 13 filter reduced indoor $PM_{2.5}$ concentrations by approximately 20%. Architects and engineers can take further steps in eliminating PM exposure indoors through design and construction techniques that eliminate infiltration, which happens when PM passes through small openings in the building envelope.

Individuals can take measures at home to reduce indoor PM concentrations as well. A portable air cleaner is a small device that can filter the air in a small portion of a building or home. In some scenarios, it may be beneficial to purchase and operate a portable air cleaner, mainly when occupants are sensitive to poor air quality or are in poor health. In this scenario, a portable air cleaner may provide a positive return on investment, lowering their expected health costs through the reduction of some of the $PM_{2.5}$ they may be inhaling. Additionally, homeowners should ensure that emissions from indoor cooking are properly removed through fume hoods vented outdoors. Some literature exists to suggest that gas stoves contribute to indoor PM emissions as well; installation of an electric stove instead of a gas range would mitigate these emissions. Lastly, omitting obvious sources of PM indoors such as smoking or burning incense will reduce indoor PM concentrations, if those activities were previously present.

Veterans experience PTSD and other mental health disorders at a higher rate than civilians. Aside from the traumas and stressors of military life, the different environmental factors that military members are exposed to could be influencing this higher rate of mental illness. For example, deployments to the Middle East expose military personnel to higher concentrations of ambient PM in the form of dust. The Air Force Institute of Technology and the Department of Veteran Affairs Rocky Mountain

Mental Illness Research Education Clinical Center (MIRECC) have partnered to study the impact that the built environment has upon military members. Veterans and active duty members have been surveyed to compare aspects of their residences to their mental health state. Identifying trends in the responses may reveal aspects of the built environment that are having effects on mental health, and future design and construction standards can utilize this information to positively impact the mental health of building occupants.

Engineers can have a measurable impact on indoor air quality, through implementation of tactics in our own facilities, as well as through supporting policy that reduces $PM_{2.5}$ and other airborne pollutants worldwide. Improved standards for industrial and automobile emissions could reduce $PM_{2.5}$ concentrations. In developing countries, finding ways to supply citizens with electricity would eliminate the emissions created from burning biomass for heating and cooking. Lastly, developing effective strategies for preventing and containing wildfires would reduce ambient $PM_{2.5}$ in certain environments. These choices can have a positive impact on the physical, cognitive, and mental health of building occupants. Providing awareness of the impact that air quality has upon health is the first step, and promoting healthy buildings through design choices is the next.

## V. Conclusions and Recommendations

### Conclusions of Research

Identifying common indoor air pollutants and analyzing their propensity to influence mental health led to following research objectives:

1. Comprehend common indoor air pollutants and the mechanisms behind their effects on mental illness.

2. Synthesize a framework model that is used to estimate the prevalence to which a specific pollutant impacts mental health on a national scale, and perform a cost benefit analysis of filtration methods for preventing mental health outcomes from said pollutant.

3. Evaluate information found from the first two objectives for applicability to military specific populations.

Answering the first question required a thorough review of academic literature pertaining to the topic of indoor air quality and mental health. "Indoor Air Quality and Mental Health Outcomes" highlighted three separate common indoor air pollutants, particulate matter, volatile organic compounds, and mold. Coming to the conclusion that these pollutants all may influence physical health, cognitive function, and mental health, and that physical health and cognitive function have an impact on mental health, leads to the recognition that mental health is influenced through three separate channels due to indoor air quality. Some confounding variables exist in this research, however. Most studies of air quality and health rely on outdoor sampled concentrations, while the majority of exposure happens within the built environment, the same concentrations of exposure may not exist indoors. These outdoor sampled concentrations are also assumed to apply to all individuals near the sample point, when in reality, personal exposures may be much different. Additionally, most studies of air quality and health do not account for the composition of particulate matter, which may influence physical, cognitive, and mental outcomes. Refining epidemiological studies of air quality and health may lead to more conclusive results in literature and applications.

The second research objective is addressed in Chapter 3 “A Framework for Estimating the US Mental Health Burden Attributable to Indoor Fine Particulate Matter Exposure.” Based on knowledge gained from Chapter 2, an indoor mass balance model was combined with an exposure-response function, generating an estimated number of major depressive disorders for selected building parameters. The model found that indoor fine particulate matter exposure may account for 2.3% of major depressive disorders in the United States. Furthermore, increased ambient concentrations and indoor emissions of fine particulate matter were found to influence the number of estimated cases of major depressive disorder. These results suggest that built environments with higher indoor concentrations of fine particulate matter may be a higher risk for occupant development of major depressive disorder. A further economic analysis portion of the model estimated that in the average United States home, it is not beneficial to buy to a filter rated higher than the ASHRAE recommended MERV6 solely for the purposes of avoiding major depressive disorder. However, the calculated benefit-to-cost ratios did not include the economic worth of avoidance of physical disease, or loss of cognitive function, due to fine particulate matter exposure. In some situations, the value of avoiding mental health outcomes does justify the purchase of a more efficient filter, such as in localities where outdoor concentrations of fine particulate matter are relatively high, or where consistent wildfires occur, or in homes with smokers. Individuals who are especially sensitive to air quality changes may also benefit from purchasing a more efficient filter, especially when the physical and cognitive effects of air quality are taken into account. These results stress the potential that air quality, specifically fine particulate matter, may influence mental health outcomes. The outcomes of this study may give legitimize additional research of epidemiological studies such as those used in the model.

Chapter 4, "The triple threat of indoor air quality" addresses the third and final research objective. The chapter gives background knowledge on sources of fine particulate matter, biological mechanisms behind the effects of exposure on health, and discusses how military members may be at more risk for exposure. Furthermore, a discussion is had regarding the effects of filtration on indoor fine particulate matter concentrations, followed by recommendations of methods to reduce indoor concentrations. Acknowledgment of the relationship between indoor air quality and mental health may be critical for addressing a portion of the veteran mental health abundance.

**Significance of Research**

Although a large amount of work has been done to understand the factors associated with mental health, the influence of environmental factors is not well validated. The research performed in this thesis adds to the literature regarding air quality and mental health, particularly in providing the first known estimation of the prevalence of major depressive disorder due to indoor fine particulate matter exposure. Providing a reference point for future studies of a similar topic can create a robust understanding of the relationship described herein. With a relationship between mental health and indoor air quality established, strategies can be implemented within the engineering community that continue to improve indoor air quality, and lessen impacts upon mental health. Strategies may include more effective whole building filtration, as extensively described in Chapter 3, or the use of portable air cleaners, green walls, or activated carbon filters. These strategies can positively impact both military and civilians, but may be more influential upon military in certain environments of higher exposure. While indoor air quality represents only a small amount of the factors affecting mental health, it is a controllable variable. For military members, especially in deployed environments, reducing risk factors for mental illness is of the utmost importance, and any potential reduction in risk is worth pursuing.

**Recommendations for Future Research**

Future research should seek to refine the relationship between fine particulate matter exposure and mental health outcomes, to include exploring the effects that different compositions of particulate matter may contribute. Odds ratios or relative risks for the relationship between fine particulate matter and other mental illnesses, such as anxiety or insomnia, can be developed through population studies, allowing the model described in Chapter 3 to estimate the affect $PM_{2.5}$ has upon their prevalence as well. More accurate pollutant exposure estimates can help to refine these associations. A model that incorporates relationships between all traditional pollutants, and their relationships with physical, cognitive, and mental health, would give the most comprehensive understanding of the influence that air quality has upon human health. More thoroughly investigating the biological mechanisms behind these health impacts may also provide new avenues of prevention and treatment. The findings presented in this paper could be implemented in healthcare risk assessment, flagging individuals living in areas with poor air quality, or as already suffering from a comorbid respiratory disease, as increased risk patients to develop mental illnesses.

For the Department of Defense, studies could be done to analyze if there is a significant relationship between mental health outcomes of military members exposed to poor air quality environments versus members not exposed. Finding significance may provide justification for implementation of methods to reduce poor air quality exposure, whether through whole building filtration, devices that reduce personal exposure, or other design and construction strategies.