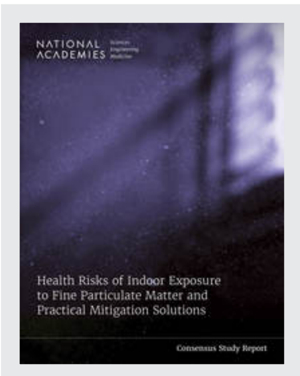

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Health Risks of Indoor Exposure to Fine Particulate Matter and Practical Mitigation Solutions

Committee on Health Risks of Indoor Exposures to Fine Particulate Matter and Practical Mitigation Solutions

Program Office

National Academy of Engineering

Consensus Study Report

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Summary

The COVID-19 pandemic taught many hard lessons. Among the most prominent of these was the tight connection between the indoor environment and health. People learned that schools, workplaces, businesses, and even homes were places where someone could be subjected to a hazard simply by breathing.

Among the indoor exposures that presents a concern. is particulate matter (PM)—a mixture of solid particles and liquid droplets found in the air. PM is a ubiquitous pollutant comprising a complex and ever-changing combination of chemicals, dust, and biologic materials such as allergens. Of special concern is fine particulate matter ($PM_{2.5}$)[1], PM with a diameter of 2.5 microns (<0.0001 inch) or smaller. Fine PM is small enough to penetrate deep into the respiratory system, and the smallest fraction of it, ultrafine particles (UFPs), or particles with diameters less than 0.1 micron, can exert neurotoxic effects on the brain.

Overwhelming evidence exists that exposure to $PM_{2.5}$ of outdoor origin is associated with a range of adverse health effects, including cardiovascular, pulmonary, neurological and psychiatric, and endocrine disorders as well as poor birth outcomes, with the burden of these effects falling more heavily on underserved and marginalized communities. Although it has been relatively poorly studied to date, indoor exposure to $PM_{2.5}$ is gaining increased attention, particularly given that Americans spend the vast majority of their lives indoors and that indoor $PM_{2.5}$ levels can exceed outdoor[2] levels.

Against this backdrop, the U.S. Environmental Protection Agency (EPA) asked the National Academies of Sciences, Engineering, and Medicine to convene a committee of scientific experts to consider the state-of-the-science on the health risks of exposure to fine particulate matter indoors along with engineering solutions and interventions to reduce risks of exposure to it, including practical mitigation strategies. EPA requested that the committee focus on residential settings but also consider schools and other non-industrial indoor environments where appropriate.

FRAMEWORK AND ORGANIZATION

Chapters 1 and 2 of the report provide introductory and background information, including the committee's full statement of task and synopses of previous National Academies studies on the indoor environment. Chapter 3 discusses the sources and composition of indoor particulate matter, while Chapter 4 covers particle dynamics and building characteristics that influence indoor PM. Chapters 5, 6, and 7 describe, respectively, exposure to indoor PM, the

[1] "Fine particulate matter", "fine PM", and "$PM_{2.5}$" are used interchangeably throughout this document.

[2] "Outdoor" and "ambient" are used interchangeably throughout this document.

health effects of that exposure, and practical mitigation solutions to such exposure. Social, economic, and cultural differences affect every aspect of these issues—what and how much fine PM people are exposed to, the circumstances in which that exposure occurs, the effects that exposure has on their health, and the opportunities for employing mitigation measures—and it thus addressed throughout the report. Major findings, conclusions, and recommendations are collated in Chapter 8.

REPORT SYNOPSIS

Human exposure to fine PM and the subsequent health effects are complex and require a systems approach for understanding and developing appropriate practical mitigation strategies. The cascade of events leading to health impacts starts with $PM_{2.5}$ sources (intrusion of outdoor sources into the indoor environment or PM generated from indoor sources), so understanding the nature of these sources as well as their size distributions and compositions is important. Once particles are emitted, they are transported away from the source, mixed into the indoor space, distributed to different parts of a building, and may be exhausted to outdoor air, deposited onto indoor surfaces, or captured by filters in a mechanical system, standalone air cleaners, or even personal protection equipment (PPE) in the breathing zone of an individual. Particles may also be transformed as they migrate through an indoor atmosphere or following deposition onto surfaces. Such processes affect the concentration, size distribution, and composition of $PM_{2.5}$ that building occupants are exposed to. These factors, along with the frequency and duration of exposure, influence the health effects caused by the inhalation of indoor fine PM, including ultrafine particles.

Sources of Indoor Fine Particulate Matter

Fine PM sources are the drivers for exposure, health effects, and the need for mitigation. As noted, they include outdoor particles that penetrate indoors as well as those emitted directly from indoor sources. Data and modeling suggest that particles of both outdoor and indoor origin contribute almost equally to indoor fine PM concentrations when measured by mass. In contrast, the number concentrations for indoor UFPs are dominated by indoor sources. During acute events such as wildfires, particles of outdoor origin may dominate indoor $PM_{2.5}$ concentrations. Inhabitants of homes with underlying housing quality issues often have larger exposure both to outdoor-origin fine PM—because of such factors as proximity to sources of industrial emissions and highways and increased natural ventilation and leakage—and to indoor-origin PM, owing to greater occupant and indoor source densities.

Indoor sources are dynamic and vary by frequency of occurrence, frequency of use, emission source strength, composition, the size distribution of emitted particles, their locations within buildings, the existence or effectiveness of local exhaust or capture, proximity to occupants, and socioeconomic factors.

Indoor combustion sources emit significant amounts of $PM_{2.5}$. Natural gas combustion is a substantial source of UFPs, particularly if the particles are not properly exhausted above a stove or vented from appliances such as water heaters, dryers, or heating systems. Wood combustion in fireplaces and wood-heating stoves can also be a prominent source via direct emissions to indoor spaces and the accumulation of outdoor $PM_{2.5}$ that penetrates back into buildings. Smoking of tobacco or other products is another major combustion source.

Indoor cooking activities are an important source and can lead to short-term but intense increases in both $PM_{2.5}$ and UFPs. Emissions depend on numerous factors, with higher temperature cooking and higher fat content foods leading to higher emissions. Countertop appliances such as toasters can also be important sources of $PM_{2.5}$ and are generally unvented.

Other sources of indoor $PM_{2.5}$ and UFPs include candles; incense; office equipment such as photocopy machines, laser printers, and 3-D printers; scenting products that are heated with oils; spray products used for cleaning and personal care; building occupants (via shedding and respiratory aerosols); and aerosolized water sources that leave behind mineral particles or microbial agents like bacteria or fungal spores. Fine PM resuspension from indoor surfaces can cause short-term spikes in particle concentrations, often near the building occupants responsible for the resuspension. Finally, indoor secondary organic aerosols can be formed from the reactions of organic compounds (in cleaning products, for example) with oxidants such as ozone that enters from outdoors or are emitted from electronic equipment including ionic and other air cleaners.

Less research has been conducted on sources of $PM_{2.5}$ in schools. However, classrooms with closer proximity to cafeterias and windows facing bus loading zones have been associated with higher classroom $PM_{2.5}$, and lack of furnace cleaning has been associated with higher black carbon concentrations. Student movement in and around classrooms also leads to the resuspension of particles from flooring and other surfaces.

Particle Dynamics and Building Characteristics that Influence Indoor PM

Once it has entered a building from outdoors or been emitted directly indoors, fine PM mixes into room air and may be transported to other spaces within the building. The rate and extent of such transport depends on the building layout; heating, ventilation, and air conditioning (HVAC) design and operation; and open doors and other connections between zones. Activities such as walking affect the direction of particle movement and dispersion, suggesting that measurements in occupied versus unoccupied spaces will result in different transport outcomes. Recent advances in consumer-grade sensors have allowed for the deployment of more monitors to investigate PM transport at higher spatial and temporal resolutions. The deployment of such monitors in homes has been used to show that emissions from cooking in kitchens can be detected in bedrooms within minutes following emission, depending on location. Inter-zonal transport can also be a source of indoor fine PM from neighboring units in multi-family buildings—secondhand smoke transfer between adjacent units, for example.

During transport, particles may undergo physical, chemical, and biological processes such as aerosol aging, oxidation, evaporation, condensation, and partitioning, which collectively interact to influence important indoor PM properties, including chemical composition, size, phase state, surface charge, and, for some biological particles, viability. Particles are also removed from indoor air by deposition onto surfaces, ventilation/exfiltration to the outdoors, and capture by filtration systems. A challenge in understanding individual sources, sinks, and transformations is that measurements of indoor fine particulate matter concentrations, size distributions, or composition alone generally do not yield insights into the presence or magnitude of specific mechanisms. Rather, indoor concentration measurements produce a measure of the net result of any number of competing or interacting processes. It is possible, though, to use a combination of mathematical models and measurements to estimate the magnitude of particle sources, sinks, and transformations.

Building Occupant Exposures to Fine PM

Despite advances in assessment methodology and instruments, there remain significant challenges to accurately quantifying exposure to $PM_{2.5}$ indoors and linking such exposures to specific sources. This hinders the ability to make informed decisions on mitigation strategies and identify disparities associated with such exposure.

Due to improvements in outdoor air quality and advances in building design and construction, indoor exposure to $PM_{2.5}$ of outdoor origin has generally been decreasing in the United States over the past decades. However, this reduction is not occurring uniformly, and communities affected by wildfire smoke and those near localized outdoor sources such as congested roadways or industrial facilities can still be significantly burdened. Furthermore, limiting the penetration and infiltration of outdoor fine particulate matter by reducing air exchange between outdoors and indoors can lead to an increase in the concentration of $PM_{2.5}$ from indoor sources.

There are several methods for quantifying inhalation exposure. Personal monitors are regarded as the gold standard for measuring individual exposure at the point of contact. However, the equipment can be cumbersome and expensive for large-scale studies. Exposure models rely on data on time–activity patterns combined with measured or modeled particle concentrations in various locations to predict exposure when personal monitoring is not feasible. Exposure reconstruction uses internal body measurements, or biomarkers, to directly measure the absorbed dose and to infer exposure from multiple pathways and sources. The literature on the utility of using biomarkers of exposure to indoor $PM_{2.5}$ is limited; however, extant studies indicate a relationship between outdoor $PM_{2.5}$ and DNA alteration.

Consumer-grade sensors are improving the ability to measure $PM_{2.5}$ exposure, but important limitations remain. Beyond improving instrument accuracy, cost, ease of use, and other performance aspects, it will be is critically important to advance understanding of how measured values are useful for determining the health impacts from exposure to fine particles and benefits of mitigation.

There are numerous complexities associated with exposure assessments, starting with the selection of the appropriate metric. PM may be characterized by such parameters as mass, number count, composition, and surface area, and it is not necessarily clear which parameter may be most useful for informing a specific exposure-related question. This issue is further complicated for UFPs, which make up a small amount of the mass of $PM_{2.5}$ but are dominant in number.

An additional complexity entails temporal variations in exposure and the resolution of short-term (acute) versus long-term (chronic) exposures. The knowledge base related to acute exposure to indoor $PM_{2.5}$ and UFPs is particularly limited, but such knowledge is important to understanding the risks related to exposures from cooking and emerging sources.

Our understanding of the potential health impacts from various indoor sources in different built environments is partly restricted by limitations in the instrumentation available to characterize exposure. Complexities associated with the varying composition of $PM_{2.5}$ (which may have health implications), and the nature of exposed populations and their vulnerability to $PM_{2.5}$ or its chemical or biological components, also complicate analyses.

Exposure studies point to the potential for large disparities among populations. Disparities occur not only because of higher indoor $PM_{2.5}$ concentrations that are associated with activities happening in smaller, densely occupied and interconnected (multi-family) homes, outdated appliances that have higher emissions, and ventilation equipment that is not present or is less effective at removing $PM_{2.5}$, but also because of elevated outdoor $PM_{2.5}$ concentrations. These large disparities in exposure can lead to excessive health burdens on some populations.

Health Impacts of Exposure to Fine PM in Buildings

Knowledge of the health effects of $PM_{2.5}$ is dominated by studies of exposure to PM of outdoor origin. Such studies are useful in understanding health effects from indoor exposures because of the encroachment that outdoor pollution makes into indoor spaces. There is also a growing base of literature on the effects of indoor $PM_{2.5}$ of combined outdoor and indoor origin on human health. Generally speaking, the literature on the respiratory and cardiovascular effects associated with indoor air pollution is more established than that of the effects on neurological and reproductive systems as well as cancer.

Respiratory effects. Indoor $PM_{2.5}$ exposure has been implicated in a range of adverse acute clinical, biologic, and physiologic manifestations of asthma and chronic obstructive pulmonary disease (COPD), including symptoms, exacerbations, inflammation, and degraded lung function and quality of life. Indoor $PM_{2.5}$ has also been linked to symptoms in populations without lung disease. The biologic components of indoor particulate matter also cause acute respiratory effects among people with and without asthma. Although there are few studies examining the health effects of $PM_{2.5}$ exposures in schools, investigations have reported associations between exposures to some airborne biologic agents—a fraction of which are fine PM—in schools and adverse health effects among children with asthma.

Cardiovascular effects. There is strong evidence that elevated outdoor $PM_{2.5}$ concentrations are associated with adverse cardiovascular health outcomes. Short-term increases in outdoor $PM_{2.5}$ are associated with increased risks of mortality and heart failure events requiring emergency department visits or hospitalizations. Studies of outdoor PM have consistently demonstrated that both short and long-term increases in $PM_{2.5}$ are associated with increases in blood pressure, a physiologic measurement that is one of the major risk factors for cardiovascular disease, including coronary artery disease, heart failure, stroke, chronic kidney disease, and diabetes, as well as for other chronic conditions. However, studies investigating indoor $PM_{2.5}$ and blood pressure, heart rate, heart rate variability, and electrocardiogram changes have demonstrated mixed results.

Cancer. There is substantial evidence to support a causal link between particulate matter of outdoor origin and lung cancer incidence and mortality. Most of what is known about the association between pollution of indoor origin and cancer has been generated from studies of secondhand smoke and biomass burning in low- and middle-income countries and has been primarily focused on lung cancer. Using an indoor wood-burning stove or fireplace has been associated with a higher risk of breast cancer in women with a family history of breast cancer.

Neurological effects. Elevated exposure to ambient $PM_{2.5}$ and also indoor work-related exposure has been associated with neurodegeneration risks such as dementia and cognitive decline and with an increased risk of depression for long-term exposure to outdoor $PM_{2.5}$. Living in areas with higher levels of particle components was associated with an increased risk of psychiatric hospitalization. In school environments, increased classroom $PM_{2.5}$ exposure has been associated with decreased performance on neurobehavioral tests for children. Children attending schools with higher levels of UFPs both indoors and outdoors experienced diminished growth in cognitive measurements. Multiple studies have demonstrated that UFPs penetrate the brain via the nose and olfactory nerve, and animal models have shown that UFPs alter neurotransmitter levels, triggering oxidative stress, inflammation, and other biochemical changes. Links between such biochemical changes and health outcomes such as cognitive decline, autism, and depression have been hypothesized.

Reproductive effects. Prenatal exposure to increased concentrations of ambient $PM_{2.5}$ has several adverse associations, including maternal depression after childbirth. Exposure to ambient $PM_{2.5}$ from wildfire smoke has been associated with pre-term birth and decreased birth rate. There have been multiple reports associating prenatal and early childhood exposures to $PM_{2.5}$ with neurological outcomes in children, primarily behavioral effects and degraded school performance.

Disparities related to health impacts of fine PM are rooted in numerous factors that culminate in the potential for greater health effects for those in economically disadvantaged households. Furthermore, there are disparities associated with the ability to purchase mitigation devices (indoor air filters, for example) or retrofit residences to improve mitigation measures as well as to obtain necessary health care for impacts of exposure to air pollution.

Practical Mitigation

Given the importance of $PM_{2.5}$ to human health and the exposures that occur indoors, there is a compelling need to address mitigation approaches to reduce exposure. Research indicates that several practical measures can be taken to effectively reduce indoor $PM_{2.5}$ concentrations. It is reasonable to assume that such reductions will result in health benefits, if for no other reason than the large knowledge base concerning the health benefits of lowering ambient $PM_{2.5}$ and the fact that a significant fraction of $PM_{2.5}$ indoors is of outdoor origin. However, studies of interventions to lower $PM_{2.5}$ exposure in residences and schools face methodological and logistical challenges that make it difficult to evaluate the efficacy of these interventions. Part of the failure to associate measured outcomes with $PM_{2.5}$ reductions can be attributed to a lack of accounting for competing removal mechanisms and other confounding factors. Furthermore, some studies only report the effect of introducing an exposure mitigation device rather than measuring whether exposures are reduced, and these are two different endpoints.

It must be kept in mind that many means for reducing exposure to $PM_{2.5}$ have associated costs and maintenance requirements, and may entail appropriate training on their effective use. Additionally, building factors such as the availability and use of effective kitchen exhaust fans and the availability of well-maintained HVAC systems, interact with mitigation measures in important ways. And mitigation approaches—particularly those related to source control—can have important cultural implications for some groups who may, for example, use candles or incense in religious practices. All of these factors must be considered when formulating strategies for limiting exposures.

Four general forms of mitigation of $PM_{2.5}$ were addressed in this report.

Source control. Source control may include the elimination or substitution of a source or a reduction in its emissions. Some studies have associated specific sources with adverse health effects, making health benefits of source control by elimination clear. However, the evidence base for source-control measures that demonstrably reduce adverse health impacts is modest for the range of sources that are within the scope of this review.

Ventilation. The amount of outdoor air brought into a residence or school affects the concentration of $PM_{2.5}$ and the impacts of changes in ventilation can be complex. For example, ventilation used for $PM_{2.5}$ control impacts other pollutants. Increased ventilation reduces indoor exposure to $PM_{2.5}$ of indoor origin and also reduces the concentrations of other pollutants of indoor origin such as volatile organic compounds (VOCs), but it may also increase concentrations of outdoor pollutants, such as ozone and PM of outdoor origin. As such, intervention studies cannot easily pinpoint the observed health outcomes related to $PM_{2.5}$ alone.

Filtration and air cleaning. Central systems and room air cleaners based on media filtration have the potential to significantly reduce indoor $PM_{2.5}$, but there is inconsistent evidence that this is an effective mitigation measure for reducing health effects. Much of the inconsistency arises from the consideration of different health outcomes, variations in study designs and study populations, and unassessed contextual factors. Room air cleaner performance varies significantly between environments due to differences in room volume, ventilation, the placement of the device relative to sources, room mixing characteristics, and user behavior such as turning air cleaners off or lowering settings to reduce noise, and intervention studies seldom characterize such effects. Over time, an air cleaner will also decline in efficiency and flow rate as particles accumulate in it.

Personal protective equipment. Interest in the efficacy of PPE to filter particles and protect human health dramatically increased during the COVID-19 pandemic. The pandemic also influenced cultural norms related to masking, which created opportunities to expand PPE use for reducing inhalation of $PM_{2.5}$ during acute events such as wildfires.

Studies investigating PPE and protection from $PM_{2.5}$ exposure are challenging to design. There are few studies of PPE use in residential or other non-occupational indoor spaces. Studies in non-occupational settings in China have indicated that respirator use can result in lower blood pressure and improved heart rate variability parameters and lung function improvements in those who wore N95 masks relative to those who did not. The beneficial effects of N95 masking were more pronounced on high pollution days.

KEY CONCLUSIONS AND OVERARCHING RECOMMENDATIONS

Five key conclusions stem from this review.

1. **There is ample evidence that exposure to indoor fine particulate matter causes adverse health effects.** Deleterious effects on respiratory health are clear, evidence of adverse cardiovascular disease effects is growing, and evidence for adverse effects on other organ systems and health conditions is emerging. Furthermore, $PM_{2.5}$ of outdoor origin generally makes up a significant fraction of indoor $PM_{2.5}$, a greater amount of $PM_{2.5}$ of outdoor origin is inhaled indoors than outdoors, and there is a wealth of literature that associates outdoor $PM_{2.5}$ with adverse health outcomes.
2. **Disparities exist in population exposure to indoor fine particulate matter of both outdoor and indoor origin.** Examples of people who are more likely to be affected adversely by such exposures include people living in economically disadvantaged circumstances and in marginalized communities near heavy industry or busy highways. Exposure to $PM_{2.5}$ and related health impacts may also be greater for populations living in older and smaller homes, and those lacking the resources to purchase lower-emitting appliances or maintain air cleaning technologies.
3. **Technological advancements have great potential for quantifying and reducing exposures to fine particulate matter.** Consumer-grade sensors that can be used by non-technical people to measure $PM_{2.5}$ and track location as well as advances in environmental data management, analysis, and modeling, enable new approaches to exposure assessment and control. These technologies—which will continue to evolve in accuracy, capabilities, and

lower cost—permit community-based participatory research that can build awareness and address critical data gaps, especially in communities that are disproportionately exposed and under-examined and can also help to provide real-time alerts to inform exposure-avoiding behavior.

4. **Effective and practical mitigation of exposure to fine particulate matter in homes and schools is currently possible.** Truly practical mitigation strategies must be affordable, available, feasible to implement, perform consistently over product life, and be devoid of adverse secondary consequences. As the report details, there are several actions that can be taken immediately, using some combination of source reduction, ventilation, central or in-room filtration, and PPE. It is reasonable to assume that reductions in indoor $PM_{2.5}$ concentration will yield health benefits, even if based solely on reduction in exposure to $PM_{2.5}$ of outdoor origin, although the literature related to the specific health benefits of such mitigation is sparse and mixed owing to the numerous confounding and limiting factors. It is not possible, though, to offer generic observations regarding which specific mitigation measures will be most practical to implement because there are myriad variables characterizing the sources of indoor $PM_{2.5}$ and ultrafine particles (UFPs): their fate, transport, and transformations indoors; the circumstances and level of exposure to them; and the health effects associated with that exposure. Different circumstances will necessarily dictate different choices.
5. **The lack of centralized responsibility for indoor fine PM policy is hindering reductions in population exposure at scale.** There are many factors that influence population exposure to indoor $PM_{2.5}$, ranging from the types and magnitudes of indoor and ambient sources, air handling and cleaning technologies, building-related features, and occupant behaviors. Currently, there is no single entity with the authority to apply an integrated systems approach toward lowering population exposure to $PM_{2.5}$. Consequently, opportunities to implement mitigation strategies where most needed and to support related research are fragmented. There has thus been limited progress to reduce exposure to indoor fine PM, even though effective and practical mitigation approaches exist.

The following overarching recommendations are offered to reduce population exposure to $PM_{2.5}$, to reduce health impacts on susceptible populations including the elderly, young children, and those with pre-existing conditions, and to address important knowledge gaps.

1. **Prioritize the mitigation of PM exposures amongst susceptible populations and do so with urgency.** Public health professionals and federal, state, local, tribal, and territorial agencies should prioritize immediate, multilevel, easily implementable, affordable, and effective interventions to mitigate exposure of economically disadvantaged and marginalized communities to fine PM. In doing so, it will be important to collaborate with community-based organizations and communication scientists to address the non-technical aspects of fine and ultrafine particle mitigation, including messaging, education, and public engagement. Consideration of behavioral factors will be critical moving forward, accounting for user behaviors related to air cleaners, HVAC systems, range hood fans, window use, source usage and frequency, choice of appliances, and more.

   While education of stakeholders is insufficient in and of itself to significantly reduce the exposure of susceptible populations to $PM_{2.5}$, it will be important to provide informative and understandable educational materials through trusted sources as a means of assisting with possible behavior modification and decision making aimed at reducing exposures, particularly in residences where individuals or families have some control over their exposure.

2. **Reduce exposure to fine PM in schools.** Reductions in exposures to fine particulate matter, including infectious aerosols, in schools have the potential to improve acute and chronic health impacts, reduce absences, and improve student performance. An immediate and highly visible program, perhaps analogous to "Green School" designations, could spur improvements in indoor air quality in schools, with opt-in by school districts and assistance from governmental entities for impoverished school districts. Clear goals should be established and effectively communicated with guidance on source reduction, ventilation, central filtration, effective and right-sized air cleaning, fine PM monitoring, and frequency of monitoring. District or school-specific improvements in measured fine PM and health outcomes, including reductions in absences, should be monitored for schools that implement the guidance and compared against national averages in order to assess the effectiveness of particular interventions.
3. **Continue to support research necessary to fill important knowledge gaps.** While the existing knowledge base is sufficient to recommend practical mitigation strategies for lowering exposure to $PM_{2.5}$ and related health effects, significant gaps in knowledge remain and should be prioritized for future research. Several important knowledge gaps and research needs are noted below. Additional research needs are included in each chapter.
    a. *Mitigation and health improvements*. Research is needed to quantify the efficacy of mitigation efforts to reduce exposure and the health benefits of practical mitigation strategies. Large-scale intervention studies should be conducted to establish an evidence base for the health impacts of indoor fine particulate matter exposure and mitigation measures, including different exposure scenarios, a range of interventions, and multiple health endpoints. Such studies should include acute exposures such as wildfire smoke and should evaluate co-benefits such as reductions in airborne infectious agent exposures. The inclusion of economically disadvantaged and marginalized communities in these studies is critical, as is the appropriate characterization of building factors such as indoor space geometry, ventilation, recirculated air flows, use of local exhaust, nature of filtration, indoor sources, proximity to outdoor sources, and the like.
    b. *Indoor aerosol characteristics*. Additional research needs to be conducted to identify and understand the variations in aerosol characteristics, including size (particularly, UFPs), concentrations, sources, and composition in different indoor residential and school environments. Such research could serve as a complementary effort to intervention studies to better understand the role of aerosol characteristics on health endpoints.
    c. *Effects of particle origin on health effects*. Understanding the relative health effects of indoor fine particulate matter of both outdoor origin and indoor origin is important for defining appropriate mitigation strategies. Advancing understanding of the source[s] associated with specific health effects is also important for informing source control measures.
    d. *New technologies for real-time indoor particle monitoring*. New technologies—particularly lower-cost and real-time sensors that capture key aerosol characteristics—would benefit future exposure and health studies as well as serve as sentinels for mitigation feedback systems or actions by building occupants to reduce exposure. Research and development are needed to expand features and improve quality control and

consistency at the single-sensor level and to aid in the installation, maintenance, and data interpretation from networks of sensors.

e. *Affordable, quiet, and effective air cleaning technologies*. While there are standalone air cleaners based on media filtration that lower indoor fine PM concentrations, research is still needed to develop cleaners that are priced in a range that allows for their widespread use; that are effective at lowering exposure to, and the health effects of, indoor aerosols; and that have features such as quiet operation that make them more likely to be used.

f. *Social and behavioral influences*. Social science and behavioral health perspectives should be included in future studies of indoor fine PM to understand how social, cultural, and behavioral factors influence exposure, health effects, and the implementation of mitigation strategies, particularly in susceptible populations. Such research should be a part of the intervention initiatives proposed above.

4. **Magnify and unify efforts to reduce population exposure to indoor fine particulate matter.** The broad recommendations listed above cannot be effectively enacted without coordinated support and action. However, as already noted, the lack of centralized responsibility has to date hindered a significant reduction in population exposure to indoor fine PM at scale. Such a reduction will require unification and integration of efforts across federal, state, local, tribal, and territorial entities. A concerted effort will be needed that spans environmental, building code, public health, and social service agencies, in collaboration with community, school-based, and other organizations that can aid with implementation. The form and details of this effort will need to be worked out among the involved parties and, while it might not be simple to bring about, the rewards in terms of improved population health will be great.

1
Introduction

This chapter provides basic information about the motivation of this report and the conduct of the study, beginning with a definition of fine particulate matter and an overview of why the health effects of indoor exposure to fine particulate matter is an important issue. It then presents the statement of task for the committee responsible for this report, followed by the committee's approach to its task. The text addresses some of the methodologic considerations that informed the committee's evaluation of the literature and concludes with a description of the report's organization.

WHAT IS FINE PARTICULATE MATTER?

Fine particulate matter (fine PM) is defined in this report as inhalable particles with diameters that are less than or equal to 2.5 µm. The terms *fine PM* and $PM_{2.5}$ are used interchangeably to refer to fine particulate matter. An important subset of fine PM is ultrafine particles (UFP), particles with diameters of less than or equal to 0.1 µm, generally extending to as small as a few nm. Ultrafine particles usually account for a small fraction of fine PM mass but dominate by number and can also be important in terms of total particle surface area. Ultrafine particles are largely emitted indoors by combustion sources and condensation of hot vapors, but also results as a product of gas-phase chemistry.

Fine PM in the range of 0.1 to 2.5 µm generally exists due to coagulation of UFP, condensation of vapors onto existing particles, emissions from indoor sources, for example, soot from combustion processes, and penetration of particles of this size range from outdoors to indoors. Particles with diameters of greater than 2.5 µm are generally referred to as *coarse particulate matter*. Coarse PM sources are dominated by mechanically generated processes such as resuspended dust (skin flakes, tracked in soil, clothing fabrics, pet dander, insect dung, and the like) and processes leading to emissions of mold spores, pollen, and other biologic agents. Some sources emit both fine and coarse particulate matter and the impacts of the fine and coarse modes are difficult to separate.[3] This is particularly true for many bioaerosols that lead to allergic reactions and airborne infectious disease transmissions, as well as the resuspension of dust from indoor surfaces. In this report the committee assumes that there is some contribution, albeit to an unknown extent, of fine PM to health impacts associated with these sources.

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[3] The literature and this report uses *PM* to refer to particulate matter without any size qualification in circumstances where this was either not measured or specified.

WHY IS IT IMPORTANT TO STUDY INDOOR EXPOSURE TO FINE PARTICULATE MATTER?

Indoor environments—homes, schools, offices, businesses, and shopping, entertainment, and other enclosed public and private spaces—affect our health, comfort, and productivity. People in developed countries spend most of their time indoors, so most of the adverse exposures that they encounter most likely take place indoors. Some of these exposures are generated indoors from indoor sources, while others originate outdoors and enter the indoor environment through mechanical or natural ventilation, or infiltration, or are generated by chemical processes that take place when pollutants emitted from various sources interact.

Airborne particulate matter is among the most concerning of these exposures, and fine particulate matter is especially problematic. These particles can easily penetrate deep into the respiratory system when inhaled, and prolonged exposure to them has been linked to a wide range of adverse health effects, including respiratory and cardiovascular diseases, exacerbation of asthma, lung cancer, and reproductive and cognitive effects. Certain groups are more susceptible to such adverse effects, including infants and children, the elderly, pregnant people, and individuals with pre-existing respiratory or cardiovascular conditions.

The National Academies' *Why Indoor Chemistry Matters* (NASEM, 2022) report highlights the growing awareness of the importance of ultrafine particles. Specifically, UFPs with diameters between 10 and 100 nm have a much higher surface area to mass ratio than larger particles and are thus efficient at transporting chemicals to surfaces in the alveolar region of the respiratory system. UFPs can cross through alveolar epithelial tissue, thus effectively reaching other organs and the smallest UFPs can be transported along the olfactory nerve to the olfactory bulb, which raises concerns regarding potential neurological effects.

The U.S. Environmental Protection Agency (EPA) considers $PM_{2.5}$ harmful to public health and the environment and regulates its concentration in outdoor air under the Clean Air Act (EPA, 2023). Other countries and governmental bodies such as the European Union have their own standards (European Commission, 2023). There are, however, no comparable regulations concerning the indoor environment as of the summer of 2023.

THE STUDY'S STATEMENT OF TASK

Against this backdrop, the EPA approached the National Academies with a request to consider the state of the science on the health risks of exposure to fine particulate matter indoors as well as engineering solutions and interventions to reduce risks of exposure to it indoors, including practical mitigation solutions to reduce exposure in residential settings. An expert committee was formed to respond to that request.

EPA charged the committee to focus on:

- synthesizing and summarizing recent scientific literature to assess the health risks of indoor exposure to $PM_{2.5}$; and
- identifying and analyzing practical intervention approaches for $PM_{2.5}$ indoors.

It was further directed to develop findings and recommendations regarding the key implications of the scientific research for public health, including potential near-term opportunities for incorporating what is known into public health practice, and to identify where additional research will be most critical to understanding indoor exposure to $PM_{2.5}$ and the effectiveness of interventions. Opportunities for advancing such research by addressing methodological or technological barriers or enhancing coordination or collaboration among governmental bodies and organizations were also to be noted. The committee was asked to limit their consideration to non-industrial exposure within buildings, as occupational exposures differ in their magnitude, duration, and composition and fall under the purview of a separate federal agency in the United States (the Occupational Safety and Health Administration). EPA requested that the committee focus on residential settings but also consider schools and other non-industrial indoor environments where appropriate. Environmental tobacco smoke (ETS) is a major component of $PM_{2.5}$ in the indoor spaces where the source is present. ETS exposure, health effects, and mitigation are dealt with in detail in other National Academies reports and were considered outside the scope of this effort, although they are noted where appropriate.

THE COMMITTEE'S APPROACH TO ITS TASK

The committee's approach to responding to the questions posed by EPA was informed by the work of earlier National Academies efforts related to the indoor environment, and the text in this section and the methodologic considerations section below reflect that antecedent work.

The committee undertook a wide-ranging evaluation of relevant research on particulate matter, sources of fine PM, building characteristics, exposure assessment, human health effects associated with indoor environments, and the effectiveness of exposure mitigation methods. EPA requested that the committee focus on residential settings but also consider schools and other non-industrial indoor environments where appropriate.

Although the committee did not review all such literature—an undertaking beyond the scope of this report—it did attempt to cover the work that it believed to have been influential in shaping scientific understanding at the time it completed its task in summer 2023.

Several sources of information were consulted in the effort. On health outcomes, the primary source was epidemiologic studies and, specifically, those related to indoor exposures if available. In situations where studies on health effects related to indoor exposures were not available, emerging evidence from ambient exposures was included. Most of the studies reviewed focused on exposures occurring in homes, reflecting the focus of researchers working in the field. The committee also examined the smaller literature addressing multifamily residences and schools. Clinical and toxicologic research efforts were considered as appropriate. The literature review was limited to English-language publications.

The literature of engineering, architecture, and the physical sciences informed the committee's discussions of building characteristics, sources of fine PM, exposure assessment and characterization, pollutant transport, and related topics, and public-health and behavioral-sciences research was consulted for the discussion of public-health implications. Those disciplines have different practices regarding the publication of research results. For example, relatively few papers in the peer-reviewed literature address building construction or maintenance issues. The committee endeavored in all cases to identify, review, and consider fairly the literature most relevant to the topics that it was charged to address. As such, it focused on studies that examined exposures, buildings, and populations in the U.S., but drew on research conducted elsewhere in circumstances where it deemed comparable and informed the issue under consideration.

Papers and reports reviewed in this volume were identified through extensive searches of relevant databases. Most of the databases were bibliographic and provided citations of peer-reviewed scientific literature. The committee staff examined the reference lists of major papers, books, and reports for relevant citations, and committee members independently compiled lists of potential citations based on their expertise. Input received from participants in a 2021 workshop series conducted by a predecessor committee served as a valuable source of additional information. The committee was charged to focus on practical intervention approaches for $PM_{2.5}$ indoors—Chapter 7 details the methodology used in the literature search conducted on that topic.

METHODOLOGIC CONSIDERATIONS

This section presents some of the considerations that informed the committee's approach to evaluating the scientific literature. It discusses, in general terms, the major issues involved in evaluating indoor PM levels and their effects on health and how building characteristics, occupant behavior, and the outdoor environment may affect them.

General Considerations

As noted throughout this report, little in the literature considers together in one place all of the elements in the committee's charge. However, substantial research has been published on many key questions. For example, there is extensive literature on outdoor particulate matter and the health risks associated with fine PM in outdoor air. Although less studied, published research also documents indoor PM levels and the relationship between indoor and outdoor PM levels. And there is a large body of work reporting on how indoor sources influence indoor air quality and human health, including several National Academies reports.[4] In contrast, little published research links the effect of specific exposure mitigation efforts to changes in health outcomes.

The nexus among sources of fine PM, PM exposure, building characteristics, health outcomes, and mitigation effects has not been well studied. However, the elements of this nexus are sufficiently well understood to permit the committee to conduct a scientific examination of issues, come to findings, draw conclusions, and offer recommendations. The approach taken in the report was to identify exposures and exposure circumstances believed to affect the health, safety, or productivity of building occupants; to describe the factors that influence source strength or exposure; and to explore how exposure mitigation efforts might influence these factors.

Issues Regarding Indoor Exposure to PM

Fundamentally, exposures occur when people and pollutants intersect in space and time. The magnitude of an exposure depends on its level while a subject is present. Three classes of factors govern conditions in occupied indoor environments. The first pertains to the adverse exposures themselves and includes such factors as the outdoor concentration, indoor sources and emission rates, and the physical properties of the agent. The second category pertains to buildings and includes the air exchange rate[5] and other characteristics related to indoor environmental controls, as well as the presence and effectiveness of deliberate air-cleaning processes. The third category of factors pertains to characteristics of the occupants and includes the timing of their presence indoors, occupant density, and activities that may influence sources,

[4] Salient conclusions from these reports are summarized in Chapter 2.

[5] The terms "air exchange rate" and "air change rate" are used interchangeably in the literature and in this report.

intake, and exposure. Subsequent chapters of the report detail how the numerous, diverse interactions between exposures, buildings, people, and interventions influence the outcomes of interest. Cultural and socioeconomic factors affect who is exposed, how and to what extent they are exposed, how the exposure impinges on their health, and the extent to which they may be able to mitigate adverse effects, and these are also addressed.

In analyzing indoor exposure to fine PM, it is convenient to consider two components: exposure due to outdoor sources and exposure due to indoor sources. The ventilation or air-exchange rate of a building or of a room in a building—which varies from building to building and within buildings over time—can substantially influence indoor air-pollutant concentrations and other environmental conditions. For particles of outdoor origin, ventilation is effective only if intake air is properly filtered prior to entering the occupied zone, something that is infrequently done in residences and only done in schools with adequately maintained central heating, ventilation, and air conditioning (HVAC) systems.

In general, higher ventilation rates cause indoor environmental quality to become more like local outdoor environmental quality. Conversely, as ventilation rates are reduced, the indoor environment is progressively less influenced by pollutants of outdoor origin and outdoor environmental conditions and more strongly influenced by indoor sources and conditions.

The consequences of fine PM exposure depend in part on how long people spend in different types of indoor environments and on differences in the populations that occupy various building types. People spend most of their time in their own residences. Children also spend a high proportion of their time in school, and they are considered more susceptible than adults to adverse health effects of air pollution. Similarly, indoor environments occupied by the elderly or individuals with chronic health conditions are of special concern because those who are in fragile health are more susceptible to further stresses than those who are healthy.

Differentiating among building types is important for reasons that extend beyond the populations that inhabit them. Different classes of buildings may be designed, operated, and maintained differently in ways that affect how their occupants are exposed to PM. Most commercial buildings in the United States are commonly ventilated mechanically, whereas the existing stock of residential buildings is ventilated by some combination of an HVAC system (where present), air leakage across the building enclosure, and natural ventilation through open windows or doors. Buildings also differ in the types of sources present. For example, cooking is a dominant activity in restaurants, common in residences, and rare in offices. Candle use primarily takes place in residences and in buildings used for religious or cultural purposes. The intensity of cleaning activities may be higher in health-care facilities than in other types of buildings. Occupant densities and the amount of time that people spend in particular kinds of buildings also vary. Schools are both high occupant density environments and ones that children spend a substantial fraction of their time in. The number of people occupying homes, how closely they are grouped together, and how much time is spent in them differs by socioeconomic status and in some cases culture. Finally, it is important to recognize that the responsibility for environmental conditions in buildings varies markedly among building classes and that this variability influences the appropriateness of policy options to address the exposure mitigation alternatives discussed in the report.

Another important characteristic of indoor environments is their broadly distributed nature. More than half of the population of the United States lives in the 52 most populous metropolitan statistical areas.[6] In total, there are over 140 million housing units in the country (U.S. Census Bureau, 2023), along with tens of millions of other occupied buildings. Taking the diversity in this building stock into account is important when working to understand the public-health significance of PM exposures.

Keeping in mind that broad diversity, what factors affect indoor fine PM concentrations? According to the principle of material balance (that is, that mass is conserved), the level of a given pollutant in a particular building can be determined by accounting for the net effect of the source terms and collective removal processes. Sources include outdoor air and direct indoor emissions. Ventilation is a dilution and removal process that must always be considered when indoor sources dominate. Other removal processes can be important, such as the deposition of particles onto indoor surfaces or active filtration.

Again, generally speaking, the primary elements that can be used to ensure good indoor air quality are source control, ventilation, the proper management of indoor environmental conditions, and the appropriate use of filtration. The central principle is to remove pollutants where they are more highly concentrated, to supply clean air where and when people need it, and to maintain healthy and comfortable environmental conditions for building occupants. Chapters 3–7 of the report go into far greater detail on all of these points.

REPORT ORGANIZATION AND FRAMEWORK

The remainder of this report is divided into seven additional chapters and supporting appendices. Chapter 2 provides background information on two topics related to the consideration of indoor exposure to fine PM: EPA's interests, responsibilities, and work on the topic and brief summaries of previous National Academies reports related to the indoor environment and health.

Sources of indoor fine particulate matter are addressed in Chapter 3. Indoor $PM_{2.5}$ concentrations and composition are described along with the important sources of indoor fine particulate matter of both indoor and outdoor origin. The latter includes $PM_{2.5}$ that penetrates through the building enclosure (its walls, windows, and the like) to the indoors. Major indoor source categories include those based on combustion processes, heating processes, resuspension from surfaces, liquid droplet evaporation, and secondary particles from indoor chemical reactions. Sources of ultrafine particles are also discussed.

The fate, transport, and transformation of indoor fine particulate matter are discussed in Chapter 4. Mechanisms that define particle dynamics inside buildings are described, and mathematical models that incorporate these mechanisms to predict the combined effects of indoor fine PM sources, sinks, and transformations are discussed. Approaches to measure particle fate, transport, and transformation are also reviewed.

Building occupant exposures to fine particulate matter are examined in Chapter 5. Inhalation exposure metrics are defined, along with a discussion of the numerous challenges associated with estimating such exposure. Exposure assessment approaches, including direct measurements, exposure reconstruction based on biomarkers and multi-pathway analysis, and indirect estimates based on deterministic or empirical models are also discussed in Chapter 5.

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[6] https://www.census.gov/data/tables/time-series/demo/popest/2020s-total-metro-and-micro-statistical-areas.html#v2022.

Past studies involving applications of exposure assessments are reviewed, along with exposure trends and disparities.

The health effects associated with exposure to indoor fine particulate matter of both indoor and outdoor origin are reviewed in Chapter 6. Primary health effects include cardiovascular, pulmonary, neurological, and psychiatric diseases, endocrine disorders and adverse birth outcomes. The chapter also examines the physiological mechanisms that are hypothesized to link exposure to cellular changes and the factors that influence an individual's susceptibility to developing clinical symptoms associated with exposure.

Practical mitigation approaches for reducing exposure to, and health effects of, indoor fine particulate matter are described in Chapter 7. The mitigation measures that are considered include source control, ventilation, central filtration and standalone air cleaning, and personal protective equipment. Factors that influence the effectiveness of these mitigation measures in reducing exposure to $PM_{2.5}$ as well as its adverse health effects (which do not necessarily coincide) are discussed, including decision making and human behavior related to the measures.

The final chapter of the report, Chapter 8, builds on the preceding text, identifying the report's major themes and highlighting the committee's key findings, conclusions, and recommendations.

Appendix A reproduces the agendas for a 2021 (virtual) workshop series on indoor exposure to fine particulate matter and practical mitigation approaches. This workshop series, which is summarized in proceedings published in 2022 (NASEM, 2022), provided valuable information and insights to the committee. Biographic information on the committee members and staff responsible for this report are listed in Appendix B.

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2
Background

This chapter provides a background for the committee's evaluation of the health effects of indoor exposure to fine particulate matter ($PM_{2.5}$) and practical mitigation solutions by briefly summarizing information on two issues of relevance to the analysis: the U.S. Environmental Protection Agency's interests and responsibilities regarding the indoor environment, and earlier reports produced by the National Academies of Sciences, Engineering and Medicine (National Academies; NASEM) related to the indoor environment and health.

THE US EPA'S ROLE IN INDOOR ENVIRONMENTAL QUALITY

The U.S. Environmental Protection Agency (EPA) manages activities related to indoor environmental quality in its Indoor Environments Division (IED), an organization that resides within EPA's Office of Air and Radiation. IED's website states that its main objective is "to improve indoor air quality in buildings where people live, learn and work."[7] Toward this end, it implements non-regulatory programs to reduce public health risks from poor indoor air quality with the goal of reducing or preventing human exposure to harmful indoor contaminants including particulate matter (PM), indoor asthma triggers, mold, environmental tobacco smoke, volatile organic compounds, and radon. IED's program activities include technical guidance and assistance; public information and education; partnerships with industry, nongovernmental organizations, other federal organizations, states, tribes, and communities; and the promotion and synthesis of research.

IED's indoor air activities involve translating the consensus science on indoor environmental quality, including risk assessment and risk reduction, into non-regulatory policy and program guidance; promoting the use and adoption of that guidance through outreach and technical assistance; and collaborating with governmental and private entities to implement that guidance. It also maintains a robust research and research support portfolio.

The division's efforts on indoor exposure to particulate matter include:

- enhancing awareness of indoor PM mitigation technology and health effects research;
- updating and disseminating web content on wildfire smoke and indoor air quality, air cleaners, filtration, and dust control; and
- increasing outreach and technical assistance to promote actions that reduce exposure to PM indoors.

Links to this work are found on the division's website (EPA, 2023). IED staff developed a comprehensive literature review on indoor PM levels that informed and provided references for the committee (Ilacqua et al., 2022).

[7] https://www.epa.gov/indoor-air-quality-iaq/introduction-indoor-air-quality.

NATIONAL ACADEMIES REPORTS ADDRESSING RELATED TOPICS

Several National Academies reports have addressed topics relevant to the evaluation of the health effects of indoor exposure to airborne agents and the mitigation of adverse effects from such exposures. Salient publications are summarized below.[8]

Indoor Pollutants (NRC, 1981) provided a comprehensive assessment of the then-available scientific literature regarding various pollutants found indoors. It addressed sources and characterization, health effects, and control of a wide range of adverse indoor exposures, including volatile organic compounds, radon, formaldehyde, asbestos and other fibers, tobacco smoke, excessive moisture, and biological agents like mold and bacteria. The report emphasized the importance of proper ventilation and control measures to mitigate exposure and offered recommendations for improving building design and ventilation systems to enhance indoor air quality. It highlighted significant research gaps and recommended a collaborative effort among federal agencies to assess exposures and their effect on health.

Policies & Procedures for Control of Indoor Air Quality (NRC, 1987) identified best practices for operational procedures to minimize air quality issues in nonindustrial office buildings. The report highlighted that poor indoor air quality can both cause illness in building occupants and reduce their productivity. It indicated that indoor PM concentration is among the important metrics that need to be characterized to evaluate the performance of building systems. The report concluded that there is a mismatch between the complexity of those systems and the knowledge base of the people responsible for operating, maintaining, and managing them, and it recommended that training and education be developed and those responsible for the systems be encouraged to take advantage of this training in order to promote the systems' proper oversight.

Indoor Allergens: Assessing and Controlling Adverse Health Effects (IOM and NRC, 1993) explored the relationship between the indoor environment and human health, focusing on the population sensitive to indoor allergens and suffering with chronic or intermittent allergic disease. The report emphasized the need to develop standardized test procedures for rating the effectiveness of air cleaning devices and other methods for removal of known size classes of particles containing allergens. It suggested that further research was needed to evaluate the role of cleaning in controlling for allergic diseases caused by the dissemination of particulate matter, noting that while housekeeping is the most common means of removing allergens, the physical cleaning process itself may risk dispersing fine particles into indoor air, and a high-efficiency particulate air (HEPA) filter may be needed to offset this allergen exposure.

Clearing the Air: Asthma and Indoor Air Exposures (IOM, 2000) assessed the literature regarding the relationship between indoor air quality and asthma. The report noted that studies consistently report an association between exposure to high outdoor levels of air pollutants, including particulate matter, and adverse respiratory health effects. It explained that fine particles of outdoor origin readily penetrate indoors and that there is an association between particulate matter exposure and asthma exacerbation but not asthma development (outside of tobacco smoke). The possible mechanisms for asthma exacerbation named in the report included reflex bronchoconstriction via nonspecific irritant effects, direct toxicity to the airway epithelium and resident immune cells, and induction of an inflammatory immune response. The report

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[8] In addition, several NASEM reports have addressed environmental tobacco smoke (ETS), an important source of multiple pollutants in indoor environments, including fine particulate matter. ETS exposure and health impacts were outside the scope of this study but were most recently addressed in the 2018 report *Public Health Consequences of E-Cigarettes*.

concluded that limiting or eliminating sources and using HEPA filters were the most straightforward means of addressing indoor particulate matter exposures.

Damp Indoor Spaces and Health (IOM, 2004) reported on a comprehensive review of the research regarding the relationship between damp or moldy indoor environments and the manifestation of adverse health effects, particularly respiratory and allergic symptoms. The report highlighted the fact that particulate allergen exposure often occurs episodically because of the inadvertent disturbance and resuspension of reservoirs of biologic agents by human activities. This means of exposure is likely not to be accurately captured by environmental area samplers, and it is nearly impossible to measure all relevant microenvironments when trying to measure particulate exposure, making personal sampling of particulate matter a preferred method for evaluating biologic agents.

Green Schools: Attributes for Health and Learning (NRC, 2007) reviewed the results of the then-available studies on green schools[9] to determine their effects on student learning and teacher productivity. The report stated that particulate matter pollutants in schools are of both indoor and outdoor origin and are associated with asthma and other respiratory symptoms and with a set of building-related symptoms including eye, nose, and throat irritation. It observed that indoor and outdoor particles and certain volatile organic compounds (VOCs) are effectively removed by filtration, but most filters used in schools are designed to collect particles larger than 10 μm and are thus relatively inefficient at removing submicron-sized particles. The report proposed strategies to mitigate particulate matter pollutants such as anti-idling measures for vehicles outside the building, the elimination of gas-fired pilot lights, and discouraging fossil fuel burning equipment indoors.

Climate Change, the Indoor Environment, and Health (IOM, 2011) summarized the state of scientific understanding with respect to the effects of climate change on indoor air and public health. The report found that climate change mitigation strategies could improve or worsen fine-particle exposure associated with cooking and that increased wildfire incidence would increase community exposure to fine particles, leaving low-income households at a higher risk. It suggested that attention should be directed toward improving understanding of the effectiveness of indoor environments as a shelter against pollutants of outdoor origin that may be altered due to climate change.

Health Risks of Indoor Exposure to Particulate Matter: Workshop Summary (NASEM, 2016) summarized a series of public workshops on the state of the science regarding the health risks of indoor exposure to particulate matter. The workshops explored the primary sources of particulate matter, the chemistry and dynamics of particulate matter, and issues related to particulate matter exposure. In addition, it discussed the health risks associated with exposure to particulate matter and how to engage the public on these issues.

Microbiomes of the Built Environment: A Research Agenda for Indoor Microbiology, Human Health, and Buildings (NASEM, 2017) reviewed both what was known about the intersection of microbial biology, chemistry, building science, and human physiology and how new tools may facilitate advances in understanding the ecosystem of built environments and effects on human health and well-being. The report discussed particle filtration and balancing ventilation and outdoor air quality for the management of fine particles. It pointed out that an emphasis on the benefits of reducing indoor fine particle concentrations for occupant health have

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[9] The report defined "green schools" as those whose goals were "(1) to support the health and development (physical, social, intellectual) of students, teachers, and staff by providing a healthy, safe, comfortable, and functional physical environment; and (2) to have positive environmental and community attributes" (p. 2).

led to requirements for and use of higher levels of filter efficiency in buildings. It observed that reducing fine particles from outdoor air via filtration required the use of filters with higher MERV[10] ratings and can be expensive but that technologies were being developed to reduce these costs.

Indoor Exposure to Fine Particulate Matter and Practical Mitigation Approaches: Proceedings of a Workshop (NASEM and NAE, 2022) summarized presentations and discussions that took place during three workshops held virtually in 2021 that addressed the state of the science on exposure to fine particulate matter indoors, its health impacts, and engineering approaches and interventions to reduce exposure risks, including practical mitigation solutions in residential settings. The workshop presentations examined sources of fine particulate matter, health effects of exposure to indoor fine particulate matter, metrics and assessment of indoor exposure to fine particulate matter, mitigation strategies, and occupant responses to indoor fine particulate matter. Speakers observed that both technological and behavioral interventions were needed to mitigate fine particulate matter exposure.

Why Indoor Chemistry Matters (NASEM, 2022) explored indoor chemistry from different perspectives, including the sources and reservoirs of indoor chemicals and the ability of these chemicals to undergo transformations and partitioning in the indoor environment. The report described the mass and number concentrations of particulate matter in various size fractions and the elemental composition of fine particulate matter with respect to typical sources. It also discussed the variety of fine particle monitors available and their ability to identify episodic events and relative changes in the same indoor setting. The committee responsible for the report highlighted the need to develop testing approaches that consider both efficacy and byproduct formation in a representative range of real-world environments with respect to fine particles.

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3
Sources and Composition of Indoor Particulate Matter

This chapter discusses recent scientific literature on the sources of indoor fine particulate matter ($PM_{2.5}$) and ultrafine particles (UFPs) in order to provide background information for subsequent chapters in this report and to identify persistent knowledge gaps on this topic. The research reviewed was mostly limited to publications in the past decade and references therein, focusing primarily on sources of importance to residential and school environments in the United States. In some cases, where there were particularly relevant earlier papers or the publication record was relatively spare, it was necessary to reach back further in time. There are numerous sources of $PM_{2.5}$ and UFP, particularly in residences, which vary in relative importance from residence to residence. As such, the focus of this report is on the most extensively studied sources which have the greatest relevance in terms of health risks associated with exposure.

The chapter first presents an overview of indoor $PM_{2.5}$ and its components. Outdoor sources of indoor $PM_{2.5}$ are then discussed, followed by the individual indoor sources of $PM_{2.5}$, which are grouped based on the mechanisms that generate or produce these particles. Five main generation mechanisms are covered: combustion processes, other non-combustion heating processes, mechanical particle resuspension, residual particles from liquid aerosol evaporation, and secondary particles formed through chemical reactions. Traditional and under-explored sources are included, with a greater focus placed on potentially new and unknown sources. When available in the literature, source-specific information on chemical composition and health effects are presented, with a more comprehensive review of health effects set forth in Chapter 6 of this report. The chapter concludes with a summary of the findings and conclusions and with the recommendations that the committee developed on the basis of the findings and conclusions.

The standard definition of $PM_{2.5}$ is the mass concentration of particles with aerodynamic diameters less than or equal to 2.5 μm. While this standard EPA definition is based on aerodynamic diameter, some studies report other size metrics including number concentrations which are more sensitive to smaller particles including ultrafine particles. Corrections can be applied to convert between different size metrics including particle shape, density, and optical properties. For a more thorough discussion, the reader is referred to the original publications for details. Finally, it is important to note that ultrafine and submicron particles often dominate particle number concentrations, whereas particles larger than 0.1 microns dominate in terms of mass concentrations.

INTRODUCTION AND BACKGROUND

Particulate matter (PM) found indoors originates from outdoor air that penetrates into buildings as well as from a wide variety of indoor sources. Indoor particulate matter reflects the great diversity of indoor environments that exist and the activities performed in each of them.

This diversity is a major challenge for understanding the impact of indoor sources on indoor $PM_{2.5}$ concentrations and compositions. While ambient PM concentrations and other characteristics vary regionally and, to some extent, locally, the contributions of indoor sources to indoor PM can vary from building to building, unit to unit, and even among different microenvironments within the same building or unit (e.g., kitchen versus bedroom in a home or cafeteria versus classroom in a school). Humans themselves are important generators of particulate matter, with the relevant activities ranging from resuspending settled dust to shedding skin flakes to exhaling respiratory particles that may contain infectious pathogens. Adding to this complexity, cultural differences and beliefs as well as socioeconomic disparities can lead to differences in both ambient and indoor $PM_{2.5}$ concentrations (Adamkiewicz et al., 2011). Understanding sources can help indoor occupants make informed decisions about limiting their exposure to fine particulate matter (Klepeis et al., 2013).

Indoor sources have been found to account for approximately half of total indoor $PM_{2.5}$ concentrations in homes, on average, with the remainder originating from outdoors (Bi et al., 2021; Meng, et al., 2005; Wallace et al., 2022). The type and nature of PM sources determine important particle characteristics, such as emission strength, particle size distribution, and chemical composition, as well as other important parameters for human exposure and health (further discussed in chapters 5 and 6 of this report), such as source duration, frequency, time of day, and source location relative to the receptor, and indoor ventilation or mitigation strategy, among others. And while the global burden of disease related to ambient air pollution has been estimated (Cohen et al., 2017), a question remains as to how to understand the implications of such estimates for outdoor exposure given the fact that people in the United States spend the majority of their time indoors (Klepeis et al., 2001).

Building-related factors contribute to indoor $PM_{2.5}$ concentrations and composition by affecting how outdoor particles penetrate from outdoors and how indoor particles are diluted and exfiltrated from indoors, as discussed in Chapter 4. Socioeconomic status also plays a role in indoor concentrations, potentially due to a combination of indoor sources and the presence of higher-leakage areas that allow greater penetration of outdoor PM (Adamkiewicz et al., 2011; Mendell et al., 2022). For example, indoor PM concentrations were found to be two times higher in social (subsidized) housing than in single-family homes in Toronto, Canada (Mendell et al., 2022). Building-related factors affecting indoor particle penetration and dynamics are also discussed in greater detail in Chapter 4.

INDOOR $PM_{2.5}$ CONCENTRATIONS AND COMPOSITION

Indoor $PM_{2.5}$ of Outdoor Origin

Ambient fine particulate matter ($PM_{2.5}$) has been widely reported as an important cause of mortality, both worldwide and in the United States (Cohen et al., 2017; Di et al., 2017; Fann et al., 2012). Although epidemiological studies rely on ambient $PM_{2.5}$ concentrations to determine health impacts, people report spending nearly 90 percent of their time indoors, on average, including nearly 70 percent in residences (Klepeis et al., 2001). Canadian estimates were found to be very similar to these U.S.-based numbers (Leech et al., 2002). It is important to note that these studies were completed two to three decades ago and have not been updated based on newer activity pattern surveys which could reflect some changes, including as a result of the COVID-19 pandemic. As further discussed in Chapter 4, because outdoor $PM_{2.5}$ infiltrates and persists indoors, the bulk of human exposure to PM of outdoor origin is likely to take place indoors. In fact, indoor exposure to $PM_{2.5}$ of outdoor origin has been estimated to account for perhaps 40–60 percent of the mortality burden of $PM_{2.5}$ exposure in the United States (Azimi and Stephens, 2018).

Ambient sources of $PM_{2.5}$ have been extensively investigated. Major outdoor contributors of $PM_{2.5}$ comprise both natural and anthropogenic sources. Ambient air quality standards refer to $PM_{2.5}$ and PM_{10}; however, the size distributions for different PM sources have the potential for myriad particle size distributions, some of which may not be properly represented through mass-based measurements in those size cutoffs (Morawska et al., 2008). Essentially, ambient particles fall into several PM size ranges determined by their formation process, sources, and sinks: ultrafine, submicron, and supermicron particles. Windblown dust and sea spray aerosols are mechanically generated and thus have larger supermicron sizes. They represent the dominant atmospheric aerosols by mass. They are composed of salts, metals, minerals, and bioparticles. In addition to salts, sea spray aerosol has been shown to contain a significant amount of organic components, particularly at the smallest submicron sizes. Ambient PM also includes bioparticles, which can penetrate into indoor areas and contribute to the complexity of the indoor microbiome. Anthropogenic $PM_{2.5}$ sources include industry, power generation, transportation, and domestic burning activities. Fuel combustion, including the burning of heating oil and wood (including wildfires), contributes significantly to ambient $PM_{2.5}$. Most combustion-derived aerosols occur in the submicron size range. The vast majority of particles (by number) occur in the ultrafine size range (<100 nm). Sources of ultrafine particles include new particle formation and direct emissions from combustion processes.

The amount that outdoor pollution contributes to indoor air depends on a number of factors, including the proximity of a building to point and mobile sources, factors associated with boundary layer meteorology, urban and regional air pollution, and a number of building-related factors such as ventilation and infiltration rates, as well as location of air intakes (for nearby sources). A significant number of schools are located near roadways (15 percent of schools are located within 820 ft of a major roadway) and thus are heavily affected by vehicular pollution (Kingsley et al., 2014). As wildfires become more common due to changing climate, a number of studies have found an impact of wildfires on indoor air quality. In California, an analysis of networks of consumer-grade particle sensors showed that indoor $PM_{2.5}$ concentrations nearly tripled during wildfires (Liang et al., 2021). A 2019 study found that wildfires and vehicle emissions significantly increased the indoor air $PM_{2.5}$ concentrations due to natural ventilation and infiltration in economically disadvantaged homes in Denver (Shrestha et al., 2019). During the wildfire season, these homes were heavily affected by long-range transported wildfire plumes, which led to indoor $PM_{2.5}$ levels that were nearly 5 times higher than outdoor levels. During transport from outdoor into indoor environments, particulate matter can undergo multiple physical and chemical transformations, leading to changes in particle concentrations and size distribution, due to transport through the building envelope and physical and chemical differences between outdoors and indoors (Abt et al., 2000). Chapter 4 further elaborates on these and other processes.

Indoor Sources of $PM_{2.5}$

Numerous everyday indoor activities produce PM, with new potential sources emerging over time as novel consumer products, activities, and habits appear. While traditional and relatively well understood indoor PM sources, such as combustion processes, still play an important role in indoor exposure, novel indoor sources, such as 3D printers and electronic cigarettes, add complexity to indoor environments. Indoor sources are complex not only because of inherent differences in source strengths, particle size distributions, and composition, but also in terms of timescale, which may even vary considerably across the same type of source. As a generalization, some sources emit particles more continuously (e.g., humidifiers, pilot lights, wood burning stoves or fireplaces), while others generally emit over shorter periods (e.g., cooking, burning incense or candles, operating printers). Table 3-1 shows some common examples of indoor particle sources and some of their typical characteristics.

Table 3-1 makes the case for the variability and complexity of indoor sources, which can be very short-lived (e.g., spray products) or longer-duration (e.g., fireplaces) and can emit very small particles (e.g., gas combustion) or very large particles (e.g., dust resuspension) with a wide range of compositions. In the next section, some major indoor sources of fine PM are presented grouped under their main underlying PM generation mechanism. Both traditional and underexplored sources are included, with more focus placed on potentially new and unknown or emerging sources. For several of these sources, the present body of knowledge ranges from very low to high, depending on the parameter of interest. Many of the studies presented in the sections below report indoor particle concentrations resulting from these sources, while others measure particle emissions rates (sometimes in terms of particle mass, sometimes particle number). Fewer studies report source-specific particle size distributions, particle composition, or, in some cases, source-specific health effects.

TABLE 3-1 Examples of Indoor Sources of $PM_{2.5}$ That Are Relevant in Many U.S. Homes and Schools, With Some of Their Characteristics

	Dynamics/Duration		
Type of source	**Intermittent**[1]	**Continuous**[1]	**Primary particle size**[2]
Combustion	• Gas stoves • Cigarettes and cigars[3]	• Fireplaces • Wood stoves • Pilot lights • Candles • Incense	• Ultrafine and fine
Heating Processes	• Laser printing • Cooking • Clothes ironing • Hair styling tools	• 3D printing • Essential oil vaporizers • Hair dryers and hand dryers • Electronic cigarettes	• Ultrafine for most sources; fine and supermicron for cooking
Water Droplet Evaporation	• Spray products • Respiratory emissions	• Humidifiers • Ultrasonic essential oil diffusers • Artificial fog machines	• Ultrafine for humidifiers, fine and supermicron for respiratory emissions
Mechanical Dust Resuspension	• Walking and physical activity • Cleaning • Vacuuming	• Motors and other machinery	• Supermicron
Chemical Processes	• Secondary aerosol formation	• Additive, oxidizing air cleaners	• Ultrafine

[1] For this table, sources that occur on the order of seconds to minutes were considered intermittent, and sources that may last for hours to days were considered continuous.
[2] The following particle size cutoff definitions are used in this report: Ultrafine: <100 nm, Fine: <2.5 µm, Supermicron: particles >1 µm.
[3] Although tobacco smoke products are not covered in this report, they are well-known indoor combustion sources.

Indoor PM From Combustion-Related Sources

Indoor combustion sources emit products of incomplete combustion and thermal nitrogen oxides (NO_x). Most of these sources are intermittent with emission periods of minutes to hours, while some emit more continuously. The extent and nature of particle emissions from combustion-related sources in the indoor environment are defined by the type of fuel (composition), fuel consumption rates, extent of oxygen supply, flame temperature, and degree of emissions containment. A summary of several important indoor combustion sources is provided below, grouped according to fuel type: natural gas, wood, other fuels used for heating (such as propane), and candles and incense. Each source in this section is relevant to some percentage of U.S. residential buildings, and a few are relevant to school buildings. Second-hand tobacco and marijuana smoke can be major sources of $PM_{2.5}$ in homes but are excluded from this discussion.

Combustion of Natural Gas or Propane

Natural gas and propane are combusted indoors for purposes of cooking (via stovetops and oven burners) and heating (via fireplaces, furnaces for space heating, hot water heating, and clothes drying). Natural gas is also combusted indoors by pilot lights that serve combustion appliances though pilot lights have been decreasing in prevalence as older equipment is retired. In each case, particle emissions to the indoor environment are dominated by ultrafine particles. Most combustion appliances are required by code to utilize exhaust vents to direct products of incomplete combustion to the outdoors. These exhaust systems often capture most but not all fine PM and, in the case of range hood exhaust, are often missing in older homes or not used by occupants while cooking.

Previous studies on emissions from natural gas cooking have focused on residential as opposed to school environments, although some of what has been gleaned from these studies has some relevance to the use of natural gas for cooking in school cafeterias. As of 2020, 38 percent of Americans used natural gas for indoor cooking, including ovens and stove top burners (EIA, 2022). States with households most likely to use natural gas for cooking are California (70 percent) and New Jersey (69 percent), with Illinois and New York both exceeding 60 percent. Other than Georgia, residences in southeastern states have relatively low (<20 percent) usage rates of natural gas for cooking.

During the combustion of natural gas or propane, a number of pollutants are emitted, including particulate matter and gasses such as carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, formaldehyde, acetaldehyde, and more (Lebel et al., 2022; Mullen et al., 2016; Singer et al., 2017). Cooking with natural gas or propane generates a substantial amount of UFPs predominantly associated with the combustion of the gas and, to a much smaller extent, desorption of SVOCs from cooking utensils followed by condensation in room air (Wallace et al., 2008; 2017). Details related to the combustion of natural gas are reasonably well understood. For example, for stovetop burners the mixture of air and natural gas flows into the bottom of the burner cap and issues from holes situated around the circumference of the cap. Primary aeration is mostly in the range of 40–60 percent of the stoichiometric air requirement, a level of aeration that results in flames that prevent soot formation and yields the characteristic blue flame of natural gas burners (Wagner et al., 2010). Moreover, unvented pilot lights that serve natural gas appliances also contribute significantly to UFP concentrations, often operating continuously (Bhangar et al., 2011).

Inhalation exposure studies specifically associated with cooking with natural gas have largely been complicated by emissions from cooking oils and foods (see section on cooking below), i.e., as opposed to just combustion of natural gas, or have focused on nitrogen dioxide and other gasses as opposed to UFPs or $PM_{2.5}$ (e.g., Logue et al., 2014; Paulin et al., 2014). Few studies have definitively resolved the health effects of such exposures, particularly as related to particle emissions.

Kile et al. (2014) identified children in the United States aged 2–16 years who lived in homes where gas stoves were used. After adjusting for other risk factors, children in homes for which an exhaust fan was not used during gas stove operation had lower lung function and higher odds of asthma, wheeze, and bronchitis compared with children in homes where an exhaust fan was used while operating a stove. The authors speculate that agents such as nitrogen dioxide and particle-bound polycyclic aromatic hydrocarbons (PAHs) may have played a role in these results, but these were not measured.

Wagner et al. (2010) studied particle emissions from a single gas burner consistent with a stovetop burner. Mean emitted particle diameters were observed to be approximately 7 nm for partially premixed flames and approximately 10 nm for non-premixed flames. These values are consistent with geometric mean diameter (GMD) ranges of 4 nm to 8 nm reported by others (Patel et al., 2021; Rim et al., 2016; Wallace et al., 2008). The percentage of primary air had a particularly strong impact on particle emissions; emissions during combustion of natural gas were at a minimum at a primary aeration level of 60–65 percent.

Pilot lights, small gas flames used to ignite a larger burner flame, were once extensively used in home stoves and ovens but have largely been replaced in favor of electric ignition systems. However, they are still used for water heaters, central heating systems, and some fireplaces. Where used, pilot lights are a continuous source of ultrafine particle emissions to indoor air. Patel et al. (2021) used measurements from the HOMEChem study to estimate ultrafine particle number and mass concentrations associated with a number of sources, including the pilot light on a propane stove. They estimated a mass emission rate of ultrafine particles to be 0.9 ± 0.2 (standard deviation [SD]) μg/min and a number emission rate of sub-10 nm particles to be $1.6 \pm 0.6 \times 10^{12}$ particles/min with a GMD of ~5 nm. Bhangar et al. (2011) reported similar emission rates, of 0.58×10^{12} and 1.6×10^{12} particles/min for pilot lights in two California homes.

Wallace et al. (2008) completed 42 experiments in a National Institutes of Standards and Technology (NIST) test house to study UFP emission rates and size distributions produced by the burner flame and gas oven alone, e.g., without pots or food. For experiments with a single burner, the peak particle concentrations across all sizes were 4 to 8 times higher in the kitchen than in a bedroom, with peak values exceeding 10^6 particles/cm^3 in the kitchen. While stovetop burners produced size distributions with GMDs in the range of 4 to 7 nm, the gas oven and broiler generally produced larger particles with GMDs of up to 24 nm. Peak emission rates of UFPs were estimated to be $2.8\times10^{14} – 7.8\times10^{14}$ particles/hr for a single gas burner with high gas flow and $1.8\times10^{13} – 3.1\times10^{14}$ particles/hr for oven bake/broil experiments. The addition of food being cooked or water boiled did not appreciably change the geometric mean diameter of particles and generally reduced UFP emissions to some extent.

Singer et al. (2017) completed field measurements in nine homes with natural gas for cooking and measured particles with diameters of 6 nm or larger in the kitchen and bedroom area of each home. The ratio of the kitchen-to-bedroom 1-hour integrated particle count concentration ranged from approximately 1 to nearly 10, with differences associated with the residence floor plan, e.g., the location of the bedroom relative to the kitchen. Boiling and simmering events were completed using the stovetop and oven in the absence and presence of range hood exhaust or air mixing by a forced air system. Particle number emission factors ranged from less than 5×10^6 to over 20×10^6 per joule of gas burned.

Studies for which ultrafine particle number emissions are back-calculated based on measurements in chamber or home air may significantly underestimate emission source strength if they do not account for coagulation and surface deposition of particles. Rim et al. (2016) completed experiments in a full-scale test house to determine UFP emissions (2–100 nm) for a number of sources, including unobstructed (no cooking) natural gas burners, with consideration of coagulation and deposition processes. Their measurements reflected a shift in particle sizes from smaller to larger over time, well predicted using a dynamic coagulation model. The UFP source strengths ranged from 1.7×10^{14}/hr to 4.6×10^{15}/hr, a higher upper bound than reported by others and values that are considerably higher than would have been the case if coagulation had not been accounted for when back-calculating emissions from indoor air measurements.

Past natural gas cooking studies have focused on concentrations or emissions of ultrafine particles, and few have reported particle mass concentrations or emissions. Hubbard et al. (2005) activated two gas burners for 15 minutes on a stovetop and observed a rapid 17 μg/m^3 increase in PM_1 concentration measured approximately 7 m from the stove, with subsequent decay shortly after switching off burners.

While the literature on natural gas combustion and its effects on indoor air quality is dominated by cooking appliances, several other sources exist, including unvented natural gas space heaters, unvented natural gas fireplaces, gas water heaters, and clothes dryers. Weichenthal et al. (2007) measured ultrafine particle concentrations outdoors and inside 36 homes in Canada and found that forced-air gas heating systems (n = 10 homes) were not an important predictor of indoor UFPs, particularly when compared with cooking and also cigarette smoking (n = 3 homes). Wallace and Ott (2011) observed significant increases above median background concentrations (multiplier of approximately 2.5 to 6) for UFP greater than 10 nm in diameter (instrument detection limit) when a vented gas space heater was used in the basement of a townhouse. Dutton et al. (2001) studied unvented gas fireplaces

in two homes and observed eight different PAHs, all with four or five rings, in $PM_{2.5}$. Wallace (2005) studied a gas clothes dryer vented to the outdoors over an 18-month period in an occupied townhouse. Ultrafine particle concentrations increased during dryer use by a factor of 10, with short-term peak concentrations exceeding 100,000 particles/cm^3 and a bimodal size distribution with peaks at less than 9.8 nm and 30 nm. The emission rate was estimated to be 6×10^{12} particles per drying episode, with emissions likely much higher given that measurements were limited to particle diameters of 9.8 nm and above. Wallace hypothesized that emissions were likely from the combustion chamber below the tumbler.

The chemical composition of ultrafine particles emitted from combustion of natural gas has not been widely explored, particularly in the United States. Murr et al. (2004) described the importance of natural gas combustion as a source of carbon nanotubes and other nanoform UFPs. A greater crystalline appearance of nanoparticles was evident for combustion of propane than for natural gas, perhaps an important difference for those who employ propane in rural areas and manufactured homes. However, the health significance of the chemical composition of ultrafine particles emitted from combustion of natural gas has not been widely explored, particularly in the United States. Murr et al. (2004) described the importance of natural gas combustion as a source of nanotubes and other nanoforms. A greater crystalline appearance of nanoparticles was evident for combustion of propane than for natural gas, perhaps an important difference for those who employ propane in rural areas and manufactured homes. However, the health significance of nanostructures was not described, and the results were qualitative as opposed to quantitative. See and Balasubramanian (2008) analyzed the composition of UFPs emitted from the combustion of natural "town" gas in an apartment in Singapore. For steaming and boiling water to cook tofu they observed that approximately 50 percent of total $PM_{2.5}$ emissions were in the form of organic carbon (OC). Sub-ng/m^3 concentrations of individual PAHs were measured, summing to less than 0.05 percent of the total organic carbon (OC). A large number of metals were associated with UFPs. The source of these metals was not identified.

Combustion of Wood

Major devices used to combust wood indoors include traditional masonry fireplaces, wood stoves, pellet stoves, and masonry heaters. Wood combustion in these devices is the primary heat source for approximately 1.7 million U.S. homes and provides for some energy needs in another 10 million homes (EIA, 2023). It is also a major source of outdoor air pollution. In all but eight states, residential wood burning is one of the three largest contributors to ambient $PM_{2.5}$ (Marin et al., 2022). In 2017, combustion of wood provided 2.2 percent of residential energy but was responsible for 98 percent of total $PM_{2.5}$ emissions associated with residential fuel combustion (EPA, 2017).

There are two pathways for indoor exposure to fine particulate matter emitted by the residential combustion of wood. The first is direct emissions of smoke that escape from a device housed indoors, e.g., a wood stove. The second involves exhaust to outdoors by a chimney with penetration back into homes (becoming outdoor pollution of indoor origin) (Pierson et al., 1989). The remainder of this section is intended to summarize knowledge of fine particle emissions from the two major types of devices used for residential wood combustion: fireplaces and wood stoves.

The health effects of short-term exposures to wood combustion have been documented, but the evidence generally does not allow for a separation of the effects of $PM_{2.5}$ and gaseous pollutants. Furthermore, health effects are often associated with outdoor pollutant concentrations. Residential wood combustion is estimated to be responsible for approximately 10,000 American deaths each year (Penn et al., 2017) as well as 44 percent of total stationary and mobile source polycyclic organic matter emissions and 25 percent of all air toxic cancer risks (EPA, 2015). Pollutants associated with wood combustion can increase susceptibility to respiratory infections, cause asthma symptoms and acute bronchitis, increase the risk of developing chronic obstructive pulmonary disease (COPD), particularly among women and smokers, elevate the risk of heart attacks, and lead to greater risk of hypertensive pregnancy disorders (Assibey-Mensah et al., 2019; Hopke et al., 2020; Marin et al., 2022; Naeher et al., 2007; Unosson et al., 2013). Furthermore, wood smoke has a disproportionate impact on rural and some low-income communities. Of rural homes, 27 percent use wood combustion for heating, while the same is only true for 6 percent of urban households (Marin et al., 2022). The amount of residential wood combustion is highest in households with annual incomes less than $40,000 per year (Marin et al., 2022). Up to 89 percent of homes in the largest sovereign Native American nation within the U.S. (Navajo nation) use wood stoves for heating (Environmental Law Institute, 2021).

Fireplaces are important sources of fine particulate matter emissions. The Environmental Protection Agency (EPA) estimated that there were over 17.5 million fireplaces in the United States in 2016 (EPA, 2016). Most are used to combust wood or synthetic logs as the fuel source.

For traditional wood-burning fireplaces, major factors that affect indoor pollutant emissions include the ventilation conditions of the fireplace at the time of combustion; the species of wood used as fuel and its moisture content; and combustion conditions, e.g., how wood is split and interacts with oxygen during combustion (Castro et al., 2018; Stabile et al., 2018). Most studies of wood-burning fireplaces have focused on indoor emissions of carbon monoxide, nitrogen dioxide, and coarse and fine particulate matter. A few have addressed the composition of particulate matter.

The inhalation dose of fine particulate matter emitted from fireplaces to indoor air can be significant. Stabile et al. (2018) completed sampling in 30 residences and observed an order of magnitude increase in estimated lung-deposited surface area of particles when an open fireplace was used as opposed to one with a closed opening. Buonnano et al. (2012a) studied 8- to 11-year-old children for 5 months and observed elevated values of inhalation dose for those who lived in homes with fireplaces. Dacunto et al. (2013) completed experiments to determine $PM_{2.5}$ emissions from three open fireplaces using cherry wood and a commercial synthetic log. They observed steady $PM_{2.5}$ emission rates of approximately 16 to 18 mg/min into the indoor spaces. A spike in emissions occurred when combustion was extinguished with water.

The composition of particle emissions from fireplaces is primarily organic carbon (OC) in nature with a small fraction of elemental carbon (Castro et al., 2018). Castro et al. (2018) studied an open fireplace with combustion of oak in a single home. They observed a 15.7 (mean) +/- 0.6 $\mu g/m^3$ (standard deviation) increase in organic carbon above pre-burn baseline in the home. The count-median diameter was approximately 0.2 µm with most particles in the coarse mode in the range of 2 to 3 µm. The organic carbon fraction includes a range of polycyclic aromatic hydrocarbons (PAHs) (De Gennaro et al., 2016). A large number of metals have also been observed in particle emissions associated with wood smoke from fireplaces (Castro et al., 2018; Stabile et al., 2018).

Wood stoves are also major contributors to fine particulate matter in both outdoor and indoor air. Fleisch et al. (2020) measured indoor $PM_{2.5}$ and its components in 137 homes occupied by pregnant women in northern New England. Moderately higher $PM_{2.5}$ and much higher black and elemental carbon concentrations were observed in homes with wood stoves in operation. Non-EPA-certified stoves, older stoves, and wood that was not properly dried were associated with higher particulate matter concentrations, particularly black carbon. Black carbon (BC) is composed almost entirely of elemental carbon (EC) and is often found in fine PM as a result of incomplete combustion of fossil fuels and biofuels, and biomass, and therefore reflects the contribution of combustion sources to fine PM. By contrast, brown carbon (BrC) is defined as light-absorbing organic carbon and is emitted primarily by biomass burning.

Semmens et al. (2015) studied $PM_{2.5}$ in 96 northwestern and Alaskan homes that used wood stoves as their primary heat source. They observed relatively high average indoor particulate matter concentrations in homes with wood stoves and an inverse association between household income and both $PM_{2.5}$ and smaller size fraction particle number concentrations. Weichenthal et al. (2007) studied PM_4 and UFP concentrations associated with wood stoves in seven Canadian homes. Homes using wood stoves had significantly higher overnight baseline UFP concentrations than homes in the same study that employed forced-air natural gas furnaces for heating. Median, 75th-percentile, and maximum UFP concentrations were higher in homes with wood stoves than in those using electric, natural gas, or oil heating systems. Salthammer et al. (2014) measured UFP and $PM_{2.5}$ concentrations in seven German homes before, during, and after operation of wood stoves. They observed significant increases in UFP concentrations in each home during wood stove use. Siponen et al. (2019) measured personal concentrations of $PM_{2.5}$ and a BC surrogate for 37 elderly subjects over a 6-month period in Finland. They observed average increases in personal concentrations of 20 percent and 9 percent of $PM_{2.5}$ and BC, respectively, when a wood stove was used for room heating. Frasca et al. (2018) studied the impacts of wood stoves in two residences and observed that the major source of exposure to particulate matter was during the removal of ashes from the stoves. This process was observed to release both fine and coarse particulate matter, with relatively high amounts of copper and manganese emitted to indoor air during ash removal from a pellet stove.

A number of factors are associated with lower fine and ultrafine particle emissions from wood stoves. In general, more efficient (typically newer) devices, pellet stoves (as opposed to stacked wood stoves), dry wood (<20 percent moisture content), wood seasoned for at least 6 months, natural fire starters, and small and hot (as opposed to smoldering) combustion all lead to lower emissions (Environmental Law Institute, 2021). The type of wood also affects particle emissions. Champion et al. (2017) completed experiments on a residential wood stove and observed higher $PM_{2.5}$ and organic carbon emission factors (grams emitted per kg of wood burned) for ponderosa pine relative to Utah juniper, but a lower elemental carbon emission factor for ponderosa pine. Li et al. (2018) observed ponderosa pine to have consistently stronger oxidative stress and inflammatory effects relative to Utah juniper and even coal burned in the same stove, with low volatility organic compounds, elemental carbon, and several metals (Cu, Ni, K) all positively correlated with adverse cellular responses. Nystrom et al. (2017) observed that the burn rate of ponderosa pine affects the degree of soot particles and organic content, with metals in residual ash defined by the wood content.

Combustion of Oil, Coal, and Other Fuels for Residential Space Heating and Combustion Source Contributions in Schools

Emissions stemming from the combustion of several other fuels used for indoor heating have been reported in the published literature, but to a much lesser extent than for natural gas and wood. Champion et al. (2017) reported emissions from the combustion of two high-volatile bituminous coals used in wood stoves for heating in the Navajo nation. Average emission factors (g of pollutant / kg of fuel burned) for $PM_{2.5}$ and organic carbon were approximately an order of magnitude greater for coal than for two types of wood fuel. Schripp et al. (2014) studied four different unvented fireplaces with eight different ethanol-based fuels (liquid, gel, and paste) in a laboratory chamber and observed elevated number concentrations of UFPs relative to background chamber air. Similar results have been observed in homes in Chile when unvented kerosene space heaters were used for heating, with elevated levels of $PM_{2.5}$, organic carbon, elemental carbon, metals, and PAHs (Ruiz et al., 2010). Indoor UFP concentrations associated with forced air oil furnaces in 10 Canadian homes were not statistically different when compared against homes using electric baseboards, natural gas, or wood stoves for heating (Weichenthal et al., 2007).

Few studies have focused on particle emissions associated with combustion sources in schools. Matthaios et al. (2022) used a least absolute shrinkage and selection operator (LASSO) mixed-effects model to study factors influencing fine particulate matter, BC, and nitrogen dioxide in 309 classrooms in 74 inner city schools in a large northeastern U.S. city. Factors that were positively associated with $PM_{2.5}$ in classrooms included proximity to a school cafeteria and classrooms with windows facing a bus loading area. Time since furnace cleaning was positively associated with BC concentrations in classrooms, accounting for 19 percent (absolute) of the 23 percent of school-related factors associated with BC.

Combustion of Candles

Candles are generally used for several hours after ignition (Wallace et al., 2019), with extensive use around holidays (Andersen et al., 2021). Primary locations in U.S. homes, in descending order, include living rooms, kitchens, and bedrooms (Wallace et al., 2019).

Studies on the health effects of candles are sparse. Lim et al. (2022) cited several studies with conflicting results related to the effects of candle emissions on reduced lung function. Lim et al. (2022) also studied inflammatory markers and lung function for pollutants of both indoor and outdoor origin and women and men between the ages of 49 and 63 years old in Copenhagen suggested no adverse effects of candles on lung function. Loft et al. (2022) found no statistically significant associations between candle use and risk of cardiovascular and respiratory events based on a cohort of 6,757 participants in Copenhagen, Denmark. Shehab and Pope (2019) exposed human subjects to candle smoke in a room, and their tests indicated a statistically robust decline in cognitive function after exposure.

Candles vary by type of wax (fuel), fragrance ingredients and load, type and composition of wick, colorants, and shape (e.g., filled container versus open pillar) (Andersen et al., 2021; Salthammer et al., 2021). The primary waxes used in candles consist of C_{20} to C_{40} hydrocarbons, long-chain fatty acids, and their esters (Salthammer et al., 2021). Common waxes include paraffin, stearin, beeswax, soy, palm oil, and associated mixtures (Andersen et al., 2021; Salthammer et al., 2021). The typical contribution of fragrances varies from 0 percent (unscented) to approximately 5 percent of overall candle weight and are generally essential oils and their mixtures (Derudi et al., 2012; Salthammer et al., 2021). The National Candle Association estimates that more than 10,000 different candle scents are available in the United States (National Candle Association, n.d.). Candle wicks are generally cotton and sometimes paper and vary by length, thickness, and the additives used as flame retardants (to control flame). Wick additives may vary for different fuels and are generally inorganic, e.g., phosphates and nitrates (Andersen et al. 2021; Salthammer et al. 2021).

Burn rates for candles are generally in the range of approximately 3 to 7 g/hr (Andersen et al., 2021; Salthammer et al., 2021). Burn modes include steady burn (generally not disturbed by air flow), sooting burn (when a flame is flow-disturbed), and smoldering (immediately after extinction). These modes greatly influence the nature of emissions from candles, particularly particle size and composition (Pagels et al., 2009).

The composition of UFPs emitted by candles is dominated by water-soluble inorganic compounds associated with the burning wick (Andersen et al., 2021). UFPs contain little elemental carbon (EC) or black carbon (BC) (Andersen et al., 2021). Emissions during unsteady burning (flickering flame) can lead to larger particles with the potential for significant emissions of BC (Andersen et al., 2021; Hu et al., 2012). Candles also emit PAHs in both the particulate and gaseous phases, and a wide range of organic and inorganic gases (Andersen et al., 2021; Derudi et al., 2012, 2014; Salthammer et al., 2021). Andersen et al. (2021) reported PAH emissions of 25–578 ng/hr. Salthammer et al. (2021) reported a similar range for summed PAHs of 79–1,286 ng/hr and noted that PAH emissions for unscented candles were much less than those for scented candles. In both of these studies, gas-phase and particle phase PAHs were not separated.

Significant variations in reported particle emissions exist in the published literature. Variations occur due to different burn rates, type of wax, type of wick, the extent and nature of fragrances, and burn conditions. Reported emissions of UFPs vary across approximately four orders of magnitude. Accordingly, candles can be major or even dominant sources of particles by number concentration in homes. For example, they were observed to be a major source of particle number concentrations in half of 56 non-smoking homes studied in Copenhagen, contributing 60 percent of exposure to particles in the diameter range of 10 to 300 nm (Bekö et al., 2013). J. Zhao et al. (2020) measured number size distributions (10–800 nm) in 40 German households over 500 days and approximately 800 indoor source events. They observed the highest emission rates from burning candles (5.3×10^{13} particles/hr). Burning candles and opening windows lead to seasonal differences in the contributions of indoor sources to residential exposures.

Emission rates for ultrafine particles have been reported by several research teams. Salthammer et al. (2021) reported a range of UFP emissions from 5.9×10^{10} particles/hr to 3.2×10^{12} particles/hr with a median of 9.4×10^{11} particles/hr across 24 experiments with a wide range of wax and fragrance conditions under steady burn conditions. They observed a particle size range of 6–60 nm with a count median diameter of 19 nm initially, dropping to 12 nm after 4 hours of steady burn. Soy-based candles had the highest emission rates across scented candles, and paraffin and palm-based candles had the lowest emission rates. Among candles without fragrances, palm and stearin-based candles had the highest emissions, and paraffin and soy-based candles had the lowest emissions. Andersen et al. (2021) reported an emissions range of 1.5×10^{13} particles/hr to 9.3×10^{13} particles/hr for five pillar candles with varying wax and wick compositions and steady vs. unsteady burn conditions. The particle diameter mode ranged from 5 to 8 nm for four candles, with a bimodal distribution with peaks at 6 nm and 200 nm for a fifth candle. Wallace et al. (2019) observed a mean UFP emission rate of 4.3×10^{14} particles/hr with a standard deviation of 4.6×10^{14} particles/hr. Some types of candles exhibited steady burn conditions while others exhibited sooting burn conditions. They suggested that the higher UFP emission rate than others had reported was due to the inclusion of a smaller particle size bin (2.33 to 2.5 nm) that dominated particle counts. They also accounted for coagulation and particle decay by deposition to back-calculate emissions; other studies used concentration measurements in chamber air without consideration of particle growth.

Reported emission rates for $PM_{2.5}$ also vary considerably. Andersen et al. (2021) reported a range of 283–3,038 µg/hr, with EC emissions in the range of 30–3,132 µg/hr and OC emissions of 46–232 µg/hr, under sooting burn conditions. Derudi et al (2014) observed a range of 5.8–270 µg/hr with particles less than 250 nm dominating overall emissions. The authors did not provide specific burn conditions. Salthammer et al. (2021) reported a range of 16–379 µg/hr with palm and stearin-based candle emissions lower than soy and paraffin-based candles under steady burn conditions. On average, they observed candles without fragrance addition to have lower $PM_{2.5}$ emissions than those with fragrances.

Several studies have reported particle size ranges for different burn modes. Manoukian et al. (2013) reported a particle number mode of less than 11 nm for steady burn and a bimodal distribution with peaks at less than 11 nm and at 92 nm following flame extinction (smoldering candle). Pagels et al. (2009) reported a particle number mode between 20 and 30 nm for steady burn and geometric mean diameters of 270 nm for sooting (unsteady burn) and 335 nm for a smoldering candle. An in-room particle diameter mode of 11–26 nm with a close-to-source range of 7–18 nm was reported by the Danish Environmental Protection Agency (2017).

Combustion of Incense

Incense is burned inside homes and in some public places, e.g., retail stores, places of worship. It is used for sacred purposes by various religions across the world. In some cultures, incense is burned in the home daily in conjunction with religious rituals (Jetter et al., 2002). Among some indigenous communities of North America, the practice of smudging involves burning sacred natural medicines (e.g., sage, cedar, sweet grass) to pray and purify oneself or a specific physical space (Ko, 2020). Incense comes in various forms, including sticks (common in the United States), Joss sticks, cones, coils, rope, powders, and smudge. In addition to religious services and rituals, it is used broadly for purposes of aromatherapy and odor masking.

Incense use in the United States is increasing. In 2018, the U.S. incense market size was $128 million and is forecast to reach $281 million in 2025, growing at an expected compound annual growth rate of approximately 12 percent from 2018 to 2025 (Francis, 2020). The United States is the top importer of incense in the world, with most of its incense products coming from India, China, and Vietnam; annual import shipments to the U.S. currently stand at 71,500, imported by 2,504 U.S. importers from 1,143 suppliers (Volza, n.d.).

Incense commonly has two main ingredients: an aromatic material that is usually plant-based and a combustible base that holds the aromatic material together. The aromatic (fragrance) is released during the burning of the combustible base. Aromatic materials include wood and bark, herbs, seeds, spices, essential oils, and synthetic substitute chemicals (Jetter et al., 2002). The combustible base is often wood powder, bamboo, mucilage, and sometimes charcoal (T.-C. Lin et al., 2008; Live Smoke Free, n.d.). Incense sticks typically employ bamboo or wood for the actual "stick" onto which the incense powder is held.

The health impacts associated with exposure to incense smoke have been studied to a much greater extent than for candles. As with candles, effects on cognition have also been reported. Greater than weekly incense use by older adults in Hong Kong have been associated with poorer cognitive performance over 3 years (A. Wong et al., 2020). Mutagenic and genotoxic effects of incense smoke have also been studied. Chen and Lee (1996) reported incense smoke condensates to be mutagenic or genotoxic or both. The genotoxicity of certain incense smoke condensates in mammalian cells was observed to be higher than from tobacco smoke condensates. Friborg et al. (2008) studied over 61,000 individuals (ages 45–74) from the Singapore Chinese Health Study completed between 1993 and 1998. The individuals were initially diagnosed as being cancer free and were followed to 2005. A strong association was observed between use of incense over the subsequent 7 to 12 year period and increased risk of squamous cell carcinoma of the respiratory tract. Similarly, Geng et al. (2019) used the same initial cohort coupled to a Singapore renal registry in 2015. They observed a likely increase in end-stage renal disease for long-term daily exposure to domestic incense smoke.

Tse et al. (2011) observed an association between lung cancer and incense exposure among male smokers in China but did not find an association with non-smokers. Jetter et al. (2002) reported on three earlier epidemiological studies where no association was observed between incense smoke and lung cancer. However, in these studies incense burning was associated with greater affluence, a healthier lifestyle, and better diet that may have affected study outcomes.

The effects of incense burning on children have also been studied; the reader is directed to cited papers for details of study design and greater insights related to outcomes. Lowengart et al. (1987) used a case–control study of children of ages 10 years and under in Los Angeles County to investigate causes of leukemia. An increased risk was found for children whose parents burned incense in the home; the risk was greater for frequent use. Wei et al. (2018) studied 15,310 infants in Taiwan and found that household incense burning was associated with a delay in gross motor neurodevelopmental milestones. Incense burning showed effects on coughing symptoms in primary school children in Taiwan (C.-Y. Yang et al., 1997).

Numerous researchers have studied particles and a wide range of speciated gas emissions from the burning of incense. Past studies have largely involved the measurement of dynamic or approximately steady-state pollutant concentrations in controlled laboratory chambers while burning one or more of the same type of incense, e.g., stick or cone. Measured emissions of $PM_{2.5}$ are generally much greater than those reported for candles during steady or soot burn conditions, with particle size distributions shifted to larger particles compared with candles. Incense sticks burned in a test house led to concentrations in some locations of hundreds of $\mu g/m^3$ (Ji et al., 2010).

Jetter et al. (2002) reported $PM_{2.5}$ emissions from 23 different types of incense. Emission rates ranged from 7 to 202 mg/hr, with emission factors of 5–56 mg/g of incense burned. Smudge bundles and cone incense exhibited the highest emission rates. Emissions for incense sticks ranged from 7 to 108 mg/hr. The authors concluded that "incense emits fine particulate matter in large quantities compared to other indoor sources" and completed model simulations for a small room with predicted concentrations of $PM_{2.5}$ that exceeded several thousand $\mu g/m^3$.

Lee and Wang (2004) measured $PM_{2.5}$ emissions from 10 different incense products (eight sticks, one bar, and one rock) purchased from around the world. Incense sticks had emission rates that varied from 10 to 301 mg/hr, reasonably consistent with the findings of Jetter et al. (2002). The rock emitted nearly 2,200 mg/hr. Emission factors ranged from 7.7 to 99.7 mg/g of incense burned for sticks and 205 mg/g burned for the rock incense.

See and Balasubramanian (2011) measured $PM_{2.5}$ emissions and composition for six different brands of incense sticks procured in Singapore. The mean emission rates for $PM_{2.5}$ varied from 18.5 to 60.9 mg/hr for five of the six incense sticks (with mean emission factors of 18.3–44.5 mg/g of incense burned) and only 0.6 mg/hr for the sixth (with an emission factor of 0.4 mg/g of incense burned). The sixth incense stick was marketed as "smokeless" but additional information was not provided by the authors. Emission factors for elemental and organic carbon ranged from 0.02 to 4.36 mg/hr and 0.04 to 44.4 mg/hr, respectively, with organic carbon to elemental carbon ratios (OC/ECs) varying between 0.09 and 0.56. Wang et al. (2006) tested 10 different types of incense and observed OC/EC ratios reasonably consistent with those reported by See and Balasubramanian (2011). Specifically, they observed a range of OC/EC of 0.07–0.39 for traditional incense, with an average of 0.22. For aromatic incense the OC/EC ratios were lower, with a range of 0.032–0.12 and an average of 0.077.

Median diameters of emitted particle size distributions from the burning of incense are generally larger than those for candles. See et al. (2007) completed real-time characterizations of the size distribution and number concentration of sub-micrometer particles emitted from incense smoke for four different brands of sandalwood and aloeswood incense sticks. Particle emission rates varied from 5.1×10^{12} to 1.42×10^{13}/hr. Peak diameters ranged from 93.1 to 143.3 nm.

Aside from OC/EC ratios, a few authors have also provided insights into the composition of incense smoke. See and Balasubramanian (2011) observed Al and Fe to be the most abundant metals associated with incense particles. B. Wang et al. (2006) observed significant variability in the composition of different brands of incense, but in general Na, Cl, and K dominated. On average, inorganic ion concentrations were such that traditional incense > church incense > aromatic incense. Li et al. (2022) studied seven different types of incense from China and characterized emission factors and composition of PAHs associated with emitted particles. PAHs constituted the largest proportion (41.5–63.7 percent) of the total quantified organics.

C. R. Yang et al. (2012) carried out laboratory experiments to explore source reduction of particulate matter (assumed to be $PM_{2.5}$ but not stated in paper) and PAHs by the addition of calcium carbonate ($CaCO_3$) to 10 different types of incense sticks. They observed a significant reduction for both as a function of the amount of $CaCO_3$ added (mean particulate matter reductions of up to 41 percent for 30 percent $CaCO_3$ addition).

Indoor PM from Other Heating Processes

Other indoor heating processes beyond combustion can also contribute significant amounts of PM to indoor environments. Examples include meal cooking (Y. Chen et al., 2016; Katz et al., 2021; Patel et al., 2020; Torkmahalleh et al., 2017), heating cooking utensils (Wallace et al., 2015), heating surfaces such as hot-water or electric radiators for indoor heating (Afshari et al., 2005), and even the operation of office and consumer products such as printers (He et al., 2007; Schripp et al., 2008; Scungio et al., 2017), electronic cigarettes (Fernández et al., 2015; Fuoco et al., 2014; Nguyen et al., 2019), and heated scent diffusers (Su et al., 2007).

Indoor Cooking Activities

Cooking is a major heating process that takes place daily in most residential environments and many schools. Thus, cooking is a significant source of indoor $PM_{2.5}$, particularly in homes but also in school cafeterias. Cooking activities have been characterized as emitters of particles from two distinct sources: the heating source and heating the food itself. The process of heating up food, regardless of the fuel or heating source that is used, leads to the evaporation of food constituents, which then recondense as particles once they reach ambient temperature. A previous section of this chapter included emissions specific to natural gas combustion as part of a broader discussion of natural gas appliances in homes. That section did not include emissions from cooking oils or food itself, but rather just the fuel. The current section also focuses on cooking with heat sources other than natural gas or propane.

Several factors can influence the emission of cooking aerosols. Foods with higher fat content have been found to have higher particle emission rates than those with less fat (Buonanno et al., 2009). Additionally, the total exposed surface area, the smoke point of the oil used, the presence of salts, and cooking temperature have also been found to affect PM emissions from cooking (Sankhyan et al., 2022; Torkmahalleh et al., 2017). High-temperature processes such as frying, grilling, broiling, and roasting have been shown to lead to high number and mass PM concentrations (Abdullahi et al., 2013; Buonanno et al., 2011). Once cooking aerosols are emitted, they can be removed from the air via a variety of processes, described in more detail in Chapter 4 and Chapter 7 of this report. Cooking activities performed on countertop appliances (e.g., toasters and toaster ovens, countertop induction cooktops, electric pots, etc.) are of particular interest for indoor PM emissions from food and heated surfaces because their emissions are less likely to be vented using range hoods, unlike many stove tops and ovens.

The composition of indoor cooking organic aerosol (COA) was found to encompass a majority of compounds with molecular formulas containing carbon, hydrogen, and oxygen atoms only, followed by nitrogen-containing organic compounds (Masoud et al., 2022). A review by Abdullahi et al. (2013) reported the following major groups to characterize COA: alkanes, fatty acids, dicarboxylic acids, lactones, polycyclic aromatic hydrocarbons, alkanones and sterols.

Particle-phase amides from cooking protein-rich foods have also been reported, with concentrations ranging from 45 to 218 μg/g (Ditto et al., 2022). Multiple studies have shown, through field and laboratory measurements, that cooking emissions, particularly cooking oils, generate aerosols with a range of volatilities, including a lower-volatility component not traditionally included in ambient COA models; this component has also been described as a "nonvolatile core" in some studies (Buonanno et al., 2011; Pothier et al., 2023; Sankhyan et al., 2022). Sankhyan et al. (2021) reported enhancements in BC and brown carbon (BrC) aerosol concentrations during indoor cooking activities and observed varying BC/BrC ratios. While breakfast (pan-fried sausage, fried eggs, fried tomato, toast, and coffee) emitted more BC than BrC, a traditional Thanksgiving meal (oven-roasted turkey, bread stuffing, brussels sprouts, sweet potato casserole, pies, cranberry sauce, and gravy) emitted more BrC than BC, and cooking a vegetable stir fry and a beef chili both emitted similar concentrations of BC and BrC. Despite significant growth in knowledge on the composition of cooking aerosol, some gaps in the literature remain in terms of the ultrafine and single-nanometer components of these emissions.

Furthermore, food preparation and cooking may release allergen-containing particles into the air (Kumar et al., 2021; Shale and Lues, 2007). In fact, exposure to some food ingredients via paths other than ingestion, e.g., skin contact and inhalation when associated with fine PM, is probably an underrecognized and underreported route for adverse reactions in highly sensitive individuals, as described by Ramirez and Bahna (2009). In residential and school settings, commonly reported food allergens include wheat flour, seafood, soy, peanuts, nuts, eggs, and cow's milk. Common manifestations of allergic reactions by inhalation include respiratory and ocular symptoms as well as skin manifestations (Ramirez and Bahna, 2009). According to a review by Caffarelli et al. (2016), inhalation of food allergens has been reported to lead to asthmatic symptoms in children.|

Studies performed in residential environments have shown that cooking is a major source of indoor $PM_{2.5}$, often leading to short-term, but intense increases in indoor PM concentrations. Wallace and Ott performed over 300 measurements in several homes and documented sharp bursts of particulate matter during several cooking-related activities, such as stovetop cooking, baking or broiling in the oven, using a toaster oven, and even popping corn in an air popper (Wallace and Ott, 2011). Another study in 15 homes in Australia reported that indoor frying and grilling elevated indoor $PM_{2.5}$ concentrations by 30- and 90-fold, respectively, compared with background levels (He et al., 2004). The HOMEChem study found that cooking emissions led to indoor $PM_{2.5}$ concentrations exceeding 250 $\mu g/m^3$ (Farmer et al., 2019; Patel et al., 2020). Emissions in terms of particle (>10 nm in size) number from cooking activities have been estimated to be in the order of 10^{13} particles per hour of cooking (Patel et al., 2021; J. Zhao et al., 2020).

Even the mass concentration of ultrafine particles (PM <100 nm in diameter) has been found to exceed 100 $\mu g/m^3$ during intense cooking events, such as the preparation of a Thanksgiving holiday meal (Patel et al., 2020). As previously noted, J. Zhao et al. (2020) performed a study in 40 German homes and found that several cooking activities, including baking, frying, using a toaster, and others, all led to particle size distributions peaking at <100 nm in size. Buonanno et al. (2009) also showed cooking emissions consisting mostly of ultrafine aerosols in terms of particle number, with particle mass peaks extending into coarse mode. Torkmahalleh et al. (2012) also reported a majority (up to 99 percent) of particle numbers in the

10- to 100-nm size range from heating cooking oils, with $PM_{2.5}$ emission fluxes ranging from 3×10^5 to 6×10^6 µg/min/m^2, normalized by the exposed surface area of oil.

In school environments, the majority of recently published studies report results obtained in other countries, particularly in Asia (Jung and Su, 2020; I.-J. Lee et al., 2022; Q. Xie et al., 2022). Published $PM_{2.5}$ measurements in cafeterias or other cooking facilities in U.S. schools are sparse (Majd et al., 2019; Zhang and Zhu, 2012). A study performed in 25 public schools in the Republic of Korea found an average $PM_{2.5}$ concentration of about 25 µg/m^3 during cooking of "oily" foods, while outdoor concentrations were about 18 µg/m^3. A study performed in different microenvironments in a university in Beijing found that the dining hall had slightly higher $PM_{2.5}$ concentrations than the other indoor areas (e.g., classroom, dormitory, laboratory, etc.). In the dining hall, cooking was performed using gas-fueled appliances. Nevertheless, the majority of indoor $PM_{2.5}$ exposure of students in this study was due to PM infiltration from outdoors (Q. Xie et al., 2022). $PM_{2.5}$ concentrations were reported in the 80–100 µg/m^3 range in two university buffets in Greece (Kogianni et al., 2021), much higher than the averages reported in other studies for indoor cafeterias, likely due to cooking activities and potentially due to indoor smoking as well. This demonstrates that indoor concentrations are likely to vary greatly depending on the amount and type of cooking activity that takes place in each cafeteria and whether there is indoor smoking.

Cookware and Other Appliances

The process of heating cooking utensils and instruments themselves, even without food, has been found to lead to the formation of particles attributed to desorption of semi-volatile organic compounds (SVOCs) present on their surface, which then recondense in the indoor air and form ultrafine particles. Wallace et al. (2015) provided evidence that organic compounds that continually deposit on indoor surfaces lead to an organic film reservoir that forms particles in air after surface heating. Dishwashing soap residue was also shown to lead to the production of large amounts of particles after surface heating. Metal objects such as pots, pans, griddles, stovetop burners, and toaster ovens all led to ultrafine particle emissions once heated (Wallace et al., 2015, 2017). This phenomenon was also observed in previous studies, although many of these studies investigated the effects of indoor dust deposition onto surfaces (Afshari et al., 2005; Ciuzas et al., 2015; Dennekamp et al., 2001; Glytsos et al., 2010; Pedersen et al., 2001). Pedersen et al. (2001) found that particle emissions occurred when the dust-laden surface was heated to at least 100 °C and that major emissions took place at >200 °C. Torkmahalleh et al. (2018) demonstrated that heating an empty pan led to similar particle number concentrations in an indoor environment as heating meat on the same pan and that particle number emissions (>10 nm in diameter) from the electric-coil stove top used for heating were negligible by comparison. This phenomenon is not exclusive to cooking surfaces; it has also been described for heating processes such as hand dryers, hair dryers, and irons, as described later in this chapter. Silberstein et al. also documented new particle formation events during mechanical heating, ventilation, and air conditioning system (HVAC) use overnight in winter following cleaning activities--evidence of SVOC desorption from HVAC surfaces by the furnace system (Silberstein et al., 2023).

Office Equipment

There are many office products whose use involve heating processes, which can lead to the evaporation of a wide variety of compounds, thus generating ultrafine aerosol upon condensation in indoor air. Office products such as photocopiers, printers, and even 3D printers can be important sources of $PM_{2.5}$ (mainly as UFPs) in schools and in some residential microenvironments.

Laser printers are known to emit significant amounts of particles, mostly in the submicrometer and ultrafine size ranges, according to multiple studies in office environments and in controlled chambers (C. He et al., 2007; McGarry et al., 2011; Schripp et al., 2008; Setyawati et al., 2020; Shi et al., 2015). Inkjet printers, on the other hand, have shown negligible particle emissions (Shi et al., 2015). Kogianni et al. (2021) measured $PM_{2.5}$ concentrations in 20 different work environments and found average $PM_{2.5}$ concentrations in the 11–15 μg/m^3 range for photocopying centers and printing shops. The printing shop exhibited the highest concentration of zinc-containing aerosols of all investigated locations. McGarry et al. (2011) showed that the peak exposure to particles from laser printers can be greater than 2 orders of magnitude higher than background levels. But not all laser printers are strong particle emitters; there is great variability among printers in terms of PM emissions and their effects in indoor spaces. A study in 62 office rooms in Germany showed that $PM_{2.5}$ concentrations increased in 70 percent of offices while printing a 500-page document using a laser printer (Tang et al., 2012). Shi et al. (2015) classified approximately 67 percent of the 55 laser printers they investigated in a controlled chamber study as "high particle emitters." C. He et al. (2007) investigated 62 printers and reported that 60 percent of those did not emit submicrometer particles.

Laser printer and photocopier toner formulations include organic and elemental carbon as well as a variety of metals and metal oxides, which can all become airborne during printing (Pirela et al., 2015). Morawaka et al. (2009) demonstrated that the particles are formed during printing when the fuser unit heats the paper and the toner, volatilizing compounds that then recondense in the indoor air. This work also showed that unstable temperature conditions were the main driving factor for particle emission in the high-emitting printers. Follow-up work a decade later by the same group showed a reduction in emissions for large, commercial printers but not for desktop printers (Moraska et al., 2019). Laser printers and photocopiers contain engineered nanomaterials; inhalation exposure to these particles may lead to oxidative stress and respiratory tract inflammation, causing a variety of respiratory symptoms (Pirela et al., 2017).

Beyond laser printers and photocopiers, there is now a large body of knowledge on PM emissions from three-dimensional (3D) printers, particularly fused filament fabrication (FFF) printers. Emissions from 3D printers that employ other types of technologies have also been identified, but at a significantly lower scale compared with FFF printers (Afshar-Mohajer et al., 2015; Hayes et al., 2021b). Powder-binder jetting printers have been shown to emit coarse-mode particles, with emissions varying according to the type of powder material used (Hayes et al., 2021a).

FFF 3D printers have been shown to emit copious amounts of ultrafine PM in office spaces (Stephens et al., 2013), homes (Khaki et al., 2021), and a classroom (Vance et al., 2017) as well as in controlled laboratory studies (Azimi et al., 2016; Jeon et al., 2020; Majd et al., 2019; Mendes et al., 2017; Vance et al., 2017; Yi et al., 2016; Zhang et al., 2018). As with other sources described in this section, FFF 3D printer emissions occur when the printer nozzle heats and vaporizes a variety of semivolatile compounds, which then condense to form particles in the air (Zhang et al., 2018). Due to their small size, over 60 percent of inhaled particles from 3D printer emissions are estimated to deposit in the respiratory system, primarily in the alveolar region (J. Park et al., 2021). A comparison across different ages showed that the total PM mass deposition of particles from 3D printer operation is highest for people in the 9- to 18-year-old age group, of particular interest to school environments (Byrley et al., 2021). PM emissions vary greatly with filament type (Gu et al., 2019; Vance et al., 2017; Zhang et al., 2019) and extrusion nozzle temperature (Jeon et al., 2020; Zhang et al., 2019). Among the two most popular types of FFF printing filaments, acrylonitrile butadiene styrene (ABS) leads to much higher emissions than polylactic acid (PLA) (Gu et al., 2019; Vance et al., 2017). However, particles emitted from 3D printing with PLA were shown to be more toxic than ABS-emitted particles at comparable mass doses in both *in vitro* and *in vivo* studies (Zhang et al., 2019).

Other Consumer Products and Hygiene/Personal Care Products that Involve Heating

Several commonplace personal products in the consumer market employ heating during use for a variety of purposes, from vaporizing fragrances to modifying hair or drying hands.

A variety of scenting products employ heat to vaporize a mixture of fragrances or essential oils into the indoor air. These consumer products are commonly used to mask odors and to promote psychological well-being (e.g., aromatherapy) in homes and in some school microenvironments such as bathrooms. Indoor scenting products include scented candles (discussed earlier in this chapter), wax warmers, plug-in or spray air fresheners, and essential oil diffusers, among others. Essential oil diffusers include a wide variety of products that employ different mechanisms to aerosolize or vaporize oils into the air, including heat (e.g., from a candle or electricity), ultrasonic vibrations, nebulizing actions, and capillary (i.e., wicking) action. Some of these products use heat to vaporize fragrances, whereas others emit sprays or mists directly into the air. The latter is discussed later in this chapter. Studies looking at direct $PM_{2.5}$ emissions or indoor concentrations from the use of heated fragrances are scarce. Demanega et al. (2021) reported modest increases in indoor $PM_{2.5}$ concentrations from heating essential oils using a candle in a chamber; concentrations peaked at 10 μg/m^3 in cool and dry conditions and 31 μg/m^3 in warm and humid conditions.

There is a paucity of research in the scientific literature on PM emissions from heating hair styling tools (e.g., hair dryers, hair straighteners, and curling irons). However, these products are expected to lead to indoor particle emissions due to their high surface temperatures, reported in the news media to be up to 232 °C for flat irons, and to the likely presence of oils from hair and scalp as well as a variety of hairstyling products (Kaplan, 2020; Leon, 2012). High $PM_{2.5}$ concentrations observed in field measurements in hair salons have been attributed to the use of hair dryers and flat irons (Shao et al., 2021). Glytsos et al. (2010) and Ciuzas et al. (2015) operated hair dryers in laboratory settings, and both studies reported large enhancements in ultrafine PM concentrations. Meanwhile, Hussein et al. (2006) showed that operating a relatively new hair dryer in a residence had negligible effect on PM concentrations. Chamber studies by Sysoltseva et al. (2018) and by Schripp et al. (2011) found large variability among the PM emissions from different hair dryers, with the commonality that the emissions were ultrafine. One study (Taylor et al.,, 2017) included examination of two ionic hair dryers marketed as emitting silver nanoparticles to promote hair growth. It concluded that the mass of these particles was below the limit of detection in the studied models; no other PM measurements were reported. A laser hair removal procedure has been found to emit high concentrations of ultrafine aerosols, leading to an eight-fold increase in particle number concentrations above background (Chuang et al., 2016).

A clothes iron is another indoor appliance that, similarly to some hair tools, employs a surface that is heated to high temperatures (commonly 180–200 °C), and can emit ultrafine aerosols when heated (Wallace et al., 2015). Vicente et al. (2021) reported very high particle number emission rates for ironing clothes, on the order of 10^{12} particles/min or approximately 2-8 µg/s[1] of $PM_{2.5}$.

Electric hand dryers are common in public bathrooms and may be used in many schools. These products may emit particulate matter during operation owing to surface heating; however, there is limited evidence published in the scientific literature. Bae et al. (2013) reported minor enhancements in particle counts (from 1 to 20 particles/cm^3) while testing a nano-coated hand dryer in a chamber.

Electronic Cigarettes

Electronic cigarettes (e-cigarettes) are battery-powered devices that heat a liquid solution (commonly called “e-liquid”) and convert it into a vapor that can be inhaled. The liquid typically contains nicotine, flavorings, and other components. E-cigarettes are often marketed as safer alternatives to traditional cigarettes because they do not produce smoke byproducts. However, there is still some debate over their long-term health effects and potential risks, particularly in non-smokers and young people, who may be more likely to start using nicotine products as a result of e-cigarette marketing (Giovenco et al., 2016; Huang et al., 2019).

Although e-cigarettes do not involve combustion, they release aerosols that can remain in the air and on surfaces of indoor environments for extended periods after use. Multiple studies have investigated e-cigarette emissions in chambers (Schripp et al., 2013) and real indoor environments such as homes (Fernández et al., 2015; Loupa et al., 2019; Shearston et al., 2023), offices (Saffari et al., 2014), and vape shops (L. Li et al., 2021; Son et al., 2020), demonstrating that $PM_{2.5}$ emissions are significant, although much lower than conventional cigarettes. There is significant evidence that e-cigarette-emitted aerosols contain a range of VOCs, particularly formaldehyde and acetaldehyde, in addition to ultrafine and fine particulate matter. Some common components of e-cigarette particles include nicotine, propylene glycol and glycerin (used to create a visible aerosol mist), flavorings, and trace amounts of metals such as nickel, zinc, lead, and chromium from the cartridge and heating the metal coils (Fernández et al., 2015; Li et al., 2020; Saffari et al., 2014; Salamanca et al., 2018; Son et al., 2020; Talih et al., 2016; Zhao et al., 2017). E-cigarettes have also been shown to emit particle-associated reactive oxygen species and environmentally persistent free radicals (Hasan et al., 2020).

E-cigarette emissions and their effects on indoor air quality depend on a variety of factors, including the type of device, the temperature and power settings used, the type of e-liquid or cartridge used, and the frequency and duration of use. Protano et al. (2018) showed that, over time, e-cigarette products have employed progressively lower electrical resistance and higher power conditions, leading to increasing $PM_{2.5}$ emissions. Several studies and literature reviews have reported particle emissions to consist mostly of ultrafine and submicron particles (L. Li et al., 2020; Protano et al., 2018; Saffari et al., 2014; Volesky et al., 2018; T. Zhao et al., 2016).

E-cigarette use has been widely reported to lead to secondhand exposure (also referred to as “passive vaping”) to exhaled emissions by nearby users (Islam et al., 2022; Protano et al., 2018; Schripp et al., 2013; Volesky et al., 2018; M. P. Wang et al., 2016; Zhao et al., 2017). In addition, e-cigarette aerosols can leave residue on indoor surfaces and particles, which can accumulate over time and potentially affect indoor air quality, commonly referred to as thirdhand exposure (Acuff et al., 2016; Goniewicz and Lee, 2015). Colby et al. (2023) found that residual emissions from an electronic cigarette partitioned from surfaces onto other airborne particles in a manner similar to compounds from conventional cigarettes (DeCarlo et al., 2018).

While e-cigarettes may be considered by users a less harmful alternative to traditional cigarettes, the health effects of inhaling e-cigarette particles are not yet fully understood, and their use is not risk-free. *In vivo* and *in vitro* studies have shown that exposure to e-cigarette emissions can lead to potential cytotoxicity and genotoxicity, probably due to exposure to reactive oxygen species and aldehydes (Ma et al., 2021; Merecz-Sadowska et al., 2020). E-cigarette use has been associated with a variety of respiratory and cardiovascular effects, particularly in children and adolescents (Islam et al., 2022; M. P. Wang et al., 2016). Specifically, secondhand nicotine vaping has been associated with bronchitic symptoms and shortness of breath in young adults (Islam et al., 2022). Hypersensitivity pneumonitis has been reported as arising from firsthand and, in rare cases, secondhand exposure to e-cigarette emissions (Galiatsatos et al., 2020). These and other health effects may become important, particularly for people with underlying respiratory conditions.

Indoor Particle Resuspension and Shedding

The movement of people or equipment indoors can detach and lift particulate matter previously deposited on surfaces. This phenomenon is called particle resuspension, and it can increase indoor particle concentrations significantly (Thatcher and Layton, 1995). While resuspension is more likely to occur in large (>1 μm, especially >10 μm) particles, it can also affect fine PM. In fact, everyday activities performed in a home, such as walking, dancing, cleaning, and organizing, have been estimated to resuspend up to 0.5 mg/min of $PM_{2.5}$ (Ferro et al., 2004a). Moreover, human movement, such as walking, dancing, etc., is known to generate a "personal cloud" of particulate matter, initially reported in detail during the Particle TEAM study, the first large-scale study of personal exposure to particles in the 1990s (Özkaynak et al., 1996). As the name suggests, the person generating the cloud is most likely to be exposed to it, with 1.4× concentration enhancements reported by Ferro et al. (2004b). Licina et al. estimated that 90±14 million particles/hour in the 0.3-10 μm size range are emitted during walking. Concentrations of resuspended particles typically increase closer to the ground (Khare and Marr, 2015).

A significant body of knowledge has been published on the subject of particle resuspension over the past decade, including experimental studies in houses and apartments (Ferro et al., 2004a,b; S. Park et al., 2021; Tian et al., 2018, 2021; Vicente et al., 2020) and schools, including classrooms (Bhangar et al., 2014; Leppänen et al., 2020; B. Wang et al., 2021) and gyms (Buonanno et al., 2012b), as well as in controlled laboratory chambers (Bhangar et al., 2016; Boor et al., 2015; Lai et al., 2017; Qian and Ferro, 2008; Tian et al., 2014; S. Yang et al., 2021a). Particle resuspension depends on several factors, including the surface type and surface loading (i.e., the amount of particles present on those surfaces), the type and intensity of activity, and indoor environmental conditions such as relative humidity and airflow characteristics (Mukai et al., 2009; Qian et al., 2014; Zheng et al., 2019).

Activities that were found to lead to high exposure to resuspended and shed particles were those that involved vigorous movement and those that disturbed dust reservoirs present on furniture and textiles, such as walking, dancing, dusting, folding clothes, making a bed, jumping on the bed, etc. Qian et al. (2014) performed a comprehensive review on walking-induced particle resuspension indoors and reported that particle resuspension increases with particle size, especially in the 0.7–10 μm range. B. Wang et al. (2021) found that walking activities lead to a $PM_{2.5}$ resuspension fraction (i.e., mass resuspended relative to mass of settled $PM_{2.5}$) of 2.2×10^{-8} per footstep and that this fraction did not vary with particle loading on the surface. Lai et al.

(2017) investigated the role of shoe type on particle resuspension and found that flat shoes induced more particle resuspension than heels and, among flat shoes, soles with no grooves were associated with more resuspension than soles with grooves. Indoor surface materials have been found to play an important role in dust resuspension. Qian and Ferro (2008) found that new, level-loop carpet led to significantly higher particle resuspension rates compared to vinyl tire flooring for particles 1–10 μm in size. Tian et al. (2014) found no significant difference in dust resuspension between carpet and hard floorings for particles in the 0.4–3.0 μm size range, but found that carpets resuspended more particles in the 3–10 μm size range. Clothing and its particle loading also influences particle emissions during human movement. McDonagh and Byrne (2014) found that up to 67 percent of contamination on clothing can be resuspended during physical activity.

Studies in real indoor environments have quantified the emissions of particulate matter from resuspension and shedding from a variety of activities. Bhangar et al. (2014) found that emissions of resuspended biological particles in a university classroom were 2×10^6 particles/h/person during lectures and peaked during class transitions, at 0.8×10^6 particles per transition, due to increased movement among students. Cleaning activities such as vacuuming, dusting, and sweeping are known to resuspend large amounts of particulate matter, including fine PM. Vacuuming can generate particles from two distinct mechanical processes: dust resuspension from surfaces and mechanical movement of the motor (S. Park et al., 2021; Vicente et al., 2020). Corsi et al. (2008) investigated the effects of vacuuming on dust resuspension in 12 different apartments and observed very small increases in indoor $PM_{2.5}$ concentrations above background levels. Ferro et al. (2004a) quantified $PM_{2.5}$ emissions from vacuuming in a home to be ~0.45 mg/min.

The chemical composition of resuspended particles has also been found to be largely influenced by the sources and surfaces to which they were previously attached. While in contact with indoor surfaces, resuspended particles take up a variety of semivolatile organic compounds (SVOCs) of health concern, including PAHs, PFAs, pesticides, flame retardants, and phthalates (Eichler et al., 2021). Liagkouridis et al. (2014) states that models might underestimate the release of low-volatility brominated flame retardants from products and onto indoor particles. Shi and Zhao (2015) gathered published concentrations of 38 different SVOCs associated with dust in residences in seven countries for a model evaluation and reported concentrations in the range of 10^{-1} to 10^5 ng SVOC/ng dust (<10 μm in size). Other toxicants, such as lead from painted surfaces, can also be present in resuspended particles from the breakdown of painted surfaces (Grinshpun et al., 2002; Thatcher and Layton, 1995).

Resuspended and shed particles have been found to include human skin flakes and a variety of biological pollutants and allergens of health concern, including animal dander, dust mites, bacteria and fungi, viruses, and a variety of allergens, endotoxins and mycotoxins (Khare and Marr, 2015; Kumar et al., 2021; Nazaroff, 2016; Qian et al., 2014; Yen et al., 2019b). Although the plurality of these pollutants is expected to exist in particles greater than $PM_{2.5}$, some of these may also be present as a component of fine PM. Yen et al. (2019b) measured significant increases in the concentrations of particulate matter (including $PM_{2.5}$), bacteria, fungi, and endotoxin from making the bed and jumping on the bed. Kvasnicka et al. (2022) developed a model showing that contaminated clothing could theoretically resuspend viable SARS-CoV-2 viruses. Indoor particle resuspension has been linked to asthma and other respiratory health conditions. Kumar et al. (2021) performed a review of biological contaminants in the indoor air environment and stated that there is a “lack of awareness about biological contamination in the indoor environment and their potential sources for the spreading of various infections." Raja et al. (2010) found that biological markers of lung inflammation in asthmatic children were associated with the concentrations of dust mite allergen and cat dander. The same study determined that the resuspension rates for cat dander and dust mite allergen were higher than those for dog dander and bacterial endotoxins.

Residual PM from Liquid Droplet Evaporation

There are several indoor processes, such as cooking, showering, spray cleaning and personal care products, and using humidifiers or nebulizers, that, by accident or by design, emit liquid droplets into the indoor air. These droplets may contain trace soluble or insoluble constituents such as minerals, salts, proteins, or microorganisms. When these droplets dry under indoor environmental conditions, they can leave behind these constituents in the form of aerosol particles that can remain suspended in air.

Respiratory Particles

Respiratory aerosols are formed by fluid film bursting and shearing forces of air passing through the respiratory system. Small aerosols which can remain suspended and build up in poorly ventilated indoor space are continuously produced by people breathing, talking, singing, coughing, and sneezing (Bake et al., 2019; Fritzsche et al., 2022; Niazi et al., 2021). The released aerosols are primarily composed of respiratory fluid, which includes a combination of water and salts, a variety of organic compounds, and microorganisms including bacteria and viruses. Prussin et al. (2023) investigated 35,000 individual respiratory particles from three healthy human subjects and found that roughly half of the emitted particles were carbonaceous (mostly organic) in nature and the remaining half were primarily made up of salt-rich particles. Notable microorganisms and viruses, primarily those responsible for a variety of respiratory diseases, have been identified in respiratory aerosol. These include *Mycobacterium tuberculosis* (Fennelly et al., 2012; Patterson and Wood, 2019), influenza virus (Yan et al., 2018), respiratory syncytial virus (Kulkarni et al., 2016), and SARS-CoV-2 (Coleman et al., 2022;) , as well as other respiratory bioparticles (C. C. Wang et al., 2021). It is important to note that infectious SARS-CoV-2 has been detected in aerosols in indoor air, including in air samples collected in residences occupied by individuals with COVID-19 (Lednicky et al., 2020; Vass et al., 2023).

Aerosols can be generated from multiple regions of the respiratory system: the upper respiratory tract, including the oral cavity, which involves activities such as speaking and coughing, larynx region, which is active during speaking and coughing, and the lower respiratory tract, including the bronchiolar region, which can produce aerosol particles during normal breathing (Fritzsche et al., 2022; Johnson and Morawska, 2009; Johnson et al., 2011; Pöhlker et al., 2023). Once released into the air, the physical behavior of these exhaled particles, including distance they travel and how long they remain suspended, will depend on particle size, shape, and density. These exhaled aerosols can undergo evaporation the rate and extent of which depend on ambient environmental conditions, particularly the relative humidity, temperature, and air flow conditions (L. Liu et al., 2017; L. Morawska et al., 2009b; Yang and Marr, 2011), which has been shown to affect the viability of pathogens in respiratory aerosol droplets. This relative humidity–dependent viability has been demonstrated for enveloped viruses, such as influenza (W. Yang et al., 2012), as well as SARS-CoV-2 (Oswin et al., 2022).

Multiple studies have investigated the size distributions of respiratory droplets and aerosol particles during a variety of breathing conditions and activity levels. Multi-modal size distributions, with at least one mode below 1 µm in size and several more modes up to 100 µm being reported (Chao et al., 2009; Firle et al., 2022; Johnson et al., 2011; L. Morawska et al., 2009b; Xie et al., 2009). Johnson et al. (2011) identified size distributions of expired aerosols during a variety of activities (e.g., breathing, speaking, coughing, etc.) and found that tri-modal, lognormal size distributions of particles were commonly emitted. For speaking and coughing, two of the three identified aerosol size distribution modes fell under 2.5 µm in size. Moraswka et al. (2009b) investigated several respiratory activities, including different types of breathing, vocalizations, and coughing, and identified up to four size distribution modes, and all respiratory activities produced particles <0.8 µm in size.

The COVID-19 pandemic brought great attention to the study of aerosol emissions from a variety of respiratory activities, including speaking, coughing, singing, and playing musical instruments. As a result, several recent studies have been published on these topics. In general, breathing has been found to emit fewer aerosol particles than speaking (Alsved et al., 2020). Aerosol emissions from human speech have been found to be proportional to voice loudness and phonation frequency (pitch), and independent of language spoken, with emissions varying greatly from study to study: Asadi et al. (2019) found emissions ranging from 1 to 50 particles per second, and Alsved et al. (2020) measured emissions of up to ~1400 particles per second. Even with this large range in emission rates, loud environments where people raise their voices (e.g., school cafeterias) are likely to contain higher concentrations of respiratory aerosols compared with quiet spaces with comparable building characteristics (e.g., school libraries). Multiple studies reported higher emissions for louder vocalizations (e.g., shouting and singing) compared to speaking or breathing, with breathing leading to the lowest emissions (Archer et al., 2022; Bagheri et al., 2023; Gregson et al., 2021). Ahmed et al. (2022) reported higher emissions increasing with phonation frequency. Age may also play a role in respiratory particle emission rates, with emissions increasing with age (Archer, 2022; Bagheri, 2023). Moreover, a study on exhaled aerosols from children showed no statistical difference in respiratory aerosol emissions between SARS-CoV-2 PCR-positive negative children and adolescents (Schuchmann et al., 2023).

Playing wind instruments also leads to respiratory aerosol emissions and may be particularly relevant in school music classrooms. Firle et al. (2022) identified the size distribution of respiratory particles emitted from playing wind instruments and found that the plurality of particles were in sizes ranging from 0.25 to 0.8 µm. Aerosol emissions from playing wind instruments vary widely according to instrument, ranging from ~1 to 2,500 particles per second. The clarinet, trombone, oboe, and trumpet have been generally reported as high emitters (Firle et al., 2022; R. He et al., 2021; L. Wang et al., 2022). Firle et al. (2022) also found that emissions were generally higher for playing wind instruments compared to speaking and breathing, and Stockman et al. (2021) found that particle number concentrations at the bell of a clarinet were comparable to singing.

Many studies have demonstrated that respiratory aerosol (Asadi et al., 2020; Leith et al., 2021; Pan et al., 2022; Stockman et al., 2021) and respiratory pathogen (Leung et al., 2020; Milton et al., 2013) emissions from speaking and singing are greatly reduced when masks or respirators are worn over the speaker's mouth. In terms of playing wind instruments, evidence has been shown that covering the instrument's bell can reduce respiratory aerosol emissions. While Firle et al. (2022) found that covering the instrument's bell with a surgical mask did not reduce emissions, Stockman et al. (2021) and Abraham et al. (2021) found that bell coverings reduced aerosol concentrations measured in front of the instrument's bell.

Spray Products

Many products commonly used indoors employ spraying action for a variety of reasons. These include cleaning products (e.g., disinfectant sprays, all-purpose cleaners, and glass cleaners), air fresheners (e.g., room sprays, fabric refreshers, and plug-in air fresheners), personal care products (e.g., hairspray, deodorant sprays, and perfume sprays), and art and craft sprays (e.g., spray paints and adhesive sprays). Some of these categories of products have been well characterized in terms of their air pollutant emissions, while the characteristics of others remain largely unknown.

Particle emissions from spray products depend on factors such as nozzle type, pressure inside the container (i.e., pressurized can versus manual spray pump), and contents in the liquid phase. The liquid contents may include dissolved or particle species which can both lead to the formation of dry or wet particles in indoor air, depending on the indoor environmental conditions (particularly relative humidity). Because there is a wide variety within each of these parameters, wide variability can also be expected in terms of emissions, ranging from negligible to substantial. A study by S. Park et al. (2021) showed that air freshener spraying for 1 min in a bedroom led to significant, but short-lived increases in $PM_{2.5}$ concentrations in that microenvironment. Similarly, a study by Uhde and Schulz (2015) showed that automatic air freshener spray units released a mist of short-lived ultrafine particles. Kogianni et al. (2021) reported high $PM_{2.5}$ concentrations (~160–170 $\mu g/m^3$) in hair salons, likely due to the intense use of hair sprays. Bertholon (2015) investigated aerosol emissions by three indoor air freshener sprays from pressurized canisters in a ventilated test chamber and found that >90 percent of particles emitted were <0.3 µm in size. A number of studies have investigated particle emissions from the use of consumer spray products that contain engineered nanoparticles as part of their formulation, with silver particles and ions as well as titanium dioxide particles as common ingredients. These have been shown to emit particles <2.5 µm in diameter (B. T. Chen et al., 2010; Laycock et al., 2020). The products tested by Quadros and Marr (2011) emitted 10^7 to 10^8 particles per individual spray action. Lorenz et al. (2011) investigated emissions from spray products containing nanoparticles and found that pressurized canisters emitted particles <0.3 µm in size, while a manual spray pump had negligible emissions.

Humidifiers and Nebulizers

A variety of products have the purpose of creating a fine mist of liquid droplets, which can then be inhaled or used for other purposes. One common method to create this aerosol employs a nozzle or orifice through which high-pressure liquids or air are passed, generating aerosol (e.g., nebulizers). Ultrasonic devices use sound waves to create liquid aerosols indoors and are also commonly used in many consumer products (e.g., some humidifiers and essential oil diffusers).

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Highsmith et al. (1988) measured particle emissions from three types of humidifiers (ultrasonic, impeller, and steam) operated with tap water with varying levels of dissolved solids content. Ultrasonic humidifiers emitted large amounts of $PM_{2.5}$, with impeller-type humidifiers emitting approximately two-thirds less and steam humidifiers emitting none. The amount of $PM_{2.5}$ emitted by ultrasonic humidifiers increased with increasing suspended solid content in fill water. More recent studies have found that the composition of aerosol emissions from ultrasonic humidifiers closely resembles their fill water composition for many types of tap water sources and that most emitted particles were in the 20–40 nm size range (Sain and Dietrich, 2015). Lau et al. (2021) demonstrated that ultrasonic humidifiers elevated indoor $PM_{2.5}$ concentrations in a house up to 100s of $\mu g/m^3$ and that humidifiers could be indoor sources of sulfate, which may complicate tracer-based techniques for estimating ambient particle infiltration (as described in Chapter 4). Sain et al. (2018) found that higher mineral content fill water increased PM emissions from ultrasonic humidifiers and Yao et al. (2020) subsequently showed that using tap water that meets water quality standards in ultrasonic humidifiers can result in substandard indoor air quality. Dietrich et al. (2023) recently demonstrated that inhalation exposures to metals emitted from ultrasonic humidifiers using tap water as fill water greatly exceed ingestion exposures from tap water alone.

Ultrasonic essential oil diffusers can emit large amounts of particles into the air, as this is their primary purpose. Schwartz-Narbonne et al. (2021) found that PM emissions from these products varied according to oil type, but three of the four tested oils released mostly ultrafine particles, with one tested oil (grapeseed) releasing particles that were dominantly >200 nm in diameter. A follow-up study by Du et al. (2022) found that exposure to both a scented and a non-scented essential oil affected the cognitive performance of the tested human subjects, specifically leading to more impulsive decision making.

Washing Machines, Dishwashers, and Showers

Common household appliances such as clothes washing machines and dishwashers might generate aerosols during their operation due to the mechanical action of water jets, sprays, and agitation. One can infer that the size, concentration, and chemical composition of aerosols generated from these appliances may vary depending on the type of washing detergent used, the mechanical movement of the machine, and the type and level of soiling on the material to be cleaned as well as the appliance itself. There is very little information published in the scientific literature on aerosol emissions from these appliances. One study found a peak aerosol concentration in a Swedish residence of 2.5×10^4 particles per cm^3 from laundry activities (Isaxon et al., 2015). Bekö et al. (2013), however, observed no changes in indoor particle number concentrations during washing machine operation in a study in 56 Danish homes.

The plurality of published works focuses on the potential of these appliances to harbor and release microorganisms of interest to human health. Dishwashers are known for harboring thermophilic fungi (Gümral et al., 2016). Zupančič et al. (2016) identified over 500 fungal strains in 30 residential dishwashers. Kulesza et al. (2021) identified microfungi inside 7 of 10 tested dishwashers and hypothesized that microbial aerosols can be emitted when opening these appliances before the cooling period is complete. Döğen et al. (2017) found abundant presence of the opportunistic pathogen *Candida parapsilosis* in a study involving 99 laundry machines in Turkey. Showers and hot faucets, on the other hand, are well-known for their potential to aerosolize microorganisms, notably respiratory pathogens such as *Legionella pneumophila* (Bollin et al., 1985; Niculita-Hirzel et al., 2022) and *Nontuberculous mycobacteria* (Shen et al., 2022). Washing machines have also been found to harbor *Legionella pneumophila* (Kuroki et al., 2017). Flushing toilets have been shown to present a potential for aerosolizing microorganisms, some of them pathogenic (Barker and Jones, 2005; Johnson et al., 2013; Lin and Marr, 2017; Schreck et al., 2021).

Secondary Particles from Indoor Chemical Reactions

There are a variety of chemical transformations that take place in indoor environments involving chemical species that can originate from the indoor environment or that can be transported indoors from outdoor air. Some of these transformations involve the chemical oxidation of volatile organic compounds (VOCs), which can lead to the formation of secondary aerosol particles in indoor air. The National Academies report *Why Indoor Chemistry Matters* describes indoor chemical transformations in great detail in its Chapter 4 (NASEM, 2022). Here, the focus is on specific scenarios that can lead to the formation of indoor particles in home and school environments via chemical transformations.

Many personal care and other consumer products release VOCs by design, such as perfumes, body lotions, air fresheners, and essential oil diffusers as well as a wide variety of cleaning products. The use of these products has been linked to increases in concentrations of terpenes, aldehydes, esters, and many other VOCs (Angulo-Milhem et al., 2021; Kim et al., 2015; Nematollahi et al., 2018; Sarwar et al., 2004; Schwartz-Narbonne et al., 2021; Su et al., 2007). If chemical oxidants, primarily ozone (O_3), hydroxyl radicals (OH), reactive chlorine species, and nitrate radicals (NO_3), are present in indoor air, they can react with these VOCs and form particles called secondary organic aerosols (SOAs). Waring and Wells (2015) modeled this process and found that VOC oxidation indoors is likely driven primarily by reactions with O_3 and OH. Nitrate radical concentrations are generally modeled to be low (or negligible) in most indoor conditions (Young et al., 2019). Ozone is considered the most prevalent indoor air oxidant and is generally brought inside from outdoors unless a device or appliance that generates indoor O_3 is operating inside the building (Nazaroff and Weschler, 2022). Nazaroff and Weschler (2022) reported average indoor O_3 concentrations of 4-6 ppb in homes, and Salonen et al. (2018) reported 4 and 5 ppb in schools and offices, respectively. Such low O_3 concentrations exist indoors because of heterogeneous and homogeneous reactions, which reduce O_3 concentrations but increase concentrations of byproducts. Hydroxyl radicals can be relevant indoors when sources of nitrous acid (HONO) or formaldehyde (HCHO) are present (Wang et al., 2020; Waring and Wells, 2015; Young et al., 2019). Nitrogen dioxide from indoor combustion sources can be hydrolyzed into HONO and nitric acid (HNO_3) (Finlayson-Pitts et al., 2003). HONO may then build up on indoor surface reservoirs and slowly release over a timescale of days, depending on indoor environmental conditions (Wang et al., 2020).

A robust body of knowledge has demonstrated the potential for new particle formation indoors from the reaction of O_3 and indoor-generated VOCs, particularly from terpene-containing household products, such as air fresheners, cleaning products, and personal care products (Nazaroff et al., 2006; Rosales et al., 2022; Singer et al., 2006). Coleman et al. (2008) performed a series of chamber experiments demonstrating the formation of particles from exposing cleaning products and an air freshener to O_3. Uhde and Schulz (2015) released a variety of fragrance products into a test chamber and then injected O_3 into the chamber, demonstrating that large amounts of SOA can be formed as a result. A study by Yen et al. (2019a) in 60 Taiwanese homes found that 30 percent of observed households made use of essential oils and that the concentration of O_3 was negatively associated with their use, indicating that their VOC emissions potentially reacted with indoor O_3.

Human skin oils have been recently identified as a potentially rich source of O_3-reactive compounds (Weschler and Nazaroff, 2023; Wisthaler and Weschler, 2010). Ozone can react rapidly with some components of skin oils that are present in human skin, hair, clothes, and other indoor surfaces. The O_3-driven oxidation of skin lipids, particularly squalene, has been shown to generate single-nanometer particles in indoor air. This has been shown in an experiment with human subjects (Yang et al., 2021b), in a chamber study using soiled T shirts (Rai et al., 2013), and in bench-scale reaction chambers using pure squalene (Coffaro and Weisel, 2022; Wang and Waring, 2014). Coffaro and Weisel (2022) showed that particle emissions decrease at high relative humidities (i.e., >50 percent), likely due to a shift in the formation of higher volatility products from the O_3-squalene reactions.

A relatively less explored oxidation pathway indoors involves the chlorine radical and chlorine-containing molecules. Chlorine-containing compounds are also present in indoor environments and can spur oxidation chemistry, particularly after the use of cleaning products that contain bleach (Mattila et al., 2020; Wong et al., 2017). The presence of these reactants can spur a variety of chemical reactions, including the formation of indoor particles. For example, Patel et al. (2020) showed that emissions from indoor cooking and bleach mopping reacted together to spur new particle formation indoors, likely using chlorine-containing compounds as the primary oxidant. Schwartz-Narbonne et al. (2018) demonstrated that hypochlorous acid in commercial bleach solutions can react with squalene and oleic acid, two common components of skin oil.

Indoor particles can also be formed as an unintended consequence of using some devices that are nominally intended to clean the air. Indoor air cleaning devices encompass a broad category of products used to reduce the concentration of particles, VOCs, odors, pathogens, etc., in indoor air. Indoor air cleaning techniques range from air filtration, commonly used in modern buildings and well researched for decades (G. Liu et al., 2017), to a variety of technologies that employ chemical or physical processes such as ozone generation, photocatalytic oxidation, ultraviolet irradiation, ionization, and more (Collins and Farmer, 2021; EPA, 2018; Siegel, 2016; Stephens et al., 2022). Filtration and air cleaning are topics further explored in Chapter 7 of this report. Chemical reactions between the constituents introduced to indoor air by some additive air cleaning technologies have been shown to generate gases and particles as byproducts. For example, some indoor air cleaners intentionally or unintentionally produce O_3 during use (Guo et al., 2019; Morrison et al., 2014), which can lead to new particle formation through the processes described above. Worth noting, O_3 generators are also commonly used for odor removal in indoor environments during remediation efforts, which should be conducted without occupants present (Tang et al., 2021). Similarly, hydroxyl radical generators and other oxidizing technologies, which have gained popularity during the COVID-19 pandemic for indoor air cleaning, may also lead to the formation of indoor particles (Collins and Farmer, 2021; Joo et al., 2021). Ionization-type air cleaners use ions generated by a corona discharge to remove particles and can, in some cases, generate O_3 and spur new particle formation indoors (Collins and Farmer, 2021; Hyun et al., 2017; Niu et al., 2001; Waring et al., 2008). The use of short-wavelength ultraviolet irradiation (UVC) for germicidal purposes can also spur the generation of indoor particles via the photolysis and photooxidation of indoor VOCs (Collins and Farmer, 2021; Graeffe et al., 2023; Kang et al., 2018).

REGIONAL, AREA, AND LOCAL DIFFERENCES AND CULTURAL/SOCIOECONOMIC DISPARITIES IN THE SOURCES AND COMPOSITION OF INDOOR PM

There are relatively well understood local and regional spatial differences in ambient $PM_{2.5}$ sources and composition across the U.S., which also often intersect with socioeconomic disparities in the population. For example, both the absolute magnitude of ambient $PM_{2.5}$ concentrations and the relative proportion of major constituents vary across North America, with nitrate being more abundant on the West Coast and sulfate being more abundant on the East Coast of the United States (Samet et al., 2005). And while ambient $PM_{2.5}$ concentrations have decreased in the United States in the last few decades, racial and socioeconomic disparities in ambient $PM_{2.5}$ concentrations have persisted (Colmer et al., 2020; Liu et al., 2021), with inequities driven by disproportionately high consumption of goods and services by non-Hispanic white populations that result in disproportionate exposures to Black and Hispanic minorities (Tessum et al., 2021, 2019). For example, areas of historical redlining—the result of a U.S. mortgage appraisal policy from the 1930s that was racially discriminatory—were found to be associated with higher ambient $PM_{2.5}$ concentrations in present times (Lane et al., 2022).

Such differences in ambient $PM_{2.5}$ presumably manifest in differences in indoor $PM_{2.5}$ concentrations and compositions, holding other factors constant. While studies of indoor $PM_{2.5}$ composition are more limited, some studies have demonstrated that the magnitude of some constituents of indoor $PM_{2.5}$ closely tracked outdoor levels (e.g., elemental carbon and sulfate), while others (e.g., organic matter) are affected more so by the presence of indoor sources (Turpin et al., 2007). Carrion-Matta et al. (2019) used a positive matrix factorization (PMF) model to estimate the major sources of indoor $PM_{2.5}$ in 32 inner-city school classrooms in the northeastern United States, finding that the major contributors to indoor $PM_{2.5}$ concentrations were secondary air pollution and motor vehicles, both infiltrating from outdoors. The infiltration of ambient $PM_{2.5}$ is also influenced by a number of building-related factors, some of which also likely vary with socioeconomic dimensions, as explained in more detail in Chapter 4.

Moreover, variability in the types of indoor sources present in buildings is broadly expected to contribute to variability in indoor $PM_{2.5}$ concentrations and compositions across spatial, temporal, socioeconomic, and even cultural dimensions, even if robust characterizations of the presence, types, and frequency of indoor emission sources for specific populations do not yet exist. For example, it is understood that there are obvious differences across regions, buildings, and populations in factors such as the predominant heating and cooking fuel types that can affect combustion emissions, the presence and use of appliances and activities that contribute to emissions from combustion and heating processes (e.g., cooking, burning incense or candles) or water droplet evaporation (e.g., humidifiers), and the frequency and intensity of cleaning activities and the types of building materials that affect resuspension from settled dust. However, beyond the fairly detailed understanding of regional differences in fuel types addressed earlier in the chapter, there is not a robust accounting to date for how such contributors to variability in indoor $PM_{2.5}$ sources, concentrations, and compositions vary regionally, locally, or across socioeconomic or cultural dimensions.

To date, efforts to use such building, cultural, and behavioral characteristics to increase understanding of the variability in indoor PM levels have generally focused on integrating information on building and housing characteristics with occupant surveys of activities. For example, Baxter et al. (2007a,b) demonstrated that information from a combination of public databases (e.g., central site ambient monitoring data, location, and housing information) and occupant questionnaires used to assess housing factors and occupant behaviors (e.g., cooking times, gas stove usage, occupant density, window opening frequency, and use of humidifiers) were significant predictors of indoor $PM_{2.5}$ concentrations in lower socioeconomic households in Boston. Similarly, Klepeis et al. (2017) demonstrated that indoor PM concentrations in economically disadvantaged households in San Diego (each with at least one smoking occupant) were associated with information obtained from retrospective interviews of occupants, including reports of indoor smoking of cigarettes or marijuana and non-smoking events including frying food, using candles or incense, and house cleaning. Higher particle concentrations were also associated with smaller-volume homes, and there were no associations between particle concentrations and reports of opening windows, using kitchen exhaust fans, or other ventilation activities. Meng et al. (2009) found that incorporating information on personal activities, in addition to simultaneous outdoor $PM_{2.5}$ concentrations, improved the accuracy of a predictive model for personal indoor $PM_{2.5}$ concentrations and even some chemical constituents in the RIOPA study.

Such information on relevant housing and behavioral factors are relatively straightforward to obtain and likely aligns with socioeconomic and cultural differences in various populations. However, such factors are not extensively documented in resources such as the EPA's *Exposure Factors Handbook* (EPA, 2022), nor are they routinely incorporated into epidemiology studies. What limited information on household activities that does exist in the *Exposure Factors Handbook* suggests that older populations spend more time cooking (Table 16-72 in the reference) and that women, individuals with lower levels of education, and married individuals spend more time doing "household activities," which includes housework, cooking, and several other activities that may contribute to disproportionate exposures to indoor $PM_{2.5}$ (Table 16-99). However, while the impacts that such behavioral differences have on indoor PM exposures are presumably apparent and likely logical, they remain largely unquantified at scale. Accounting for such differences may be a worthwhile endeavor to (1) identify disparities in exposures to indoor PM, (2) ensure that policies or actions to reduce exposure such as eliminating particular sources or adopting specific interventions would address disparities that exist, and (3) inform estimates of the societal benefits of mitigation, or, alternatively, the societal costs of not mitigating. A more detailed discussion on $PM_{2.5}$ exposure is presented in Chapter 5 of this report.

FINDINGS AND CONCLUSIONS

This chapter describes in detail numerous indoor sources of fine and ultrafine particulate matter and their indoor concentrations and compositions. Although particles from indoor sources may account for approximately half of people's exposure to fine PM mass concentrations—and even more in terms of particle number—indoor sources and their health effects are relatively unexplored when compared with historic ambient sources. Major gaps in knowledge remain, especially related to source strengths, source characteristics that dictate emissions, pollutant composition, and source-specific health effects.

Given the literature reviewed in this chapter, the committee finds:

Ultrafine particles are an important component of many indoor sources of $PM_{2.5}$. Ultrafine particles (<100 nm in diameter), a subset of $PM_{2.5}$, usually contribute a small portion of the total $PM_{2.5}$ mass but represent a large portion in terms of particle number concentrations. A plurality of indoor sources emit primary aerosol particles through processes that involve combustion, evaporation and condensation, or chemical reactions, and all of these lead to the formation of very small clusters of primary particles which can grow into larger sizes or be lost to indoor surfaces, given sufficient time (Chapter 4). In the case of continuous sources, a background of ultrafine particles can be expected to persist indoors for prolonged periods of time. Information on indoor ultrafine particles, especially their composition and health effects, is currently limited.

Many indoor sources are intermittent and lead to localized, short-lived, and high concentrations of UFPs and $PM_{2.5}$. Indoor sources of particles such as cooking, personal care products, and some office products can emit copious amounts of UFPs and $PM_{2.5}$ for the duration of the emitting activity, leading to high, sometimes short-lived, PM concentrations in their vicinity. This can lead to high exposure to the people performing the activity—and potentially lower exposure to other people who may be located farther away but still in the same indoor environment. This spatiotemporal behavior of $PM_{2.5}$ occurs more strongly indoors than outdoors, where the air mixing volume and timescale for particle dynamics are much larger.

Indoor sources of $PM_{2.5}$ change continually with the development of new products and activities. The indoor environment changes as society and the consumer market change over time. New products are always entering our lives, homes, and schools, creating the need for a continuous reevaluation of indoor $PM_{2.5}$ sources and their associated exposures. Examples at the time of writing include electronic cigarettes, air fryers, and an abundance of air cleaning devices created or reintroduced during the COVID-19 pandemic that did not exist or were not as prevalent in years prior.

Respiratory aerosol has a $PM_{2.5}$ component. Discoveries related to the production of infectious aerosols during the COVID-19 pandemic indicate that aerosol particles are emitted from humans doing natural activities such as speaking and singing. These discoveries have shifted thinking on appropriate types of personal respiratory protection as well as highlighted the importance of indoor air quality in all settings.

Socioeconomic and cultural disparities in exposure to indoor $PM_{2.5}$ from different sources exist but remain underexplored. While there are documented socioeconomic and cultural disparities in ambient $PM_{2.5}$ sources, concentrations, and composition, less is known about how such differences manifest in differences in indoor $PM_{2.5}$ exposure. Moreover, while it is expected that there is high variability in the types and magnitudes of indoor $PM_{2.5}$ sources attributable to such differences, robust characterizations of the presence, types, and frequency of indoor emission sources—as well as technologies to mitigate exposures—for specific populations do not readily exist.

RECOMMENDATIONS

The committee's review identified a number of gaps in the literature addressing the sources and composition of indoor particulate matter that limit the confidence with which it and others can offer guidance on the health effects of indoor PM and the mitigation steps that might limit adverse consequences. These gaps lead the committee to recommend that **EPA, in collaboration with other governmental entities, private funders, and standards and professional organizations, should foster additional research on:**

Ultrafine particles (UFP) from indoor sources. Relative number, surface area, and mass emission rates for a range of different UFP sources would help to prioritize source removal, reduction, and control. Further knowledge of chemical composition may also be valuable for purposes of both source attribution and better understanding potential health effects. With this knowledge, researchers and the public could prioritize action where there is greater potential for impact. Mitigation strategies could be developed along with education initiatives to minimize people's exposure to those indoor sources that lead to worse health outcomes. There is an opportunity to educate the general public on indoor sources of fine particulate matter, including UFP, to enable more informed decision making when choosing indoor products and activities to minimize exposure.

Ambient air pollution as a source of indoor particles. The penetration of outdoor air pollutants into the indoor environments is relatively well understood and on average particles of outdoor origin contribute approximately one-half of indoor fine PM by mass. Evidence is clear that increases in outdoor $PM_{2.5}$ concentrations lead to a wide range of health effects. Knowledge of the extent to which those health effects are due to exposures to fine PM of outdoor origin while indoors remains an area for more research. Furthermore, the relative importance of particles of indoor fine PM of outdoor origin versus those emitted directly from indoor sources also remains unknown and could shed significantly light on practical mitigation strategies that maximize health benefits for building occupants.

Spatiotemporal $PM_{2.5}$ variability indoors. The concentration of fine PM varies both spatially—whether a measurement is taken near or far away from a particular source—and temporally—as air movement and mixing dilutes near-source concentrations and distributes PM through a space. This variability, which results from indoor sources in indoor environments—particularly residences and schools—may significantly affect the exposure of indoor occupants. Questions remain on how acute exposures (high concentrations, short time periods) cause health effects and can be influenced by practical mitigation choices. New knowledge could help inform the type and location of mitigation strategies contextually. Simply put: not all mitigation strategies may work for all indoor $PM_{2.5}$ sources, but if there is an understanding of which sources play a larger influence in the exposure of indoor occupants, decisions can be made to optimize mitigation strategies.

Establishing uniform criteria for the information needed on indoor sources to inform the assessment of exposure, health effects, and mitigation. It is impractical to address all indoor sources of $PM_{2.5}$, including sources of UFPs, because they continually evolve and change along with the consumer market. If uniform criteria existed for characterizing indoor sources, it could provide a pathway to harmonize future studies in indoor particle physics and chemistry as well as the development mitigation strategies and associated communication to the public. As an initial step in this process, compiling a comprehensive indoor emissions inventory (including outdoor sources) across a wide range of particle sizes, mass and number concentrations, and compositions would help researchers and policy makers to better compare different source categories and their resulting exposures.

Methodological advances for measuring PM in the indoor environment. Many of the studies reported in this chapter evaluated different indoor sources of PM in controlled laboratory chambers or real indoor environments, and both types of studies have their own inherent challenges and limitations. One of the greatest challenges is the deployment of large, research-grade instrumentation into real, occupied indoor environments, thanks to several reasons (noise, space requirements, safety limitations, transportation, etc.). Recent advances in lower-cost, consumer-grade sensors have shown the potential for investigations in a wide variety of indoor environments and sources, but continued evolution of these sensors to measure particle counts at much smaller sizes than existing optical scattering instruments would be valuable. To capture the diversity of indoor sources and indoor environments, advances must be made in miniaturized research-grade instrumentation to characterize PM in terms of size, concentration, chemical composition, etc., and to do so at the large scales needed to advance our understanding of health effects of indoor $PM_{2.5}$.

How the indoor PM knowledge gaps and research needs vary across different socioeconomic and cultural contexts. While there is a fairly detailed understanding of regional differences in ambient $PM_{2.5}$ sources and its infiltration into buildings, the same does not currently exist for indoor sources of $PM_{2.5}$. This knowledge would provide the tools for better public education and for the application of context-aware mitigation strategies that are sensitive to the target population and culture.

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4
Particle Dynamics and Building Characteristics that Influence Indoor PM

This chapter describes the mechanisms that affect indoor particle dynamics, how those mechanisms are measured or modeled, and how building characteristics affect these mechanisms. It concludes with recommendations for research to enhance knowledge of indoor particle dynamics in order to improve understanding of the health effects of indoor particulate matter (PM) and the effectiveness of practical mitigation measures. The fundamental dynamics described in this chapter apply to a broad range of particle sizes beyond the $PM_{2.5}$ (2.5 µm and smaller) size range; however, the quantitative information presented in later sections of this chapter are focused on all particle sizes that contribute to $PM_{2.5}$, given the scope of this report. The National Academies *Why Indoor Chemistry Matters* report (NASEM, 2022) addresses fate, transport, and transformation issues related to chemical species like polycyclic aromatic hydrocarbons that exist in the $PM_{2.5}$ range.

PARTICLES IN INDOOR ENVIRONMENTS

The fate of particles in the indoor environment governs the magnitude and route of occupant exposure to indoor PM and depends on a variety of mechanistic processes and the factors that affect those processes. Broadly, the major categories of mechanistic processes that affect indoor PM concentrations include PM (1) sources, (2) losses, and (3) transformations (Nazaroff, 2004).

The relative importance of specific PM sources, losses, and transformation processes depends on the nature of the PM sources as well as the type and location of the building in which an occupant resides and how the building is designed, built, and operated. Differences in building types and their operational characteristics are relevant for the fate of indoor PM because they influence how PM enters from outdoors (e.g., via infiltration through leaks or via mechanical outdoor air intakes), how and when PM is generated indoors (e.g., what types of activities, appliances, and fuels are present), and what types of practical mitigation measures can be implemented effectively (e.g., can central air cleaning be used?).

There are nearly 130 million occupied housing units in the United States, of which approximately 81 million are single-family detached homes, 32 million are multi-family homes, 8 million are single-family attached homes, and 7 million are manufactured/mobile homes (U.S. Census Bureau, 2022). The vast majority of existing homes rely on infiltration (i.e., air leaks), natural ventilation (i.e., window openings), and intermittent exhaust (e.g., bathroom and kitchen exhaust fans) for outdoor air ventilation rather than on dedicated mechanical ventilation systems (ASHRAE, 2017). There are also approximately 6 million commercial buildings (EIA, 2022) in the United States, the majority of which are designed to use mechanical heating, ventilation, and air conditioning (HVAC) systems that intentionally deliver outdoor air for ventilation; infiltration is also often not negligible in these building types, albeit not by design (Emmerich and Persily, 2014). There are also approximately 130,000 elementary and secondary schools in the United States (National Center for Education Statistics, 2022), with a much larger total number of classroom units within these schools, which vary widely in the types of HVAC systems that are installed and how they are operated (Batterman et al., 2017; Jaramillo and Ermann, 2012; McNeill et al., 2022). Importantly, a large fraction of schools have HVAC systems that are in need of significant retrofits or replacement (Chan et al., 2020; GAO, 2020), which affects the types of indoor PM mitigation measures that can be deployed and the effects they can have.

Some differences in building characteristics that can affect the fate, transport, and transformation of indoor PM are also associated with differences in geographic and socioeconomic factors that may contribute to disparities in exposure to indoor PM and associated health effects. For example, lower-priced homes tend to be leakier, with greater amounts of outdoor air infiltration (Chan et al., 2005, 2013) and thus greater amounts of outdoor pollutant entry (Stephens, 2015). Larger homes have been associated with lower indoor particle concentrations (Klepeis et al., 2017), and home size scales with income (U.S. Census Bureau, 2022). And more frequent kitchen range hood use has been associated with higher income and education levels (Zhao et al., 2020). However, the extent to which such factors contribute to disparities in indoor PM exposure has not been explored in depth or at scale to date.

INDOOR PARTICLE DYNAMICS: DEFINING MECHANISMS

The dynamic characteristics of indoor PM can be broadly classified into three fundamental processes: sources, losses, and transformations. Important sources of indoor PM are described in more detail in the previous chapter and are not the focus of this chapter. In brief summary, the sources of indoor PM include:

- Entry/delivery from outdoors through ventilation and/or infiltration,
- Primary indoor emissions,
- Resuspension from settled dust, and
- Formation as a byproduct from homogeneous or heterogeneous reactions (e.g., oxidation reactions between oxidants and volatile organic compounds [VOCs]).

Indoor PM simultaneously undergoes any number of other losses, also referred to as “sinks”, including:

- Deposition to surfaces,
- Removal by ventilation/exfiltration, and
- Removal by central or in-room air cleaning/filtration.

Indoor PM is also subject to a number of transformation processes, which can act as either sources, sinks, or merely a change in aerosol properties, including but not limited to:

- Transport, including intra-zonal transport (e.g., mixing within a room) and inter-zonal transport (e.g., from room to room)
- Coagulation (i.e., smaller particles combine to form larger particles or aggregates), and
- Change in properties such as composition, size, phase state, surface charge, viability (for biological particles), affected by processes such as aerosol aging, oxidation, evaporation, condensation, and partitioning.

Many of these source, loss, and transformation processes interact to influence the size, composition, and concentrations of particles in indoor air and are influenced by factors such as indoor and ambient environmental conditions (e.g., temperature and relative humidity) and building operational characteristics. For gaining a deeper understanding of some of these fundamental aerosol transformations, the ambient atmospheric chemistry and physics community has a number of resources available (Seinfeld and Pandis, 2016; Zhang et al., 2022). And as ambient atmospheric scientists have recently turned their attention to indoor air, several resources describe how some of these aerosol processes interact in indoor environments (Abbatt and Wang, 2020), including the 2022 NASEM report *Why Indoor Chemistry Matters*.

Figure 4-1 illustrates how sources, sinks, and transformation mechanisms interact to affect indoor PM. Table 4-1 further describes these mechanisms and key parameters that influence the strength or importance of each measure for indoor PM. The parameters in Table 4-1 include those that arise from an inherent property of the building and its systems, those that are a function of the operation of the building (e.g., how the building is operated at any given moment), those that are a function of weather or outdoor pollution conditions, and those that are a function of particle size, composition, or the presence of gas-phase pollutants. These layers of interacting factors and often high temporal dynamism makes general statements about practical mitigation challenging. For example, a building with open windows will generally have diminished marginal benefit on reducing indoor particle concentrations from the use of air cleaning because of competition by the additional ventilation and high rates of delivery of outdoor fine PM. The extent of the impact of these factors depends on parameters such as the inside–outside temperature difference, the wind speed and direction, the number, extent, and location of open windows, and the concentration of ambient fine PM. Thus, the sign and the magnitude of the impact of a given air cleaner on fine PM is specific to the details of the specific application. The same logic is necessary to consider for other mitigation measures as well.

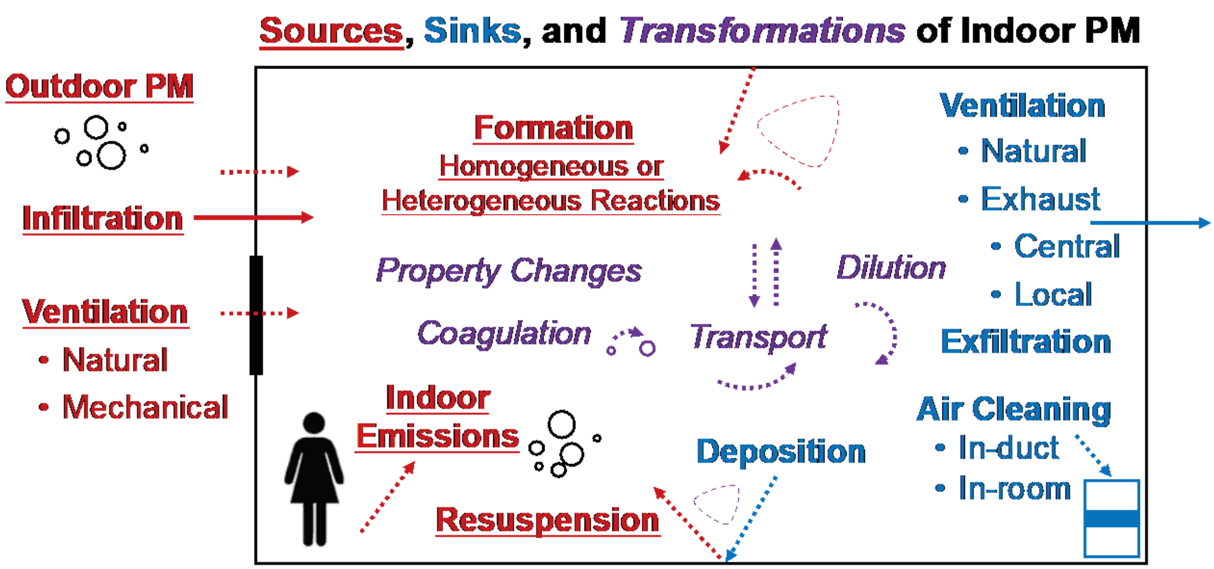

FIGURE 4-1 Sources, sinks, and transformations of indoor particulate matter (PM).

TABLE 4-1 Sources, Sinks, and Transformations of Indoor PM and Key Affecting Parameters

Mechanism	Key parameters that affect that mechanism
Sources	
Indoor emissions	Occupant activity type and schedule, source type and frequency (see Chapter 3)
Resuspension	Surface area, surface roughness, prior deposition and surface loading, air flow near surface, occupant activity
Formation (e.g., secondary organic aerosols)	Concentrations of precursors in air (homogeneous reactions) and on surfaces (heterogeneous reaction), temperature and humidity
Entry from outdoors	*Mechanical ventilation:* HVAC type (e.g., central or local), outdoor air flow rate, HVAC control strategy (e.g., damper position and schedule), outdoor air cleaner/filter efficiency
	Natural ventilation: Window/opening size and operational behavior, driving forces (wind speed and direction, inside–outside temperature differences, HVAC induced pressures), penetration factors
	Infiltration: Building leakage area and geometry, driving forces (wind speed and direction, inside–outside temperature differences, HVAC-induced pressures), penetration factors
Sinks (losses)	
Removal to outdoors	*Mechanical ventilation (central exhaust):* HVAC type, flow rate, HVAC control strategy (e.g., damper position and schedule) *Mechanical ventilation (local exhaust):* Flow rate, capture efficiency, occupant behavior and operation schedule, local exhaust location relative to source, mixing *Natural ventilation:* Window/other opening size and operational behavior, driving forces (wind speed and direction, inside–outside temperature differences, HVAC-induced pressures) *Exfiltration:* Building leakage area and geometry, driving forces (wind speed and direction, inside–outside temperature differences, HVAC-induced pressures)
Deposition to surfaces	Surface area, material properties (e.g., material, roughness), and orientation, particle deposition velocity, space and surface air flow characteristics
Air cleaning	*In-duct:* Flow rate through air cleaner/filter relative to space volume, installed removal/filtration efficiency, system runtime, mixing *In-room:* Flow rate through air cleaner relative to space volume, installed removal/filtration efficiency, air cleaner runtime, location relative to source
Transformations	
Transport	*Intra-zonal transport (mixing):* Source characteristics (e.g., point or area), zone/room volume, room air flow characteristics (HVAC, fans, buoyancy, activities), operation of local sinks (e.g., air cleaners, local exhaust)

Mechanism	Key parameters that affect that mechanism
	Inter-zonal transport (between zones): Space layout, HVAC layout, leakage area of walls/partitions, driving forces (e.g., pressure differences caused by wind, temperature, HVAC operation)
Coagulation	Particle concentration (high concentrations needed), particle size distributions (smaller sizes needed)
Change in aerosol properties (e.g., size, phase state, charge, composition, viability)	Initial composition, size, and surface area; residence time; environmental conditions (e.g., temperature, humidity, pH); presence of sunlight; presence and concentration of interacting compounds

MEASURING INDOOR PARTICLE DYNAMICS

A major challenge in understanding individual sources, sinks, and transformations is that measurements of indoor PM concentrations, size distributions, or composition in buildings alone generally do not yield insights into the presence or magnitude of any particular mechanisms. Rather, indoor PM concentration measurements yield a measure of the *net result* of any number of competing or interacting processes (i.e., the concentration that remains after competing mechanisms interact). Moreover, it may not always be critical to assess specific mechanisms in the context of a health or mitigation study. For example, measurements of indoor and outdoor concentrations in buildings under relatively tightly controlled conditions, such as air cleaner on versus air cleaner off conditions, can yield insights into the effectiveness of an intervention while not necessarily yielding direct measurements of the magnitude of individual sinks or transformation processes. Also worth noting is that recent advancements in low-cost PM sensors that provide real-time displays of indoor PM concentrations to building occupants may also be useful in promoting behavioral interventions that affect indoor PM concentrations (Klepeis et al., 2013). However, it is possible to use a combination of (1) mathematical models and (2) targeted/scripted measurements to quantify the magnitude of particle sources, sinks, and transformations in real buildings. Laboratory measurements with certain parameters constrained also yield fundamental insight into these processes. In either field or lab tests, mathematical models are used to establish a theoretical framework for quantifying mechanisms that one observes or expects to observe and then are applied to measurements of indoor PM concentrations that result from targeted or scripted experiments, such as intentional perturbation experiments, to parameterize those models and quantify specific mechanisms.

Mathematical Modeling of Indoor PM Sources, Sinks, and Transformations

The earliest mathematical model for predicting indoor aerosol size distributions and concentrations dates to 1973 with an application in a computer facility at Bell Laboratories (Lum and Graedel, 1973). Nazaroff and Cass (1989) presented what is believed to be the first comprehensive mathematical model for predicting the concentration and fate of PM in indoor air that included both size resolution and chemical composition of indoor PM and accounted for indoor emissions, ventilation, filtration, deposition on surfaces, and coagulation. The model was validated using measured aerosol size distributions resulting from combustion of a cigarette in a single room, setting a precedent for how measurements and models can be combined to yield mechanistic insights into indoor PM. Such modeling efforts have since been extended to estimate or predict the effects of numerous other processes in a variety of indoor environments, including but not limited to predicting shifts in gas-particle partitioning with outdoor-to-indoor transport in homes (Hodas and Turpin, 2014); simulating residential $PM_{2.5}$ infiltration across the U.S. housing stock factoring in size- and chemically-resolved penetration factors, evaporative losses, deposition losses, and filtration (Logue et al., 2015); predicting the effects of oxidative aging (i.e., continuously changing aerosol chemistry evolving by oxidative chemistry) on organic aerosol concentrations in residences under varying conditions (Cummings and Waring, 2019); and predicting the impacts of the phase state (e.g., semisolid or liquid) of indoor organic aerosols of outdoor origin on gas-particle partitioning (Cummings et al., 2022). Such models are also applied to measured indoor PM concentration data to estimate parameters such as emission rates (Chan et al., 2018), envelope penetration factors (Rim et al., 2010; Zhao and Stephens, 2017), indoor deposition loss rates (Lee et al., 2014), and filtration losses and filtration efficiency (Stephens and Siegel, 2012, 2013). Experimental investigations of mechanistic source, sink, or transformation processes often begin with controlled laboratory chambers, where parameters can be tightly controlled to yield observations that can be used to parameterize models, and then commonly extend to field measurements in individual homes or groups of homes to yield further insights in real buildings. Common approaches to measuring sources, sinks, and transformations of indoor PM are described in the next sections, with the goal of illustrating how such measurements are made in the event that they may be useful for incorporation into indoor PM health or intervention studies.

Measuring Indoor PM Sources

Because indoor PM in buildings results from a mixture of ambient sources that enter through ventilation/infiltration plus indoor sources, targeted in-situ measurements must be used to characterize the relative contributions of ambient and non-ambient sources from field measurements of indoor and outdoor PM concentrations. Such efforts generally begin with characterizing the time-averaged *infiltration factor*, or the fraction of ambient PM that infiltrates (i.e., enters) and persists indoors (a value bounded by 0 and 1) over a certain time period, which may vary by the nature of ventilation air, the magnitude of air change rate, ambient particle size distributions, or other building characteristics. Once the infiltration factor is known and applied to calculate the fraction of indoor PM originating from outdoors, the remaining fraction of indoor PM can be estimated to be generated from indoor sources (Özkaynak et al., 1996; Wilson et al., 2000). This approach can be applied to concurrent indoor and outdoor PM concentrations using either (1) time-integrated gravimetric measurements combined with a chemical tracer of ambient-infiltrated PM (e.g., sulfur, which historically has been assumed to have predominantly outdoor sources and minimal indoor sources) (Wallace and Williams, 2005) or (2) time-resolved measurements of PM concentrations (or surrogates of PM concentrations, see Chapter 5) with algorithms applied to mathematically remove the influence of indoor sources (Kearney et al., 2014; MacNeill et al., 2012, 2014).

Numerous studies have used such approaches and estimated that the time-averaged infiltration factor for ambient $PM_{2.5}$ in residences commonly ranges from as low as ~0.1 to as high as nearly 1, with an average of ~0.5 (the average infiltration factor for ultrafine particles is lower, around ~0.3) (Chen and Zhao, 2011). Other recent studies using low-cost optical particle counters to approximate $PM_{2.5}$ concentrations have found lower mean values of $PM_{2.5}$ infiltration factors in U.S. homes of ~0.25 to ~0.4 (J. Bi et al., 2021; Liang et al., 2021). Use of air cleaning systems can reduce infiltration factors to even lower than 0.1 (Singer et al. 2017). With sufficiently broad characterizations of infiltration factors across a specific building stock, it is possible to model infiltration factors with reasonable accuracy using factors such as frequency of window opening, use of forced air heating or cooling, and use of air cleaning/filtration (Allen et al., 2012; Tang et al., 2018), which in turn could be used in epidemiology studies to characterize population exposures. An analysis of indoor and outdoor $PM_{2.5}$ samples from the RIOPA study further showed that measured air change rates were a strong predictor of infiltration factors, but that air change rates were difficult to accurately predict using simple indicator variables (Meng et al., 2009). Infiltration factors have been less well characterized in schools, especially in the United States; a few studies in European schools have estimated $PM_{2.5}$ infiltration factors ranging from ~0.3 to ~0.8, likely varying by factors such as the source and rate of ventilation air delivery and the type and use of HVAC systems and filtration (Korhonen et al., 2021; Rivas et al., 2015).

Other studies have also explored the infiltration of outdoor PM in greater depth by attempting to estimate the penetration factor of the building envelope (and any connected systems that may draw in outside air). The *penetration factor*, which is also bounded by 0 and 1, describes the fraction of ambient PM that passes through the building's boundary between inside and outside (i.e., its enclosure, or envelope) (Liu and Nazaroff, 2001). The parameter is fundamentally important because it characterizes the fraction of the PM in outdoor air that enters a building, allowing one to understand the relative impacts of the building envelope versus indoor sinks such as deposition or air cleaning on indoor PM of outdoor origin. However, it is notoriously difficult to measure, as approaches to measuring it are time-consuming, cumbersome, and invasive to occupants, while also requiring solving for two unknowns (penetration factors and indoor loss rate constants) using only one mass balance equation applied to measured concentrations from the space (Diapouli et al., 2013). Approaches to estimating penetration factors for $PM_{2.5}$ using statistical methods combined with integrated $PM_{2.5}$ mass measurements have suggested that penetration factors in U.S. homes may be close to 1 (Meng et al., 2005; Wilson et al., 2000), whereas specific measurements of size-resolved penetration factors suggest that values range from ~0.2 to ~1 depending on particle size and various building factors (Chen and Zhao, 2011; Rim et al., 2010), which in turn suggests that ambient $PM_{2.5}$ infiltration factors may also range in magnitude depending on the same factors. A 2017 study used targeted measurements in an unoccupied apartment unit to estimate size-resolved penetration factors for particles approximately 0.01–2.5 μm in size with doors and windows closed, which were then used to estimate penetration factors for an integral measure of $PM_{2.5}$ by scaling to concurrent outdoor size distributions, resulting in a mean estimated $PM_{2.5}$ penetration factor of ~0.73 (Zhao and Stephens, 2017). A 2010 study of size-resolved ultrafine particle penetration into an unoccupied test house revealed that both infiltration factors and underlying penetration factors were approximately two times higher with a single window open approximately 3 inches (7.5 cm), depending on particle size (Rim et al., 2010).

As mentioned, the same approaches that are used to estimate infiltration factors can also be used to estimate the contribution of indoor sources to total indoor $PM_{2.5}$. Applications of such approaches have shown that the contribution of indoor sources to indoor $PM_{2.5}$ may range from negligible to nearly dominant, depending on how much ambient $PM_{2.5}$ infiltrates and persists indoors and on the magnitude of indoor source strengths (Kearney et al., 2014; MacNeill et al., 2014). Therefore, numerous studies have quantified the strength of indoor sources using in-situ (i.e., in-home) measurements with either scripted (or documented) field experiments with specific sources (Hussein et al., 2006; Sain et al., 2018; Stephens et al., 2013; Wallace, 2006;

Zhao et al., 2021) or unscripted experiments to capture whole-house emission rates (Chan et al., 2018), or, more commonly, using controlled chamber experiments with specific sources (Afshari et al., 2005; Azimi et al., 2016; Géhin et al., 2008; Licina et al., 2017; Vance et al., 2017). In any of these approaches, emission rates from indoor PM sources can be estimated using mass balances applied to control volumes with a number of assumptions such as well-mixed conditions and measurements or estimates of parameters such as PM loss rates and test space volume. Such field-based approaches provide insight into sources as they behave in the field, albeit with less well controlled conditions, while lab-based approaches offer greater control and provide the ability to easily isolate specific sources. However, it is worth noting that emission rates measured in a laboratory or chamber might not accurately predict the emission rates measured in the field. Similar approaches have also been used to estimate PM resuspension rates from settled dust (Ferro et al., 2004; Qian and Ferro, 2008) and the formation rates of PM (and other mechanistic factors such as yields) resulting from indoor reactions (Petrick et al., 2011; Wang and Waring, 2014; Youssefi and Waring, 2014). Results from this literature were summarized in Chapter 3.

Measuring Indoor PM Sinks

The impact of indoor PM sinks, especially those associated with mitigation measures such as air cleaning, can be measured in two main ways: (1) measurements of the resulting effectiveness of an intervention or (2) direct measurements of the magnitude or rate of an indoor sink process. To measure the effectiveness of a mitigation intervention, indoor PM concentrations can be measured with and without an intervention, and comparisons between test conditions can yield insight into the magnitude of impact, holding other important parameters such as ventilation rates constant (or accurately measuring them concurrently). Such approaches have been widely used to quantify the impacts of air cleaning interventions such as portable HEPA air cleaners (Batterman et al., 2012) and in-duct particle filters (Bennett et al., 2018; 2022) on indoor PM concentrations and the impacts of air filtration or UV air cleaners on indoor concentrations of airborne microbes (Kunkel et al., 2017; Lai et al., 2003). Similar test approaches in controlled chambers and smaller-scale field studies have also been useful in quantifying the effectiveness and demonstrating some of the potential consequences of air cleaning technologies that rely on the addition of reactive constituents to air, such as the formation of secondary organic aerosols and gas-phase oxidation byproducts from the operation of ozone-generating ionizing and other oxidizing air cleaners in the presence of unsaturated organic compounds (Joo et al., 2021; Waring et al., 2008; Ye et al., 2021; Zeng et al., 2022).

Both indirect and direct methods have been used to quantify the magnitude or rate of specific indoor PM sink processes in buildings. Historically, statistical approaches have been used to indirectly estimate the magnitude of PM sinks such as total indoor loss rate constants from time-integrated concurrent indoor and outdoor concentration measurements (e.g. Meng et al., 2005; Williams et al., 2003). With the development of real-time and time-resolved instrumentation to monitor particle concentrations, methods to directly quantify indoor PM sinks have emerged. Direct measurements of indoor PM sinks generally involve analyzing time-series concentrations that characterize an elevation period followed by a decay towards background levels. Such approaches can be used with intentional perturbation experiments that involve purposeful elevation of indoor PM (e.g., He et al., 2005; Lee et al., 2014; Wallace et al., 2004) or with natural experiments that involve exploring resulting concentration data to find periods of concentration elevation and decay that naturally occurred with regular occupancy and activity

(Chan et al., 2018; Hussein et al., 2005). Either way, estimates of first-order indoor particle loss rate constants can be made using mass or number balance approaches applied to the resultant data with a number of appropriate assumptions, which allows for direct quantification of such sinks (Thatcher et al., 2002).

In the absence of other information, such estimates of total PM loss rates will account for losses due to the combined effects of surface deposition, loss by ventilation/exfiltration, and losses by any air cleaning strategy or other sink or transformation process that might be present (Boedicker et al., 2021). Simultaneous measurements of other parameters such as air change rates can account for some of these interacting mechanisms and allow for isolating the impacts of, for example, surface deposition or air cleaning alone. Comparisons of loss rates measured between different conditions in a building can also allow for directly quantifying the impact of a change in condition (e.g., an intervention), assuming other mechanisms remain constant or are measured and accounted for. For example, comparing loss rates between different in-duct filter or portable air cleaner configurations can make it possible to quantify the impact that higher efficiency filtration or stand-alone air cleaning has on loss rates in a space, which also allows for estimating the in-situ clean air delivery rate (CADR) of the filter or air cleaning system (Alavy and Siegel, 2020; MacIntosh et al., 2008; Stephens and Siegel, 2012, 2013). Additionally, the impact of improved particle filtration on indoor PM concentrations can also be assessed by measuring PM concentrations upstream and downstream of a filter and quantifying airflow rates in buildings; recent studies have applied such approaches to characterize the impacts of interventions on PM loss rates in residences with central HVAC systems with various efficiency filters (Li and Siegel, 2020) and also in a renovated school that received a combination of MERV 8 and MERV 16 filters (Laguerre et al., 2020).

It is worth noting that the in-situ methods described above originate from controlled chamber studies that are routinely used to characterize the performance of air cleaners (Offermann et al., 1985; Shaughnessy and Sextro, 2006) and have also been used to yield mechanistic insights into factors that affect various sink processes, such as air speeds and surface characteristics, on deposition loss rates (Lai et al., 2002; Thatcher et al., 2002). Such controlled chamber test approaches are useful because they allow for the direct quantification of parameters such as CADRs or equivalent air change rates of air cleaners, both for PM broadly (Sultan et al., 2011; Waring et al., 2008) and for specific constituents of PM such as varying chemical compositions or source types (Peck et al., 2016) and microbial viability (Eadie et al., 2022; Kujundzic et al., 2006; Miller-Leiden et al., 1996). These measures conceivably translate to real indoor environments as well; however, such studies are limited in that laboratory performance may not accurately reflect performance in the field, for a variety of reasons. Many fewer studies in the literature have measured in-situ CADRs or other sink mechanisms in real field settings compared with controlled chamber studies, likely because of the increased complexity involved in doing so.

Recent advances have also been made in the experimental characterization of local mitigation strategies such as residential kitchen range hoods (Kim et al., 2018) and the placement of air cleaners near the breathing zone of occupants (DuBois et al., 2022). The capture efficiency of range hoods characterizes the fraction of particles generated through cooking that are removed by operating an exhaust fan over the cooking area. Capture efficiencies for fine PM have been shown to range from less than 10 percent to greater than 80 percent, depending on factors such as the exhaust hood flow rate, the burner location (i.e., front versus back), and particle size (Lunden et al., 2015; Rim et al., 2012b; Sun et al., 2018). However, such measurements have not been made at scale to characterize variability among different building stocks.

Measuring Indoor PM Transformations

Indoor PM of both indoor and outdoor origin is subject to a number of transformation processes as particles interact with each other and the environment. Transformation processes can act as a source or a sink, or lead to changes in aerosol properties such as size distribution or toxicological profile, depending on a number of factors and conditions. For example, when particles are first emitted from an indoor source such as cooking, if particles are small enough (e.g., <50 nm) and at high enough concentrations (e.g., >20,000 particles/cm^3), coagulation can occur whereby smaller particles collide with like-size or larger particles to form yet larger particles (Rim et al., 2012a). Thus, coagulation simultaneously acts as a loss for the colliding particles and as a source for the larger aggregate particles that are created, affecting the overall size distribution but not total particle mass. For small nanoparticles at high concentrations, coagulation can be a dominant loss mechanism and be much greater than room ventilation (Jeong et al., 2021). However, coagulation is not considered a dominant mechanism for larger particles which generally contribute more to indoor $PM_{2.5}$ mass concentrations, and understanding coagulation processes is probably not critical for understanding the impacts of most practical mitigation measures under most circumstances.

As mechanisms such as coagulation, deposition, and ventilation are simultaneously competing following emissions of indoor particles from a source, other mechanisms are also interacting, including intra-zonal transport (e.g., dispersion or mixing within a room), inter-zonal transport (e.g., movement from room to room or unit to unit), and also processes that affect composition and size, such as evaporation, condensation, and partitioning. Intra- and inter-zonal particle dispersion has been investigated using multiple calibrated PM monitors stationed at various distances and directions from point sources. A 1999 study investigated intra-zonal dispersion of incense particles in a home along horizontal distances of up to ~5 m, finding pronounced source proximity effects during the active combustion period in which fine PM concentrations within ~1 m of a source were approximately three times greater than those ~5 m from a source (i.e., in a central location in a house on the same floor) (McBride et al., 1999). Human activity (e.g., walking and moving) also affected the direction of particle movement and dispersion, suggesting that measurements in occupied versus unoccupied spaces would result in different outcomes for PM transport. In an investigation of both intra- and inter-zonal particle dispersion resulting from incense burning on the first floor of a three-story house in France, while particle concentrations were obviously higher in close proximity to the source, incense burning also increased particle concentrations throughout the second and third stories of the home, albeit with dilution, ventilation, and deposition offering some protective effects throughout the home (Ji et al., 2010). Recent advances in low-cost PM sensors have made it possible to deploy more monitors to investigate PM transport at higher spatial and temporal resolution following indoor generation from point sources than what was previously feasible (Lau et al., 2021; Li et al., 2018). Deployment of such monitors in homes has been used to illustrate that cooking emissions from kitchens can be detected in bedrooms sometimes within minutes and usually less than an hour following emission, depending on location; that PM concentrations were generally ~30 percent lower in bedrooms than in kitchens; and that the presence of interior partitions (e.g., walls, closed doors) delays transport from kitchen to bedrooms, with the fastest transport occurring in homes with no internal walls (Sankhyan et al., 2022). The extent to which transport from a point source to other indoor locations affects spatial indoor PM concentrations varies by house size, room size, direction of airflow, and other factors (e.g., Singer et al. 2017).

Inter-zonal transport can also act as a source of indoor PM from adjacent/neighboring units in multi-family buildings. A classic, often directly noticeable, example is secondhand smoke (SHS) transfer between adjacent units. King et al. (2010) found evidence of $PM_{2.5}$ from SHS transporting from smoking-permitted units to smoke-free units in 2 of 14 (14 percent) smoke-free units in 11 multifamily buildings that were investigated. Bohac et al. (2011) investigated airflows between units in six multifamily buildings in Minnesota using passive perfluorocarbon tracer (PFT) gas tests and found that the median fraction of air entering a unit that came from other units ranged from ~2 percent in a new building to ~35 percent in a 1930s duplex. Air sealing retrofits helped reduce this fraction, on average. Although PM transport was not investigated, nicotine—a semi-volatile compound that strongly adsorbs to surfaces—transferred at a much lower rate than air alone. Thus, it is plausible that PM may also transfer at lower rates than air alone due to unit-to-unit penetration factors of less than 1 (e.g., Dacunto et al. 2014), but the committee is not aware of such investigations.

Finally, numerous physical, chemical, and biological processes such as aerosol aging, oxidation, evaporation, condensation, and partitioning interact to influence important indoor PM properties such as composition, size distribution, phase state, surface charge, and, for biological particles, viability. A detailed review of such processes is beyond the scope of this report, and such characterizations are often challenging to conduct in field measurements, but it is useful to have a high-level understanding of these mechanisms. For example, semi-volatile chemical species can undergo phase changes during outdoor-to-indoor transport and affect the resulting indoor $PM_{2.5}$ concentrations and composition, subject to influences by indoor and outdoor temperature differences and the availability of indoor PM for sorption (Hodas and Turpin, 2014). Such phase changes can lead to losses of PM mass as it transports from cooler outdoor air to warmer indoor air and, conversely, gains of PM mass as warmer outdoor air transports into cooler indoor environments (humidity, and thus total enthalpy, as well as PM composition, also interact to influence the magnitude and direction of partitioning, but the above simplification is useful for illustration). Avery et al. (2019) provides further insight into how aerosol composition and indoor/outdoor temperature and humidity influence the concentration and composition of indoor PM of outdoor origin in a classroom. Transformations can also interact with sources and loss rates to affect both PM and gas-phase pollutant exposure. For example, reducing PM concentrations also removes sorption sites onto which semi-volatile organic compounds (SVOCs) can no longer partition, which may shift the fraction of SVOCs that are found in the particle phase into the gas phase (Liu et al., 2013; Lunderberg et al., 2019). Such phase and compositional changes may also influence the toxicity of indoor PM of ambient origin. For example, one 2021 study characterized the oxidative potential (OP) of indoor $PM_{2.5}$ of ambient origin in an unoccupied apartment unit with doors and windows closed and found that the intrinsic (mass-normalized) OP was higher for indoor PM samples than for concurrent outdoor PM samples and that the extent of enhancement of intrinsic OP was correlated with differences in indoor and outdoor temperature and relative humidity (RH) (Zeng et al., 2021). Natural ventilation (airflow through open windows) has also recently been shown to alter the composition of indoor PM, for example by providing more PM surface area (from increased PM introduction from outdoors) for partitioning of semi-volatile compounds onto indoor PM (Fortenberry et al., 2019) and by temporarily altering SVOC removal processes (Kristensen et al., 2019). Recent work has also demonstrated that SVOCs from material sources directly partition to settled dust, which in turn affects SVOC exposure in resuspended particles (W. Bi et al., 2021), and that particles emitted from indoor sources (e.g., candles) enhance partitioning of gas-phase SVOCs to indoor particles, affecting the particle composition and enhancing surface off-gassing (Kristensen et al., 2023). The dynamics of partitioning of SVOCs to PM in indoor air is important since indoor environments tend to be much richer in specific SVOCs with known adverse health effects (e.g., endocrine disruption, cancer) than are found outdoors. These SVOCs include plasticizers, flame retardants, some pesticides, and per- and polyfluoroalkyl substances (PFAS) used to provide stain resistance on many indoor materials as well as use in other consumer products. Understanding the interaction of airborne and settled PM with these SVOCs and the impacts of such interactions on human exposure to these chemicals is important as new SVOCs are substituted for those being phased out.

Also worth noting, the chemical composition, pH, and surrounding RH conditions of human respiratory droplets (or surrogates of respiratory droplets) have also been shown to affect the viability of airborne viruses contained within PM (Ahlawat et al., 2022; Huynh et al., 2022; Lin and Marr, 2020; Lin et al., 2020). Such transformation processes are clearly important for influencing indoor PM properties but remain challenging to empirically assess in real-world environments.

SOCIOECONOMIC DISPARITIES IN INDOOR PARTICLE DYNAMICS

The extent to which socioeconomic disparities in individual source, sink, and transformation processes contribute to disparities in indoor PM exposure has not been explored in much depth in the literature, but there are several logical ways in which known socioeconomic differences in buildings and their occupants and their activities likely contribute to such disparities.

First, the concentration and composition of outdoor PM varies geographically, and such differences have been shown to be associated with socioeconomic status, age, and race/ethnicity. For example, concentrations of ambient $PM_{2.5}$ (Miranda et al., 2011) and many of its chemical constituents (Bell and Ebisu, 2012) are higher in non-Hispanic Black populations than in White populations. Such racial disparities in ambient $PM_{2.5}$ concentrations have been demonstrated at all income levels (Paolella et al., 2018) and, as noted in Chapter 3, can lead directly to similar disparities in exposure to indoor $PM_{2.5}$ of ambient origin, holding all other factors constant.

Second, there are known differences in primary building characteristics that plausibly contribute to disparities in indoor $PM_{2.5}$ sources, sinks, and transformations. For example, lower-cost homes tend to have lower airtightness (i.e., they have leakier building envelopes), which means they allow greater amounts of outdoor air infiltration (Chan et al., 2005, 2013) and thus greater amounts of outdoor pollutant entry (Stephens, 2015). Along these lines, one study found that higher predicted infiltration air change rates in residences were associated with increased risks of emergency department visits for asthma and wheeze associated with outdoor $PM_{2.5}$ when ambient $PM_{2.5}$ concentrations were below a certain level (Sarnat et al., 2013). Another study found that "variability in factors that influence the fraction of ambient $PM_{2.5}$ that infiltrates and persists indoors (such as the air change rate) could possibly bias health effect estimates in study designs for which a spatiotemporal comparison of exposure effects across subjects is conducted" (Hodas et al., 2013, p. 573). As another example, larger homes have been associated with lower indoor particle concentrations (Klepeis et al., 2017), and home size scales with income (U.S.

Census Bureau, 2022). Similarly, one 2021 study observed that renters in multifamily housing units experienced a higher proportion of indoor $PM_{2.5}$ concentrations from indoor sources than homeowners in either single-family or multi-family housing, suggesting that differences in indoor sources had less to do with housing type and more to do with socioeconomic factors (Chu et al., 2021). And of course, occupants of multi-family housing units can experience transport from adjacent units, whereas occupants of single-family housing units cannot (and lower income occupants are more likely to live in multi-family housing). Conversely, occupants of single-family housing units may have more entry points for ambient PM to infiltrate. Moreover, a higher prevalence of central air conditioning, which is also more prevalent in higher-income groups, has also been associated with a lower risk of mortality associated with ambient $PM_{2.5}$ (Franklin et al., 2007).

Third, there are also known differences in human activities that plausibly contribute to disparities in indoor $PM_{2.5}$ sources, sinks, and transformations. For example, window opening frequency has been shown to be an important predictor of the amount of ambient $PM_{2.5}$ that enters and persists indoors (Allen et al., 2012). Until very recently, few studies of window opening behavior in homes had been conducted, with limited geographic coverage (El Orch et al., 2014; Johnson and Long, 2005). The first known nationwide survey of window opening behavior in U.S. homes was published in 2022 (Morrison et al., 2022); it found that approximately 44 percent of respondents said that at least one window was open prior to taking the survey. Greater window-opening frequency was associated with having a lower income, living in attached homes or apartments, renting, lack of air conditioning, and being Asian or Hispanic. Window-opening frequency was also different by geographic region; people living in the western and northern parts of the United States reported opening windows more frequently than those in the southeastern United States. Such rich information does not yet exist for schools, although there are more robust datasets available for offices, especially internationally (Fabi et al., 2012). Better understanding window-opening behaviors could lead to a better understanding of how window opening acts as a source of ambient PM and a loss for PM of indoor origin. Additionally, more frequent kitchen range hood use, which can lower occupant exposures to indoor PM from cooking sources, has been associated with higher income and education levels (Zhao et al., 2020). A recent nationally representative sample of residential range hood use in Canada found that only 30% of respondents who had mechanical ventilation devices over their cooktop surfaces reported regularly using their devices; more frequent use was associated with the device being vented to the outdoors (approximately two-thirds of the devices vented outdoors), having quiet operation or multiple fan speed settings, covering over half the cooktop, and having higher perceived effectiveness (Sun and Singer, 2023).

There are other plausible links between socioeconomic factors and the source and composition of fine PM indoors. For example, research suggests that smoking rates are higher in lower-income and lower-education populations (CDC, 2023) and exposure may be further exacerbated in these populations due to such factors as inadequate ventilation, poor building condition and maintenance, overcrowded living spaces, and lack of access to or information on air filtration and other technological and behavioral means of limiting PM. Such links, however, remain to be explored in depth.

OBSERVATIONS AND RECOMMENDATIONS

There are two primary reasons for wanting to learn more about individual source, sink, and transformation processes in indoor environments. The first is to be able to understand and model population exposures to indoor PM at scale to extend the types of epidemiology studies that can be conducted. To do this, a broad and deep understanding of the presence and magnitude of many specific indoor source, sink, and transformation processes across the building stock is needed, akin to how ambient air quality models have advanced to yield estimates of local ambient PM concentrations at very high spatial resolution (Di et al., 2016, 2017; van Donkelaar et al., 2016). Such an understanding would make it possible to target appropriate practical mitigation measures for different contexts, and, specifically, to use practical mitigation to address exposure disparities.

The second reason is to be able to understand results from investigations of practical mitigation interventions within the context of the other mechanistic impacts on indoor PM that might exist in a study population. The aforementioned example of a building with an air cleaner operating and with windows open illustrates this need; results from an air cleaning intervention study in such a building under those operational conditions would lead to the conclusion that air cleaning did not have a significant impact on reducing indoor PM or on reducing health effects. However, the lack of impact would be due to competition from ventilation or the introduction of non-monitored outdoor air pollutants. To overcome such limitations, the research community needs to adopt a more "building-aware" epidemiological approach whereby research characterizing the effects of a practical mitigation approach provides the context of the mechanisms that affect fate, transport, and transformations of indoor PM (e.g., if an air cleaner intervention is done in homes/locations with other competing mechanisms like high air change rates/windows wide open, was that characterized and how?). In order to make this contextualization possible, clear, practical, and relatively low-cost monitoring approaches will be needed to identify and quantify important parameters that potentially affect the effectiveness of practical mitigation measures.

To date, there is a relatively strong body of literature and a deep fundamental understanding of the types of mechanistic processes that influence the fate, transport, and transformations of indoor PM. It is often more economically or practically feasible to model such processes than to measure them because of the significant requirements for equipment and labor to conduct field measurements, although the gap between measurements and models is closer for some processes than others. Models enable extrapolations from measurements that necessarily must occur in a limited number of buildings and conditions, and also enable simulated experimentation to assess possible impacts of mitigation efforts or other factors on exposures. The research community has also demonstrated the ability to observe previously unobserved mechanisms and to learn to quantify those mechanisms that are expected to exist. It is important for the research community to continue to build and maintain capacity for identifying, quantifying, and measuring new mechanisms for sources, sinks, and transformations of indoor PM as they arise and to subsequently understand the potential impacts of such mechanisms on the toxicity of indoor PM.

There is a narrower understanding of the magnitude and range of many individual source, sink, and transformation processes across the building stock and different types of buildings. Measurement approaches are often complicated, cumbersome, or invasive or require specialized (and expensive) equipment, so sample sizes are often very limited. Moreover, while a broad characterization of every mechanism across the building stock is not feasible or necessary, it remains to be understood what minimal information of indoor PM dynamics is needed to meaningfully improve understanding of the health effects of indoor PM exposure (e.g., by modeling exposures across the building stock) and the impacts of practical mitigation measures (e.g., by measuring their impacts in intervention studies).

In summary, then, the committee offers the following recommendations:

The indoor air research community should:

- **continue to build and maintain capacity for identifying, quantifying, and measuring new mechanisms for sources, sinks, and transformations of indoor PM as they arise and to subsequently understand the potential impacts of such mechanisms on the toxicity of indoor PM.** This recommendation echoes two recommendations offered in the *Why Indoor Chemistry Matters* report: 6 – "[r]esearchers who study toxicology and epidemiology and their funders should prioritize resources toward understanding indoor exposures to contaminants, including those of outdoor origin that undergo subsequent transformations indoors" and 7 – "[r]searchers and their funders should devote resources to creating emissions inventories specific to building types and to identifying indoor transformations that impact outdoor air quality" (NASEM, 2022; p. 7). Such work is needed to gain a more complete understanding of the chemical complexity of the indoor environment and its attendant health implications. It should be noted, though, it is not the sole province of EPA—some falls under the responsibility of agencies like the Consumer Product Safety Commission or falls into a regulatory void where responsibility for action is unclear.
- **come to consensus on what minimal information on indoor PM dynamics is needed to meaningfully improve understanding of the health effects of indoor PM exposure,** for example, by modeling exposures across the building stock for use in epidemiology studies.
- **adopt a more building-aware epidemiology approach whereby research characterizing the effects of a practical mitigation approach would need to also provide the context of the mechanisms (i.e., source, sinks, and transformations) that affect indoor PM.** In order to enable this contextualization, research should explore what minimal information on indoor PM dynamics is needed to meaningfully improve understanding of practical mitigation measures for indoor PM. To do so, there is a specific need for clear, practical, and relatively low-cost monitoring approaches to identify and quantify important parameters that potentially affect the effectiveness of practical mitigation strategies.
- **identify the subsets of building types and locations that may be particularly vulnerable to high indoor PM exposures for occupants based on our understanding of the characteristics that influence the fate, transport, and transformation of indoor PM.** The same reasoning that is used to specific susceptible populations of individuals for inclusion in a health or mitigation study could be applied to such identification of vulnerable building types and locations.

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5
Exposure to Indoor PM

This chapter addresses exposure assessment methods for fine particulate matter indoors, with a focus on exposure metrics. Particle concentrations and other attributes that form the basis for these metrics—mass, surface area, number, size fraction or distribution, chemical composition and bioactivity, temporal patterns—and the state of currently available instrumentation to resolve these features with varying degrees of accuracy, sensitivity, and specificity, are then reviewed. The chapter then covers the application of these tools to measure exposure directly or indirectly, with models that resolve concentrations as a function of human location. Emerging and novel tools and approaches for characterizing and mitigating exposure uncertainty and error through better characterization of particle size, composition, spatial and temporal resolution, and human location are highlighted.

Observed trends, with an emphasis on determinants of exposure that result in exposure disparities are considered. Influencing factors, such as indoor sources, building characteristics, environmental factors, and human activities are discussed. The chapter then further explores how advances in exposure assessment can improve our understanding of health effects and practical mitigation. It closes with a summary of the findings and conclusions that flow from the literature review.

SCOPE AND INTRODUCTION

Indoor exposure to airborne particles occurs when humans inhale the air in their homes, schools, and other built environments or come into contact with the particles by other routes. Exposure may be thought of as the time-integrated airborne concentration experienced at the point of contact between humans and particles. As shown in Figure 5-1, once particles are breathed in and the human interface is crossed, particles are referred to as an *intake*. Inhaled particles are either breathed back out or deposited and retained in the body. The term *dose* applies after absorption and transport result in a final, delivered quantity, which can cause one or more health outcomes.

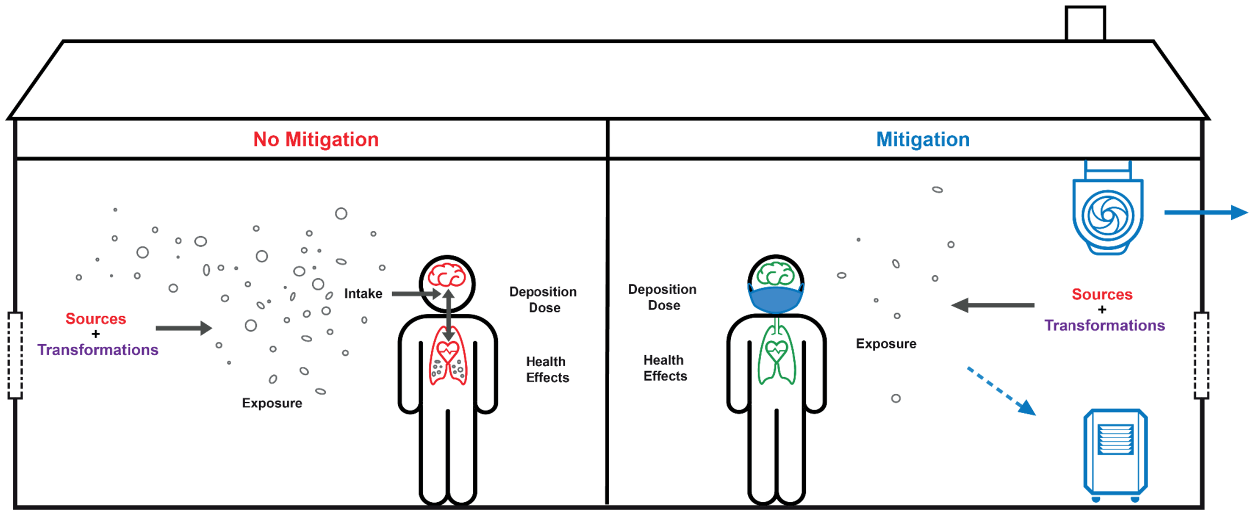

FIGURE 5-1 The connections among sources, transformations, and mitigation, and their influence on indoor exposure to fine PM.

Exposure assessment is the process of characterizing the magnitude, frequency, and duration of individual(s) exposure to a pollutant. It is an important step in understanding the human health risks resulted from indoor PM exposure in the context of this review. Because people are indoors most of the time, being able to characterize indoor exposure is important not only to understand health impacts from indoor particle sources, but also for understanding the health impacts from indoor exposure to fine PM of outdoor origin (Morawska et al., 2013). The right choice of exposure metric depends on the application (as reviewed by Lowther et al., 2019). Appropriate exposure metrics for health studies are informed by the type of health outcome of interest, which also informs the temporal and spatial resolutions that are appropriate. Exposure assessment is also used to inform where reduction in concentrations is most needed and to validate the success of control efforts. Exposure misclassification, when individual or group exposures are not accurately characterized, can limit the ability to understand the health impacts from fine PM, for instance, around vulnerable or underserved populations (Ashayeri and Abbasabadi, 2022; Gray et al., 2013; Marshall, 2008; Tonne et al., 2018).

Personal monitors quantify individual exposure at the point of contact (Brook et al., 2011). Modeling techniques may be used to work backward along the environmental health paradigm shown in Figure 5-1 to reconstruct the contributing sources, influencing factors, or microenvironments associated with an exposure measurement. Models may also be used to predict individual or population exposures in a forward direction, by combining data on sources, environmental dynamics, human time-activity patterns, and physiological factors to extrapolate from exposure to intake, deposition, and dose.

Earlier chapters of this review have elucidated the first step in the environmental health paradigm—the emission of particles from sources and their transport and transformation in the environment, as depicted in Figure 5-1. These processes govern where, when, how much, and what types of particles are present in various environments and ultimately where they are encountered by human receptors. As a result of the complexity of sources and transformation processes described in chapters 3 and 4, human exposure to fine particulate matter has significant heterogeneity in terms of particle size and composition, which in turn creates a need for defining metrics that can properly characterize PM exposure. This chapter discusses the intermediate steps in Figure 5-1, whereby humans are exposed and experience a dose, which leads to the final step of health effects, covered in Chapter 6.

EXPOSURE ASSESSMENT METHODS

Exposure Metrics

Definitions Based on Mass, Surface Area, or Number

Fine PM, also referred to as $PM_{2.5}$, are airborne particles with an aerodynamic diameter of 2.5 micrometers or less. $PM_{2.5}$ is most commonly quantified as total mass per unit volume of air. When applied this way, the $PM_{2.5}$ mass metric is nonspecific with respect to composition and integrated over all particle sizes below 2.5 micrometers. Ambient PM standards in the United States are based on this metric, with compliance traditionally monitored with offline, gravimetric filter-based methods. The resulting measurement is typically collected at a frequency of once per day and is only feasible at moderate to low spatial density due to sample handling and labor requirements.

Though the mass-based metric has been repeatedly associated with respiratory and other symptoms (as discussed in Chapter 6), its adequacy for measuring and managing the health risks from PM has been brought into question by the growing number of studies demonstrating the importance of other particle attributes such as number count, surface area, and composition (Lowther et al., 2019). As expected, the discrepancy between mass- and number-based measures is greatest for the smallest particle sizes, referred to as ultrafine particles. Therefore, the representativeness of the PM mass metric may be especially pronounced in indoor environments where people are exposed, in proximity, to fresh emissions from combustion and other indoor sources that emit in the ultrafine range, as discussed in Chapter 3.

At present, the majority of epidemiological studies are based on the PM mass metric. And while the health evidence base is being transformed by the ability to capture a wider range of particle attributes in exposure assessment studies and the understanding of the mechanisms underlying various adverse health outcomes from PM grows, the mass-based metric will continue to be a useful indicator.

Addressing Temporal Complexity

The timing and duration (short-term versus long-term) of exposure measurements are also important factors. Continuous, time-resolved data are important for resolving both short-term (acute) and long-term (chronic) exposures and the evaluation of diurnal and seasonal patterns. Insight into temporal patterns is particularly useful for source identification and mitigation planning as well as for extracting health effect time-scales, such as the lag between an exposure and its effect and the duration of exposure associated with an effect. The range of temporal metrics used in epidemiological studies for ambient PM varies from the average over a lifetime (N. Li et al., 2022; Morawska et al., 2013) to the average daily level over the preceding 5 years (S. Li et al., 2020), to an annual average with no lag (N. Li et al., 2022) and prior-day or even prior 10-min exposures (Woo et al., 2022). Some long-term studies also address the potential additive effects of multiple prior exposures. A careful treatment of timescales is particularly important for the intermittent sources described in Chapter 3, which result in highly variable indoor exposures.

Tapered element oscillating microbalances and beta attenuation instruments (Lowther et al., 2019) offer a means to measure time-resolved particle mass concentrations, but the cost and complexity pose a barrier for use in indoor exposure studies. Optical particle counters (OPCs), based on principles of light scattering, measure particle number concentrations within a certain size range at a reduced cost relative to real-time mass concentration measurement techniques, enabling dense monitoring networks. The number concentration data can be converted to a lower-fidelity mass measurement by making assumptions about particle shape, density, and composition. Low-cost sensors, discussed below, offer a practical means of acquiring time-resolved data, but with a further decrease in reliability, accuracy, and precision, especially when the light scattering data are converted to a mass estimate.

Addressing Size Complexity

Fine particle sizes range over a 16 million-fold span in mass between the smallest and largest particles (NAE, 2022). OPCs are used to measure size-resolved number counts of particles 0.3–10 micrometers in diameter. Condensation particle counters and instruments based on electrical mobility—scanning mobility particle sizers, diffusion chargers, fast mobility particle sizers—are used to evaluate count- or size-distribution-based exposure metrics for the smaller, submicron and ultrafine fraction (Lowther et al., 2019). Multistage impactors and aerodynamic particle sizers provide size- and time-resolved measurements for a wide range of particle sizes, based on their time of flight.

As the conventional $PM_{2.5}$ mass metric has come under scrutiny, attempts have been made to determine whether the breakpoint or diameter thresholds used to delineate coarse and fine—and fine and ultrafine—particles should be amended (Morawska et al., 2008). The reasoning is that health effects are likely to be source-specific, and so by selecting size fraction breakpoints based on the particle size distribution (PSD) profiles of major source-types, a size-based metric will better encompass other health-relevant particle attributes. Regardless of the broad consensus on metrics, source-specific PSDs can be used, when available, to customize exposure assessment tools to the sources under investigation.

Addressing Composition Complexity

Chemically, the composition of fine particles includes elemental and organic carbon, with vastly diverse chemical compositions, as well as crustal materials, inorganic salts, metals, microbes, allergens, and other constituents (NAE, 2022). The microbial components can have variable immunologic and inflammatory effects. Recently, it has also been reported that radionuclides attached to PM were associated with respiratory effects (Vieira et al., 2019, Wang et al., 2023). Chapter 3 presents composition profiles associated with common sources of indoor PM. Particle measurement instruments capture composition variability with different levels of sensitivity, specificity, and resolution. An indirect way to account for composition differences is to measure source-specific exposures.

Many species are present in a wide range of particle sizes, extending beyond the 2.5-micrometer diameter cut-off for fine particles, making it hard to determine to what extent a composition-specific measure such as the amount of black carbon, polycyclic aromatic hydrocarbons, metals, allergens, or flame retardants, or the infectious agent load, are fine particle measures in any given context. The link to fine particle exposure is even harder to predict for attributes such as oxidative potential or reactive oxygen species that are related to particles and gases in an air sample. Health effects studies need to be attentive to the independent but overlapping effect from exposures to multiple parameters from the same underlying source. For instance, as described by Biel et al. (2020), urban populations are often simultaneously exposed to multiple air pollution measures and noise, which are independently associated with cardiovascular disease.

Exposed populations or individuals may vary in their susceptibility to various composition measures, which suggests that the most impactful metric depends not just on the source profile, but also on the human receptors.

Addressing Practical Barriers to Exposure Assessment

In addition to capabilities such as size resolution, time resolution, and composition resolution, particle measurement devices are selected for exposure assessments based on their ease-of-use features, including cost, form-factor and weight, operating noise, labor to install and maintain, power requirements, connectivity, and data-processing capabilities. Emerging tools and methods for acquiring or predicting spatially dense data at scale—low-cost sensors, HVAC filter media as opportunistic samplers, participatory research, mobile monitoring, satellite data, and models— are discussed below.

The use of low-cost particulate matter sensors has grown rapidly, with the majority of papers reporting their use published in the last 5 years (NAE, 2022). Internet-of-things based particle monitors typically cost $100–500. Most sensors function as bulk nephelometers, but lower-cost miniaturized versions of single-particle counting laser technology that offers greater size resolution and accuracy are also now available (Particles Plus, 2023). Black carbon sensors are also available. Implementation on urban, building, and personal scales has generated unprecedented amounts of data that can be integrated to develop more accurate personal exposure models at scale (Pantelic et al., 2022).

Numerous studies have compared performance among various sensor and device types. Researchers have found a generally high correlation between readings from low-cost sensors and reference instrument readings, although accuracy decreases in uncontrolled "real world" environments where particle attributes are unpredictable, heterogeneous, and dynamic (Demanega et al., 2021; Sá et al., 2022). Low-cost sensors can also have issues related to their limits of detection and temperature and humidity compensation. Techniques and recommendations have been developed to guide sensor selection and placement and to boost performance, including methods based on machine learning, neural networks, and fusion with higher fidelity data (Chojer et al., 2022; Fritz et al., 2022; Y. Li et al., 2017; Omidvarborna et al., 2021; Park et al., 2017). However, there are as of yet no standards or widely accepted protocols for quality control and appropriate use.

Community-based participatory research and citizen science are increasingly used as mechanisms to increase the availability of PM data, especially around communities of color and those with lower socioeconomic status, as reviewed by Commodore et al. (2017). These communities tend to disproportionately reside close to ambient sources such as industrial facilities and freeways (Johnston et al., 2020) and to face social inequalities in the distribution of sensors (Mullen et al., 2022). The accessibility of low-cost sensors has expanded monitoring via citizen- and community-based science, though the focus has been mainly outdoors (Colorado Dept. of Public Health and Environment, 2023; EPA, 2021; State of California, n.d.).

Filters installed in HVAC systems can serve as opportunistic PM sampling devices (Haaland and Siegel, 2017; Mahdavi et al., 2021). House dust also serves as a convenient particle reservoir that can be analyzed for insight into the chemical or biological composition of PM, but it is harder to parse for the previously (or potentially) airborne fraction. Other measurement techniques to fill spatial data gaps efficiently, without recourse to large numbers of devices, are mobile monitoring (indoor through robots, or outdoors through vehicles) and satellites (Knibbs et al., 2018; Y. Li et al., 2017).

A variety of deterministic and empirical models have also been developed to fill "gaps" in ambient and indoor air quality data, including models on outdoor to indoor infiltration (e.g., Chapizanis et al., 2021; Gariazzo et al., 2015; Özkaynak et al., 2013; Vette et al., 2013). This topic is covered in Chapter 4 on transport and transformation processes. A distinct class of exposure metrics that bypasses concentration measurements or estimates is based on models of those transport and transformation processes. They include indirect indicators such as infiltration rate, intake fraction, air change rate, and indoor/outdoor ratio (Baxter et al., 2013; Breen et al., 2018, 2019; Shi et al., 2017).

Inhalation Intake, Deposition, and Dose

As illustrated in Figure 5-1, intake, deposition, and dose occur downstream from the point of contact between a pollutant and the human interface. Intake is evaluated as the product of the concentration in the breathing zone, and the breathing rate. The intake fraction (iF) is a dimensionless parameter representing the intake of PM per unit of emissions. The iF can be used to evaluate the effect of building, human, and pollutant-specific factors on exposure without measuring or modeling environmental concentrations (Hodas et al., 2016). Inhalation rate can be used to personalize dose based on activity type. Yoon et al. (2012) demonstrated the use of heart rate monitors to evaluate breathing rates, which they used in turn to estimate total inhalation mass.

Models of the amount of inhaled particles deposited in the human respiratory system depend additionally on human factors such as lung morphology and breathing patterns, level of activity and its effect on respiratory minute volume, fluid dynamic properties of the environment, and particle properties including size and composition, as reviewed by Hofmann (2011). Dosimetry models may be used to estimate whole-lung or regional (extrathoracic, tracheobronchial, and alveolar-interstitial) deposition.

Deposition metrics are based on mass (Patel et al., 2020; Sánchez-Soberón et al., 2018), number, and surface area (Pañella et al., 2017) and may be presented as rates (Liao et al., 2006) or fractions (Martins et al., 2015) or as a function of composition (Wang et al., 2022). Prominent respiratory tract dosimetry models are maintained by task groups of the National Council on Radiation Protection and Measurements and of the International Commission on Radiological Protection (Yeh et al., 1996). Newton et al. (2021) presented an innovative empirical alternative to dosimetry models: a polyurethane foam sampler whose particle capture mechanisms are posited to simulate the behavior of the human lung.

Finally, the absorbed dose may be estimated by combining intake measures with pharmacokinetic models (EPA, 2015) or directly from biomarker data.

Exposure Assessment Approaches

Direct Measurement

Personal monitoring via wearable or "point-of-contact" (EPA, 2015) sensors is considered the gold standard for exposure assessment. It is commonly used to evaluate the accuracy of exposures modeled and estimated through indirect methods (e.g., Ha et al., 2020; Nethery et al., 2008). Personal measurements capture total exposure, integrated over all sources and microenvironments, at the individual level, over the time-frame studied.

The contribution of various sources, influencing factors, and microenvironments to the total measured exposure can be modeled or reconstructed in conjunction with time-activity and other contextual data, to inform mitigation. For example, Buonanno et al. (2012) used data collected with a global positioning system (GPS) logger and activity diaries to interpret exposure results. Using a similar study design, which is echoed across many studies (e.g.,Braniš and Kolomazníková, 2010), Uzun et al. (2022) measured personal exposures to black carbon and applied time-activity diaries to attribute the fractional contribution from transportation versus home-based activities on weekends versus weekdays, while Milà et al. (2018) used questionnaires, GPS, and wearable camera data to model the sources and factors influencing exposure and to identify dominant microenvironments. Extrapolation from individual to population exposures and from exposure measured in a discrete time window to long-term exposure also relies on modeling techniques.

Historically, personal PM monitoring has been cumbersome, requiring study subjects to carry relatively large, heavy, and delicate measurement devices in backpacks and requiring researchers to download data manually after collection (Buonanno et al., 2014). Large-scale personal monitoring studies have been made more feasible by the development and proliferation of low-cost, portable, connected sensors (e.g., L. Li et al., 2021).

Exposure Reconstruction

Direct exposure monitoring of particulate matter (PM) in indoor spaces gives an estimate of the potential exposures of individuals in that environment. When combined with environmental and human data, such monitoring can be used to estimate inhalation intake and lung deposition. However, the techniques discussed above fall short of elucidating the dose of PM that an individual receives. Exposure reconstruction uses internal body measurements, or biomarkers, to directly measure the absorbed dose and to infer exposure from multiple pathways and sources (EPA, 2015).

Exposures to environmental pollutants are highly heterogeneous across populations, and individuals who are chronically exposed to these substances are viewed as being at higher risk for developing biological signals of exposure or cellular alterations indicative of exposure effects. The signals or alterations, called biomarkers of exposure or effect, are essential tools in understanding the potential effects of exposures on human health. The health effects associated with exposure to particulate matter is likely linked to biotransformation processes that result in the formation of reactive metabolites, or reactive species of oxygen and nitrogen, that can damage cells, cause chronic inflammation, and lead to disease processes in the human body.

Biological monitoring provides the ability to assess the uptake or dose by an organism that often is the result of personal factors and individual susceptibility. In environmental science, biomarkers are divided into three types: markers of internal exposure, markers of effect or response, and markers of susceptibility. The biomonitoring approach implies that internal exposure to a toxicant can be determined by measuring the toxic substance or chemical or its metabolites, i.e., reaction products that can be found in the blood, urine, saliva, or exhaled breath.

The literature on the utility of using biomarkers of exposure to indoor particulate matter is currently limited, but the research on particulate matter in air pollution and biomonitoring is directly applicable. Many epidemiological studies have shown a relationship between outdoor $PM_{2.5}$ and DNA damage, though the mechanism is unclear. Most frequently the hypothesis is that substances attached to the particulate matter play an important role in the DNA damage. The extent to which the chemicals associated with outdoor pollution also apply to indoor pollution is not clear, further complicating the ability to compare the utility of biomonitoring in indoor environments. The discussion on biomarkers of susceptibility and effect is further expanded on in Chapter 6, while this discussion focuses on the feasibility of biological monitoring of exposure to particulate matter, primarily in the indoor environment.

The ideal biomarker for exposure to particulate matter should be sensitive, specific, biologically relevant, practical, inexpensive, and available. To date there is not a specific biomarker for PM in the indoor or outdoor environment that meets these criteria. In studying indoor exposures, the population characteristics, the practicality of collecting biological samples, seasonal variations in exposure, the nature (e.g., composition) of PM, and background comparison ranges all need consideration. A study by Hachesu et al. (2019) found that phagocytized carbon load in airway macrophages could serve as a biomarker of internal particulate matter in the human body; however, macrophage sampling has limited utility in epidemiological studies, given that bronchoalveolar lavage is needed to obtain the sample of lung macrophages (low practicality) and that no background comparison ranges are available. Small studies have been done that are compartment specific for elements associated with particulate matter exposure. For example, Zetlan et al. (2023) measured metals and inflammation in the nasal epithelial lining fluid of patients with chronic obstructive pulmonary disease (COPD) exposed to air pollution. While this finding could be associated with particulate matter exposure, it does not precisely measure exposure to particulate matter.

Given the lack of a specific marker of biological absorption of particulate matter, it is more often the case that various compounds that attach to particulate matter, such as polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds, endotoxins, allergens, or metals, are used to assess exposure. For example, the main metabolite of pyrene, urinary 1-hydroxypyrene (1-OHP), is frequently used to estimate overall biological exposure to PAHs present in air pollution and has been shown to be a suitable biomarker of exposure. PAHs are compounds released during the incomplete combustion of fossil fuels, wood, incense, coal, and oil products present in indoor air, and they are widely known for their toxicity, mutagenicity, and carcinogenicity. Airborne PAHs can be found in both a gaseous phase and also bound to particulate matter, depending on moisture, temperature, volatility and other factors.

There is evidence that children attending schools in urban areas are exposed to higher concentrations of airborne PM and PAHs, and higher levels of PAH metabolites have been found in the urine of children in urban schools compared to children in non-urban schools. Oliveira et al. (2019) completed a review of 17 studies, including a small number carried out in U.S. schools, on the exposure of children in school environments to particulate matter and PAH through biomonitoring in school environments. These studies found that median PM_{10} and $PM_{2.5}$ exceeded World Health Organization guidelines in European and Asian schools and that Asian schools had higher levels of both PM and PAHs than other countries. Levels of PAH metabolites were increased in children from schools in polluted areas. The results of this review point out a major limitation of biomarkers of exposure—the inability to attribute the biological load to the source of exposure, in this case the indoor school environment or the outdoor air pollution sources. Still, the authors stressed that PAH exposure is directly associated with indoor and outdoor levels of PM, principally the smallest fractions, and that there would be utility in studying the synergistic effects of both PM and PAHs in future studies.

The National Health and Nutrition Examination Survey (NHANES) is the most comprehensive source for human biomonitoring data in the United States (EPA, 2015). PAH metabolites are included in the battery of chemicals that are assessed in human urine, and PAH levels have been shown to be higher in populations who smoke. More intricate relationships between the presence of PAH biomarkers and the indoor air environment have not been published from the NHANES data.

Indirect Estimation

Exposure models, also known as *scenario evaluations* (EPA, 2015), rely on data on time-activity, which is the amount of time people spend doing various activities, in various locations. This information may be combined with information about particle concentrations in those locations to predict exposure when personal monitoring is not feasible or desirable (e.g., Lane et al., 2015). Exposure models may be based on real contextual data or on hypothetical scenarios of interest, making models the tool of choice to predict the impact of changes anticipated due to policy measures, climate change, and other exposure determinants. The accuracy of an exposure model depends on the spatial and temporal granularity of the underlying time-activity and location-specific concentration data. More complex integrative models can be used to quantify exposure for a population of interest (EPA, 2015).

Population-level surveys and residential addresses obtained from census tracts and administrative registers are sources of position and time-activity data that are freely available and are, as such, a practical if low-fidelity resource for large-scale exposure characterizations. Examples of population-surveys from different geographies are the National Human Activity Pattern Survey (Klepeis et al., 2001; Zhang and Batterman, 2009), the Canadian Human Activity Pattern Survey (Leech and Smith-Doiron, 2006), the Consolidated Human Activity Database (Che et al., 2015), the London Travel Demand Survey (Smith et al., 2016), and the Exposure Factors Handbook of Chinese Population (Shen et al., 2021). The limitations of these data are that they are static and coarse-grained and do not capture stochastic and adaptive behavior variability, resulting in exposure prediction errors and misclassification for pollutants that are spatially heterogeneous (Özkaynak et al., 2013).

Higher-fidelity human data may be obtained by acquiring individual-level time-activity budgets with questionnaires and diaries (e.g.,Takaro et al., 2015; J. Kang et al., 2021, reviewed for assessing children’s exposure by Branco et al., 2014; Kaufman et al., 2012). Questions about the timing and frequency of potential particle emitting activities such as cooking, cleaning, or the use of candles are included when source attribution is a goal. Limitations of this data class is that it is resource-intensive to collect. Automated methods reduce the processing overhead associated with surveys and diaries, but self-reported time-activity data are intrinsically limited in terms of the temporal and spatial granularity that is feasible and the subjective reporting bias involved.

Particle concentration data may also be obtained at varying levels of resolution, ranging from regional (from central stations and satellites) to zip code or address level (from atmospheric dispersion models, spatial interpolation techniques, empirical models, neighborhood sensor networks or mobile monitoring), all the way to concentrations adjusted by indoor infiltration rate or directly measured from indoor microenvironments, as reviewed by Özkaynak et al. (2013).

New technology and tools enable dynamic, objective mobility and activity tracking. Measurement and modeling tools to assess particle levels at increasingly granular scales and to match the scales at which human data are collected have also become increasingly sophisticated. Most of the newly available location-activity and concentration tracking methods take advantage of advances in sensor technology and “big data” capabilities, including connectivity and cloud storage and processing.

One class of location-activity tracking tools captures macro-scale individual mobility. These rely on GPS and geographic information system (GIS) mapping technologies, often in conjunction with smartphones and applications like the Google Maps program, for real-time and historical data (Gulliver and Briggs, 2005; Pañella et al., 2017; Yarza et al., 2020; Yu et al., 2019). Milà et al. (2018) integrated GPS with wearable cameras to attribute exposures to time of day, location, and activities in South India. Micro-scale—i.e. within a building—mobility tracking was demonstrated by Quinn et al. (2020) through the combined use of GPS and motion, temperature, and light sensors. Researchers have demonstrated other approaches to monitor occupancy and activities associated with indoor PM, such as cooking and range hood use. Examples include Dedesko et al. (2015), who tested low-cost, non-invasive methods to estimate occupancy and occupant activities in hospital patient rooms, based on data from CO_2 sensors and non-directional doorway beam-break sensors; Johnson et al. (2020), who adapted a temperature sensor to track stove use; and Zhao et al. (2020), who applied a similar approach to Johnson et al. in the United States, using anemometers to measure range hood use. Pollard et al. (2023) evaluated indoor positioning systems (IPS) for the study of the movement and interaction of people in offices, finding that just over a week of data collection was sufficient for characterizing typical movement behaviors in these settings. While the committee is not aware of similar IPS efforts in residences or schools, a feasibility study demonstrated that networks of motion sensors could be useful for characterizing in-home human behavior and associated impacts on indoor air quality (Lin et al., 2017).

Note that in addition to serving as an input parameter for exposure models, time-activity pattern data may also serve as a qualitative proxy for a quantitative exposure measurement. For instance, Leech and Smith-Doiron (2006) reported that COPD patients spent more time indoors at home and were more likely to have air conditioning than controls from the general population. Whether or not the association implies a causal link between time indoors and the development of COPD, the finding supported the recommendation that mitigation strategies emphasize source control in the patient's home. Data on the presence or absence of known sources such as candles and incense (Chapter 3) can also serve as a crude, qualitative proxy for exposure.

EXPOSURE TRENDS AND DISPARITIES

Exposure Trends in Homes

A literature review by Ilacqua et al. (2021) found that indoor PM concentrations in homes over the past three decades (1990–2019) displayed generally decreasing trends in concentrations of all size fractions in North American and European studies. In the United States, indoor $PM_{2.5}$ concentrations have been decreasing at a rate of about 0.4 ± 0.1 $\mu g/m^3$ per year (87 studies, from 1987 to 2019), and concentrations of PM_{10} have been decreasing at a rate of 1.0 ± 0.4 $\mu g/m^3$ per year (31 studies, from 1987 to 2014). Based on these downward trends, the estimated mean indoor $PM_{2.5}$ concentrations for 2016 was 5.2 $\mu g/m^3$, and the estimated mean indoor PM_{10} concentrations for 2014 was 9.7 $\mu g/m^3$. Downward trends were also observed when the regression analyses were performed at the city-level using published data from Baltimore, Boston, Detroit, Los Angeles, and New York City. In contrast, there are fewer studies on ultra-fine particle (UFP) number concentrations in U.S. homes (four studies, from 2006 to 2015), and regression analysis found no significant changes over the years. The review found that outdoor air pollution remains a major influence on indoor concentrations of PM of all sizes. But large variabilities in indoor PM concentrations in homes suggest that indoor sources and interventions are important factors that can affect human exposure.

The general downward trend of indoor PM exposure is expected to continue, according to a modeling study by Fazli et al. (2021) showing a decrease in population-average indoor concentrations of pollutants of ambient origin in U.S. residences from the baseline year 2010s to 2050s assuming business-as-usual conditions. Model predictions suggested that population weighted mean indoor concentrations of $PM_{2.5}$ are expected to decrease slightly, largely due to a reduction in indoor $PM_{2.5}$ of outdoor origin. The model study made assumptions about changes that retrofits and new constructions would bring about, such as reductions in outdoor air ventilation rates because of structures becoming more airtight, decreases in window use, and increases in HVAC system runtimes, and acknowledged that it did not consider more transformative changes to the housing stock, such as deep energy retrofits, or adding high efficiency mechanical ventilation and filtration more widely. There are considerable uncertainties on the impact of home retrofits on indoor PM concentrations, according to a review by Fisk et al. (2020). In one study, I. Kang et al. (2022) show that adding mechanical ventilation in 40 Chicago area homes, including filter upgrades among those with central forced air systems, resulted in a reduction in the indoor-to-outdoor PM ratio. The study suggests that the magnitude of reduction is largest in homes that received continuous ventilation systems, compared with homes that received intermittent systems. More data are needed to assess how other approaches to home retrofits can affect indoor PM exposure.

The COVID-19 pandemic prompted concerns about an increase in indoor exposure owing to the increase in the time being spent at home, but very few studies have measured the effect of this change (Adam et al., 2021). Increases in exposure to PM emitted from indoor sources such as cooking, cleaning, candles, and environmental tobacco smoke (ETS) are described as some of the primary concerns, especially among susceptible populations such as children, elderly, and those living in crowded housing in poor conditions. For example, a modeling paper by Dobson et al. (2022) reported an increase in exposure to ETS from COVID lockdown measures for the U.K. population, but changes in $PM_{2.5}$ exposure were minimal for most individuals despite the simulated increase in cooking activity. To the best of our knowledge, there is no available assessment of how indoor PM exposure may have changed since the pandemic for the U.S. population.

Exposure Trends in Schools

Several reviews on exposure to air pollutants in schools (Mejía et al., 2011; Morawska et al., 2017; Oliveira et al., 2019; Salthammer et al., 2016) summarized measurements of fine PM concentrations, including in some U.S. schools. PM exposures in schools are shaped by indoor emissions and resuspension caused by occupant activities and the effect of ventilation and surface sinks. School proximity to traffic has been identified as a crucial factor affecting indoor exposure. The review also points out significant temporal and spatial variations in exposure in different microenvironments within the school (e.g., classrooms, gymnasium). Similar to the case with residential studies, very few studies have measured UFP number concentrations in schools. Overall, the reviews point to a need to monitor personal exposure of children to PM in schools, with a focus on particle size and composition, in order to better understand the associated risks for the health of children.

In 2014, the U.S. Environmental Protection Agency (EPA) awarded a number of grants to study school factors and environmental conditions related to children and teacher/staff health and performance. Several of these studies included PM monitoring. Ren et al. (2020) measured PM in seven high schools in Texas over 2 years (2015–2017), and found that the average $PM_{2.5}$ concentrations in classrooms were low compared with health guidelines due to air filtration as part of HVAC use. The study observed that flooring type had an effect on the resuspension of PM_{10}, where carpet flooring was associated with significantly higher indoor concentrations compared with classrooms with vinyl composition tile flooring. Kabirikopaei et al. (2021)

measured fine and coarse PM counts in 220 classrooms from 39 schools in the Midwestern United States over 2 years (2015–2017). The study found associations of student achievement scores with a number of building and environmental factors, including fine PM counts. Majd et al. (2019) measured PM and other indoor air pollutants in 16 schools in an urban area in the mid-Atlantic region in three different seasons (2015–2017). Monitored schools did not have central HVAC systems and relied on opening windows for ventilation. The study points out the significance of outdoor sources in proximity to schools, including the length of the nearby roads (as proxy of total nearby traffic volume) and the number of nearby industrial facilities, on indoor exposure. A related study (Zaeh et al., 2021) measured $PM_{2.5}$ and other indoor air pollutants in seven schools from the same region before and after building renovations. Renovations included HVAC retrofits, window replacement, and other major improvements; one of the seven schools was completely replaced with new construction. Study data showed substantial reductions in indoor $PM_{2.5}$ concentrations post-renovation.

Factors Associated with Fine PM Exposure

A review by Morawska et al. (2013) outlined a number of factors that affect indoor exposure to fine PM. In summary, both proximity to outdoor sources (e.g., traffic, industrial emissions) and the presence of indoor sources (see Chapter 3) are important determinants of indoor exposure. The transport and fate of indoor PM depends on a range of building and environmental factors (see Chapter 4), and together they influence the particle size and composition of indoor PM. Time activities of humans and their behaviors can affect the intake and deposition of fine particles in the lung, and human susceptibility will determine the health risks resulting from indoor exposure (see Chapter 6). A review by Hodas et al. (2016) identifies major factors influencing the inhalation of $PM_{2.5}$ using intake fraction (iF) as the metric. Variability in iF is driven by a combination of building parameters such as building size, air exchange rate, and interzonal mixing; human factors such as inhalation rates, occupancy, and time-activity patterns; and pollutant characteristics such as particle size distribution, physical and chemical processes like deposition, resuspension, and transformation.

There is extensive literature on factors associated with higher exposure to ambient fine PM. For example, Marshall et al. (2006) calculated the inhalation of diesel fine PM and other ambient air pollutants by people living in California's South Coast Air Basin. The analysis revealed that exposure concentrations in different microenvironments, population mobility, and temporal correlations between ambient concentrations and breathing rates affected the calculated inhalation intake by 40 percent, on average. As a result, subpopulations who are non-whites and economically disadvantaged households had higher inhalation intake than the population as a whole.

Many studies have identified risk factors among economically disadvantaged communities that are associated with higher indoor PM exposure in homes. Adamkiewicz et al. (2011) measured indoor concentrations of multiple pollutants in economically disadvantaged households and found that exposures are driven by the combined influences of indoor sources, outdoor sources, physical structures, and residential activity patterns. However, the study also found that exposure is not the sole determinant of health risk. Other individual and neighborhood characteristics with strong ties to economic disadvantages also influence how environmental exposures can affect health and may heighten the influence of indoor environmental exposures. This point is echoed by Escobedo et al. (2014), who carried out a study of in-home $PM_{2.5}$ exposure in an economically disadvantaged Latino community in Boulder, Colorado. The researchers emphasized that even though the levels of in-home $PM_{2.5}$ were low (all non-smoking homes, where cooking was likely the primary source), prior exposures from abroad for immigrant communities and contributions from work environments could add to the overall health burden.

Studies that focus on strong participant engagement in targeted subpopulations have identified factors associated with fine PM exposure. For example, Do et al. (2021) used high-resolution wearable sensors to study behavior-dependent patterns of $PM_{2.5}$ exposure in high-traffic, industrialized regions of Southern California. Results from the study indicate that participants from the most economically disadvantaged community, despite their high level of mobility and low variability in ambient $PM_{2.5}$ concentrations, experienced overall higher personal exposure, mostly because of high PM in homes where participants spent the majority of their time. The study of 18 participants (half of them college students) showed that acute exposures (less than one hour) at high concentrations (> 35 $\mu g/m^3$) in these microenvironments: homes, work/university, restaurants, suspected smoking/vaping. Another example is by Webb et al. (2021), who used a community-based participatory research approach to measure $PM_{2.5}$ concentrations in two tribal communities. Two of the 15 homes monitored for $PM_{2.5}$ showed daily concentrations exceeding 35 $\mu g/m^3$ (EPA 24-h standard for outdoor $PM_{2.5}$). These data point to indoor sources, such as smoking and candles and potentially woodstoves, as potential contributors.

Studies on Exposure Disparities

A study on the exposure disparities to outdoor $PM_{2.5}$ found that U.S. public housing developments are significantly overrepresented in areas with higher outdoor air pollutants (Chakraborty et al., 2022). Housing and occupant factors can further exacerbate such disparities in terms of indoor exposure. Multifamily homes that are smaller in size, higher in occupant densities, and located in areas close to outdoor sources are associated with higher indoor PM exposure and health outcomes. Baxter et al. (2007), as part of a prospective birth cohort study assessing asthma etiology in urban Boston, Massachusetts, collected indoor and outdoor $PM_{2.5}$ samples in 43 homes across multiple seasons from 2003 to 2005. The studied homes represented economically disadvantaged households and consisted almost entirely of multifamily residences. The study found cooking time, humidifier use, cleaning activities, and occupant density were associated with $PM_{2.5}$ and trace elemental concentrations. The study points out particular concerns and a need for more research in urban areas where more people reside in multifamily homes with higher occupant densities.

Stevenson et al. (2001) found racial disparities in housing (e.g., year built, crowding) and community factors that are associated with asthma morbidity. More recently, Grant et al. (2023) provided an overview of disparities for children with asthma from their exposure to indoor allergens. The review points to increased exposure to PM from various sources, including proximity to traffic-related air pollutants and indoor PM sources, that are adversely affecting both homes and schools, particularly in urban inner-city neighborhoods. The review also points out that environmental exposures and influences affecting pediatric urban asthma are complex and intertwined. Thus, multimodal interventions targeting allergen, mold, and air pollution exposures in conjunction with changes on income, housing, and other social inequalities will be needed to meaningfully change pediatric asthma.

A review by Diaz Lozano Patinõ and Siegel (2018) on indoor environmental quality in subsidized and public housing (also referred to as social housing) found evidence that residents may be disproportionately exposed to higher levels of $PM_{2.5}$, largely because of the higher prevalence of smoking in the building, compared with non-social-housing multifamily homes. The review also found that there are strong indicators that residing in social housing is associated with negative health effects, with a high prevalence of respiratory problems. In contrast, Zhao et al. (2021) found that in recently (2013–2017) constructed or renovated non-smoking, mechanically ventilated multifamily homes in California, the measured $PM_{2.5}$ concentrations were similar to those observed in larger, less densely occupied single-family detached homes of similar vintage and cooking frequency. This underscores the potential of using building controls, such as mechanical ventilation, to mitigate indoor exposure.

Chu et al. (2021) found disparities by homeownership, where renters in multifamily housing experienced a higher proportion of $PM_{2.5}$ concentrations from non-ambient sources due to a combination of behavioral and building factors amenable to interventions. The research team worked with a community-based organization to recruit renters and homeowners and conducted week-long $PM_{2.5}$ measurements in 71 homes in Greater Boston, Massachusetts. By concurrently monitoring both outdoor and indoor $PM_{2.5}$ using real-time and time-integrated gravimetric methods and using information gathered from home visual assessment, participant interview and daily activity logs, the study estimated $PM_{2.5}$ from non-ambient origin and found associations with indoor source activities. The researchers found that the majority of indoor $PM_{2.5}$ was of non-ambient origin, with increasing contributions in homes with higher indoor $PM_{2.5}$. Major source predictors of non-ambient $PM_{2.5}$ were cooking, smoking (reported among renters in multifamily homes only), increased range hood use, and being in heating season.

Studies on vulnerable populations residing in other types of housing institutions are sparse in the United States. For example, Reddy et al. (2021) found only one study in the country (Tebbe, 2017), which evaluated indoor air quality in four nursing homes in Ohio. In 2022, there was a relevant study published using wildfire smoke exposure measurements at four skilled nursing facilities in the western United States (Montrose et al., 2022). Residents in nursing homes spend large amounts of time indoors, and their advanced age and susceptibility to prolonged exposure are reasons for concerns. Studies from Europe had reported inadequate ventilation and high concentrations of other indoor air pollutants (e.g., NO_2, formaldehyde) in nursing homes (Bentayeb et al., 2015). Early childhood education is another area where there are few studies of fine PM exposure and the potential impacts on the health and development on young children. Early childhood education facilities differ from K–12 schools in terms of building characteristics (e.g., home-based settings are common) and occupant activities. Several exploratory studies (Gaspar et al., 2018; Gilden et al., 2022; Quirós-Alcalá et al., 2016) measured indoor particle concentrations in early childhood education facilities over short periods of time (e.g., over the course of a day). These studies found that indoor levels of PM were either the same or higher than outdoor levels. Resuspension and PM that originated from outdoors from proximity to traffic and the use of windows for natural ventilation are among the contributing factors. In addition, common indoor sources such as scented candles, air fresheners, and cleaning products may also have contributed to indoor PM levels.

INDOOR EXPOSURE ASSESSMENT TO INFORM HEALTH AND MITIGATION

Advances in exposure assessment of indoor PM are important not only for improving the understanding of health impacts—they are also important to motivate practical actions to mitigate. This section will discuss how exposure assessment can improve the understanding of the health disparities from indoor exposure to fine PM of outdoor origin, and the health implications from indoor PM more broadly. The role of exposure assessment to raise awareness on the importance of indoor PM to health is also discussed.

Disparities in Indoor Exposure to Fine PM of Outdoor Origin

While there are examples of epidemiological studies of outdoor fine PM considering building factors as modifiers (Allen et al., 2012; Breen et al., 2014; Hodas et al., 2012; Hystad et al., 2009), the majority of the literature examining exposure inequality to air pollutants of outdoor origin does not consistently incorporate factors that modify indoor exposures (Bell and Ebisu, 2012; Jones et al., 2014). Continuing to improve the characterization of housing and behavioral factors can help improve understanding of inequalities in exposure to outdoor PM. For example, ambient air pollution epidemiological studies that apply building outdoor air change rates (ACH) as a covariate or modifying factor have produced less exposure measurement error and, thus, more precise effect estimates of associations between residential exposure to ambient air pollution and health outcomes, compared with traditional analyses (Sarnat et al., 2013). Rosofsky et al. (2019) used spatially and temporally resolved estimates of $PM_{2.5}$ concentrations and calculated ACH to analyze exposure inequality and found that neighborhoods containing parcels with both high ambient $PM_{2.5}$ and high ACH disproportionately included non-White, economically disadvantaged, and low-educational-attainment populations. Stratified analyses also confirmed an a priori hypothesis that historically marginalized populations experience a cumulative burden of both high ACH and high ambient air pollution concentrations and that the exposure inequalities are magnified when ACH and ambient $PM_{2.5}$ are overlaid.

Studies that directly measure or approximate indoor exposure to fine PM of outdoor origin, rather than relying on outdoor measurements alone, illustrate the importance of considering indoor environments. For example, in the NEXUS study, Vette et al. (2013) included indoor sampling at participants' homes and at two schools to better characterized how building factors such as infiltration could impact near-road exposures and the resulting health effects among children with asthma in Detroit, Michigan. Lane et al. (2015, 2016) demonstrated the value of using time-activity adjustments on exposure assessments to better understand the impact of UFPs on systemic inflammation biomarkers and cardiovascular disease risk. These study findings reinforce the importance of the indoor environment for examining differences in exposure patterns and associations among racial/ethnic sub-populations for causal interpretation.

Indoor Exposure to Fine PM for Understanding of Health Implications

The ability to characterize exposure with sufficient specificity (e.g., speciation, size, spatial, and temporal variations) is critical to understanding health impacts from indoor fine PM. One example is a study by Isiugo et al. (2019) which found that reduced lung function is more strongly associated with indoor particles, in particular indoor PM associated with smoldering organics (e.g. wood burning fireplace), than with outdoor particles or black carbon. Studies that are designed to understand the health impacts from indoor fine PM have consistently found that indoor exposures are often higher and more variable than outdoor exposures. Zusman et al. (2021), in an effort to understand indoor exposures in a large cohort of adults with COPD, recruited across 12 clinic centers in the United States. The study, known as SPIROMICS Air, monitored 2-week integrated $PM_{2.5}$ concentrations indoors and outdoors and found indoor concentrations to be higher and more variable than outdoor concentrations. Advancement in modeling of indoor PM exposures from information such as home and behavioral survey data and socioeconomic and meteorological parameters can improve understanding of health effects from fine PM exposures.

There are other examples of health cohort studies that included indoor exposure as part of the environmental assessment. The National Human Exposure Assessment Survey (NHEXAS) was designed to establish environmental exposure estimates and trends in a number of study cohorts in the United States. As part of NHEXAS, Williams et al. (2013) conducted personal air monitoring for selected PAHs in children and adults residing in urban, suburban, and rural areas near Baltimore, Maryland. The study found notably higher PAH exposures among participants living in urban and suburban areas compared with rural areas. More recently, the Environmental Influences on Child Health Outcomes (ECHO) Program has been evaluating environmental factors affecting children's health (Buckley et al., 2020). Apart from biomonitoring, several ECHO cohorts will include air sampling and other environmental monitoring in the homes of study participants. Such data will be invaluable in shedding light on the role of in-home exposure, including chemical components of fine PM, on children's health.

Increasing Public Awareness of Exposure to Indoor PM

There is a wide difference in public knowledge concerning outdoor air quality versus the hazards associated with indoor air quality. To design high-quality epidemiological studies of indoor PM exposure and its health effects, advances in exposure monitoring are needed. Advances in exposure monitoring in indoor environments are beginning to help overcome some of the challenges in measuring exposure and documenting mitigation effectiveness. Low-cost PM monitors are enabling larger sample sizes in cross-sectional studies. Such methods are also allowing longer-term monitoring so that changes pre and post intervention can be properly captured.

Making exposure visible is critical to motivating actions to mitigate, and participatory $PM_{2.5}$ monitoring is important to increasing environmental health literacy and raising awareness. One example is the A Day in the Life project by youth living in disadvantaged communities in Southern California (Johnston et al., 2020). The project used air monitoring coupled with photography and mapping to increase youth-centered understanding of personal exposures, fine PM sources, and vulnerability to air quality. Rickenbacker et al. (2020) measured indoor air quality, including fine PM, and collected quality-of-life surveys from 41 homes in Pittsburgh, Pennsylvania. This study is another example of community–academic partnership that is driven by the desire from participants to learn based on their unique set of personal concerns.

FINDINGS AND CONCLUSIONS

Findings

This chapter describes different methods (e.g., direct methods such as biomarkers, wearables for personal monitoring, low-cost sensors, time-activity measurements and exposure modeling, etc.) to characterize exposure to indoor fine PM. It is challenging to characterize exposure comprehensively, given the spatial and temporal variability in particulate matter indoors, its heterogeneity in size and composition, the dynamics of human movement and behavior, and the conditions of the built environment. Our ability to fully measure and quantify exposure to indoor fine PM is intrinsically limited. Given these intrinsic limitations, characterizing exposure is still a valuable tool that helps to connect fine particulate sources to health effects and aid our understanding of mitigation effectiveness.

Indoor exposure to PM is generally decreasing in the United States, with decreasing outdoor air pollution and lower prevalence of smoking among likely contributors (Ilacqua et al. 2021). This implies a shift towards indoor exposure being even more dominated by indoor PM generated from other sources. It is expected that this trend will continue in response to decreasing reliance on fossil fuels, energy efficiency improvements, and the like. However, the reduction in indoor exposure to outdoor PM is not occurring uniformly. For example, areas affected by wildfire smoke are exposed to high levels of indoor PM of outdoor origin, and communities affected by localized outdoor PM sources are still burdened by their indoor exposure to those sources. These changes, among others, are contributing to disparities in indoor PM exposures.

Disparities exist in population exposure to indoor fine particulate matter of both outdoor and indoor origin. Disparities occur not only because of higher indoor exposure concentrations due to more activities happening in smaller, densely occupied, and interconnected (multi-family) homes or because of outdated appliances that have higher emissions or ventilation equipment that is less effective at removing PM, but also because of the susceptibility of the exposed populations leading to excess health burden. Settings where indoor PM exposures, the associated health impacts, and mitigation opportunities are particularly limited include schools and early childhood education facilities as well as institutional housing such as homeless shelters, transitional homes, skilled nursing facilities, and correctional facilities.

Low-cost sensors and personal monitoring are providing greater abilities to measure exposure, although important limitations remain. The accessibility of these lower-cost sensors has greatly expanded monitoring capabilities, but further advancements to measure particles in the ultrafine range and provide information on particle size would greatly enhance their usefulness in characterizing indoor PM exposure. Beyond improving instrument accuracy, cost, form factor (ease of use, connectivity), and other performance aspects, it is critically important to advance our understanding of how measured values are useful for determining the health impacts from exposure to fine particles or mitigation effectiveness. While indoor PM is generally expected to contribute to excess morbidity and mortality, the lack of a standardized approach to readily obtain indoor fine PM exposure levels, especially in historically marginalized communities, limits advances in our understanding of the connection between exposure and disease.

Our understanding of the sources of high intermittent exposure to indoor PM is particularly limited. There are emerging concerns about new sources, such as vaping, more frequent cleaning and disinfection, and electronic air cleaners. Very high exposure to indoor fine PM is occurring in some microenvironments. Our understanding of the potential health impacts of these indoor sources in different built environments is partly restricted by the availability of instrumentation to characterize exposure. In particular, understanding of indoor exposure to some specific types of PM, such as UFPs and specific PM compositional constituents, remains poor. Studies point to a need for innovation to improve measurement techniques and study methods to enable better characterization of the total exposure and health impacts to fine particles in indoor environments.

Conclusions

A national effort to measure and report indoor exposure to PM using validated methods and sufficient characterization of the built environment, occupancy, and activity patterns is needed to identify critical determinants of indoor exposure to fine particles (and other indoor air pollutants) so that source-specific exposure can be assessed and to guide mitigation efforts that can target subpopulations overburdened with exposure to fine particles in homes, schools, and other building types. The data would greatly improve the existing understanding of the exposure and potential health impacts of indoor PM on the U.S. population in indoor environments including homes, schools, and other vulnerable settings.

There is a need for clear guidance on indoor PM exposure metrics, in particular to support programs implementing practical mitigations—e.g., woodstove replacement, healthy home retrofits, school HVAC upgrades, portable air cleaner deployments, etc.—**and to inform building standards and practices that can bring about significant changes at scale.** These programs require evaluation of their benefits to motivate funding and continuing support. Guidance on how to measure the potential reduction in indoor fine PM exposure and what metrics to use is needed so that such programs can adjust and improve over time to bring more benefits to the communities.

Collaborations to study indoor PM exposure in susceptible, underserved, and disproportionately exposed communities should be encouraged. Indoor environments and the people who live in them are diverse. They have unique characteristics that may lead to high indoor fine PM exposures that require focused attention. More targeted data on such exposures are necessary to improve the current understanding of them and ultimately to protect susceptible populations. Indoor environment researchers need to collaborate with community-based organizations and community members if they are to conduct the kinds of culturally sensitive studies that will produce information relevant to these populations and develop effective messaging on PM exposure issues to help motivate practical mitigation.

There is a need to make indoor exposure to fine PM more visible to the public, such as by using low-cost sensors which can be a powerful way to educate building occupants and to motivate them to take actions that can reduce indoor sources and increase use of mitigation measures. At the same time, there is a need to advance the capabilities of low-cost sensors in order to better characterize indoor fine PM exposures and provide sufficient specificities useful for understanding health impacts. Beyond low-cost sensors, improvements in other measurement techniques and methodologies are also important to reaching this goal.

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6
Health Effects from Exposure to Indoor PM

This chapter presents the findings of the committee's review of recent literature on the health effects associated with exposure to particulate matter in indoor environments, including cardiovascular and pulmonary disease, birth outcomes, neurological and psychiatric effects, and endocrine disease. Sections focus on the physiological mechanisms hypothesized to link exposure to cellular changes and factors that influence an individual's susceptibility to developing clinical symptoms associated with exposure. Where relevant, early preclinical biomarkers that indicate cellular or biological changes associated with potential effects from exposure to indoor particulate matter are discussed. The chapter concludes with the committee's recommendations to the indoor air research community and to the Environmental Protection Agency (EPA) and other funders of that research.

INTRODUCTION

The Lancet Commission on pollution and health reports that pollution is responsible for approximately 9 million deaths per year globally, of which the greatest proportion is attributable to ambient air pollution and household air pollution, with ambient fine particulate matter being the largest contributing risk factor in ambient air pollution (Fuller et al., 2022). Household air pollution includes not only pollutants from outdoors, but also air pollution from indoor sources, which may include allergens sources (pets, pests, fungi), microbes, the burning of biomass, and non-biomass combustion. Globally, much of this burden is attributable to biomass fuel burning (WHO, 2022); other sources of indoor air pollution have been less studied. The National Academies have conducted two series of workshops on the health risks of indoor exposure to particulate matter. In 2016 a series of experts in this area outlined the major areas of concern, including respiratory, cardiovascular, reproductive, and neurological and psychological effects (NASEM, 2016). The experts at this initial workshop pointed to the epidemiological challenges of characterizing the contribution of indoor exposure to particulate matter, separate from that of outdoor air pollution, in the development of disease.

In 2022 the National Academy of Engineering held a second virtual workshop series in which health effects were again summarized and potential mitigation approaches were discussed (NAE, 2022). The areas that were emphasized in that workshop included cardiovascular and pulmonary effects, including a discussion of important susceptibility factors.

Approach

Much of what is known about the health effects of exposure to particulate matter has been derived from measurements of outdoor air pollution, with the primary emphasis in the past being on the effects on the respiratory system. The past two decades have greatly expanded the focus on health effects on other body systems as well. More recently, in 2017, a joint statement was published by the European Respiratory Society and the American Thoracic Society of a general framework for interpreting the adversity of the human health effects of air pollution (Thurston et al., 2017). This framework is used in this chapter to apply and transfer this knowledge to the understanding of health effects associated with indoor exposure to particulate matter. Figure 6-1 shows the biological systems that have been associated with health effects associated with exposure to outdoor air pollution. Its content reflects the fact that populations breathing indoor air are exposed to a mixture of outdoor air pollution that has entered the indoor environment and additional $PM_{2.5}$ exposure generated from sources inside homes and other buildings. Given the significant contribution of $PM_{2.5}$ of outdoor origin to the indoor environment, the figure of health effects is relevant in reviewing potential health effects associated with exposure in indoor environments.

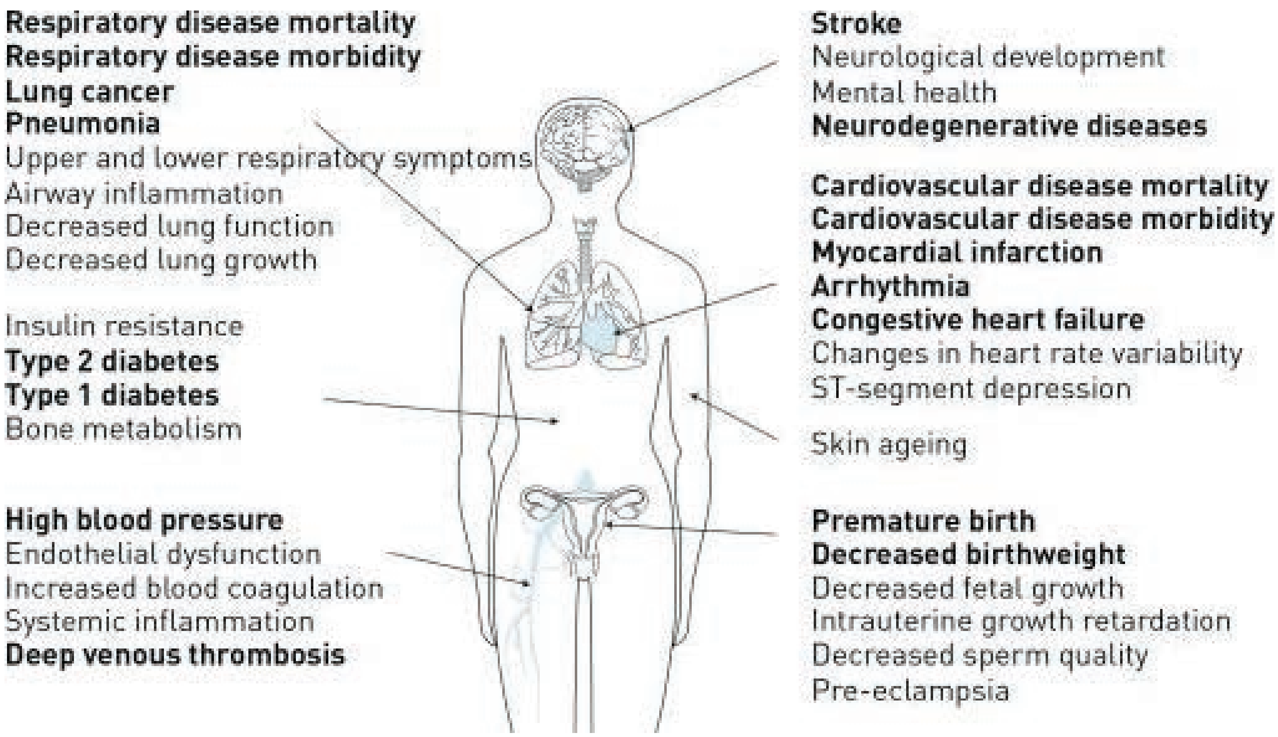

FIGURE 6-1 Overview of diseases, conditions, and biomarkers affected by outdoor air pollution. Bold type indicates conditions included in the Global Burden of Disease categories at the time of publication.
SOURCE: Thurston et al. (2017) Figure 1. Reproduced with permission of the © ERS 2023: European Respiratory Journal 49 (1) 1600419; DOI: 10.1183/13993003.00419-2016 Published 11 January 2017.

As described in the previous chapters, air pollution, either indoor or outdoor, consists of particulate matter and gaseous contaminants. For the purposes of describing human health effects, it is difficult, if not impossible, to separate the influence of these different components of indoor air on the resulting health conditions, though there have been outdoor studies that have documented certain gaseous components with specific increased risk for health effects. Research focused on this level of specificity on the harmful components of different elements of indoor air pollution is just beginning. This chapter also includes important toxicology papers that are informative for understanding the mechanisms by which $PM_{2.5}$ exerts its effects on different body systems.

Studies of health effects associated with exposure to ambient air pollution necessarily capture health effects that occur from both outside and indoor exposure. An important caveat when considering such studies is that outdoor air pollution concentrations are just a proxy of "exposure" to the outdoor sources of air pollution and that a more appropriate assessment would incorporate an estimation of penetration of outdoor air pollution to indoor spaces and the time spent indoors. The implications are that, depending on how indoor fine PM exposure is defined and assessed, part of its health effects are attributable to PM of outdoor origin.

The committee did not attempt to conduct a systematic review of all literature on the health effects of exposure to indoor particulate matter, but rather highlighted the major studies and reviews in this area. Where necessary, this chapter uses the results of studies of outdoor exposure to illuminate the mechanisms that may be driving these effects in human populations. Health effects related to chemical exposures from particulates are addressed in the National Academies' *Why Indoor Chemistry Matters* report (NASEM, 2022).

The dependency upon literature describing the association between particulate matter and health effects varies by the type of body system. In general, the literature on pulmonary and cardiovascular effects associated with indoor air pollution is much more established than that of other body systems, such as neurological and reproductive effects. In the review of different body systems, there was an attempt to focus primarily on literature from studies conducted in the United States, if possible. Finally, epidemiological studies that involve interventions to reduce exposure to particulate matter and the effects on health outcomes are the focus of Chapter 7.

Environmental and Vulnerability Considerations

As discussed in Chapter 5, exposure to $PM_{2.5}$ indoors varies across certain subgroups and may be higher or more prevalent among communities of color and populations living in poverty. These same groups have disproportionate burdens of different types of diseases associated with exposure to particulate matter. Underlying health conditions can disproportionately increase one's risk of exhibiting a health condition related to $PM_{2.5}$ exposure, and the elderly, pregnant people and infants and children have disproportionate risks for exhibiting health conditions associated with exposure to environmental contaminants. Effects may be amplified by inequities in circumstance (such as older housing stock, denser occupancy, and characteristics of ventilation systems), co-existing stressors (additional toxic exposures, poor nutrition, and the like), access to care, and other social determinants of health. The chapter thus includes studies that illustrate how the social determinants of health and environmental exposures result in differences in health risks.

RESPIRATORY HEALTH EFFECTS

$PM_{2.5}$ exerts its effects on the lower respiratory tract in part due to its size. This size fraction penetrates to the small airways, including the terminal bronchioles. The majority of the ultrafine fraction deposits in the nasal, pharyngeal and laryngeal parts of the airway, but this fraction also penetrates to the alveoli (Oberdörster et al., 2005). Because of their small size, they can cross the endothelial and epithelial barriers, entering the circulation, and can also be taken up by cells. PM elicits inflammation and oxidative stress responses in the airway, and the immunologic pathways by which some biologic components of PM exert respiratory effects are well understood. These effects include the elicitation of allergic immune responses and eosinophilic inflammation by allergens among those who are sensitized to the allergen and elicitation of innate immune responses through the TLR4 receptor for endotoxin. PM from combustion elicits neutrophilic immune responses in the airways.

The section that follows discusses the respiratory health effects of $PM_{2.5}$. The bioaerosols examined include environmental allergens, non-pathogenic/non-infectious microbes and their components, infectious microbes, and others. Chemicals may include organic and inorganic compounds as well as metals. Although the report does not include a review of the voluminous literature on smoking, secondhand smoke is addressed in its capacity as a major contributor to indoor $PM_{2.5}$. The approach taken is to review the major epidemiological literature focused on respiratory effects of indoor fine PM, including those that include biomarkers of effects.

Acute Effects: Clinical Effects, Inflammation, and Lung Function

Indoor $PM_{2.5}$ has been implicated in a range of clinical, biologic, and physiologic manifestations of asthma and chronic obstructive pulmonary disease (COPD), including symptoms, exacerbations, quality of life, inflammation, and lung function. Indoor $PM_{2.5}$ exposure has also been linked to symptoms in populations without lung disease.

Multiple epidemiologic and intervention studies have established indoor $PM_{2.5}$ as a cause of asthma symptoms and exacerbations in children with asthma as well as respiratory infections such as influenza, COVID-19, RSV, and other common respiratory viruses. In one study, there was a 7–14 percent increase in days with asthma symptoms or rescue medication use with each 10 $\mu g/m^3$ increase in indoor $PM_{2.5}$ (McCormack et al., 2011). These populations, which were socially and economically disadvantaged, tended to be exposed to high levels of indoor $PM_{2.5}$. There is scant literature concerning adults, but one epidemiologic study reported associations between both ambient $PM_{2.5}$ and a measure of indoor PM and respiratory symptoms among adults with asthma (Balmes et al., 2014). There are several trials that have tested an intervention aimed at reducing indoor $PM_{2.5}$ concentrations (Fisk, 2013). Two trials were conducted in populations exposed to secondhand smoke, and they are discussed below. One trial, which was not blinded, tested HEPA air cleaners among a population of rural Latino/a children who were not exposed to secondhand smoke at home and had poorly controlled asthma (Drieling et al., 2022). The primary outcome of the Asthma Control Test (ACT) score did not differ between groups; however secondary analyses found that assignment to the HEPA air cleaner group was associated with a reduced risk of poorly controlled asthma, symptoms in the past 2 weeks, and urgent clinical visits compared with the control group (Drieling et al., 2022).

Although two small panel studies of individuals with COPD did not find associations between indoor PM and either lung function or symptoms (Hsu et al., 2011; Linn et al., 1999), these studies each included only about 25 participants, limiting their statistical power. In a more recent and larger longitudinal study of 84 former smokers with COPD, indoor $PM_{2.5}$ was associated with respiratory symptoms, rescue medication use, and severe exacerbations (Hansel et al., 2013). This observational study was followed by a randomized trial of a HEPA air cleaner intervention among former smokers with COPD. Those randomized to the active air cleaner intervention did not have significant improvement in respiratory status, as measured by the St. George's Respiratory Questionnaire but did have improvement in respiratory symptoms, the need for rescue medications, and rate of COPD exacerbations. A per-protocol analysis that was defined by using the air cleaner as directed over 80 percent of the time demonstrated a greater than 50 percent reduction in indoor $PM_{2.5}$ concentrations and improvements in symptoms, rescue medication use, and exacerbation risk (Hansel et al., 2013). Notably, those with greater use of the air cleaner and who spent more time at home experienced the greatest benefit. Interactions have also been observed between other environmental factors and indoor $PM_{2.5}$ on respiratory health among people with COPD. In one study, indoor heat and indoor $PM_{2.5}$ had multiplicative effects on symptoms among a cohort with moderate to severe COPD (McCormack et al., 2016).

Studies have also found associations between indoor $PM_{2.5}$ and acute changes in lung function. In an observational study of children with asthma, indoor, but not outdoor, $PM_{2.5}$ was associated with decreases in FEV1/FVC (a lung function measure that examines the volume of air that is forcefully exhaled) (Isiugo et al., 2019). In a panel study of children with asthma, indoor/home 24-hour PM concentrations were associated with reductions in FEV1 percent predicted of ~1.6 percent for each 6.7 $\mu g/m^3$ increase (IQR) in $PM_{2.5}$ (Delfino et al., 2004). In an interventional study, peak expiratory flow (PEF) increased with the use of a bedroom air cleaning/ventilation unit among children with asthma (Xu et al., 2010). One study of 125 older adults with COPD observed associations between indoor $PM_{2.5}$ and indoor BC and decreases in pre-bronchodilator FEV_1 and FVC but found little relationship between ambient $PM_{2.5}$ and black carbon levels and lung function indices (Hart et al., 2018).

There is sparse literature and less consistent evidence regarding the effects of indoor $PM_{2.5}$ on biomarkers of effect (Gong et al., 2014). In a trial of HEPA air cleaners among rural Latina/o children with asthma, discussed above, assignment to the air cleaner group was associated with a 10 percent greater decrease in measured urinary LTE4 concentration than the control group, but this finding was not statistically significant (95% CI: −20% – 1%) (Drieling et al., 2022). In an observational study of 16 older adults with respiratory disease, for the 7 participants with asthma, higher indoor PM concentrations were associated with higher fractional exhaled nitric oxide, but not lower lung function (Jansen et al., 2005). In an observational study of 19 children with asthma, a model was used to estimate the relative contributions of indoor-generated and ambient-infiltrated PM to total indoor $PM_{2.5}$ concentrations in the children's homes; only the ambient-infiltrated components were associated with changes in exhaled nitric oxide (Koenig et al., 2005). Another study of 16 adults with COPD developed separate estimates of personal exposures to ambient and non-ambient (indoor-generated) PM and found that although total $PM_{2.5}$ exposures were dominated by exposures to non-ambient particles (which were not correlated with ambient fine particle exposures or ambient concentrations), only exposure to ambient particles were associated with decreased lung function, decreased systolic blood pressure, increased heart rate, and increased supraventricular ectopic heartbeats (Ebelt et al., 2005). In another study, exhaled breath condensate (EBC) nitrate decreased and pH increased in children with asthma with an air cleaning/ventilating unit**.** However, it is difficult to attribute the improvement in the EBC markers to decreases in PM or any of its particular components because not only did PM10 decrease, but total VOCs, endotoxin, and allergens also decreased (Xu et al., 2010). Another limitation of this study was that there were two groups of participants and these effects were only observed within one group of participants, but not the other. The authors postulated that that the lack of improvements in EBC markers with use of the air cleaning/ventilation unit in one group may have been due to a lack of a washout period as this group had the system running for 12 weeks and then turned it off for the final 6 weeks of observation under "untreated" conditions. The statistical approach also did not appear to account for repeated measures within individuals, and the study was not blinded. In two studies of 82 adults with COPD, higher indoor black carbon concentrations were associated with higher concentrations of urinary markers of oxidative stress and systemic markers of inflammation (Garshick et al., 2018), highlighting the potential of outdoor sources of PM penetrating indoors and exerting health effects (Grady et al., 2018). This observation is further supported by an association between higher indoor PM concentrations and greater black carbon content in airway macrophages among former smokers with COPD (Belli et al., 2016).

The sources and composition of PM are likely important in determining its biologic effects, but these characteristics are not captured by conventional volumetric sampling and gravimetric methods or light-scattering measurement methods. Further complicating matters is that, as discussed in Chapter 5, exposure to PM components may be estimated by measuring concentrations in a compartment such as settled dust or by measuring biomarkers of exposure rather than by measuring airborne particle concentrations. For example, the major contributor to indoor $PM_{2.5}$ in many populations is secondhand smoke (SHS), and there is a lengthy scientific literature pointing to SHS as a cause of asthma symptoms and exacerbations, and here the exposure metric is often cotinine or nicotine concentrations in a biologic sample. At least two randomized trials of air cleaners in children with asthma exposed to secondhand smoke demonstrated reductions in indoor $PM_{2.5}$ and biomarkers of SHS exposure and improvements in asthma, including an increase in symptom-free days (Butz et al., 2011) and reduction in exacerbations. There is scant literature about the effects of secondhand smoke on acute respiratory outcomes in COPD populations (Putcha et al., 2016a). Other combustion sources of indoor $PM_{2.5}$ include incense and candle burning. There is little literature concerning the effects of these $PM_{2.5}$ sources on respiratory health, and overall the findings are mixed. Incense has been implicated in pulmonary inflammation and linked to chronic respiratory symptoms in some contexts, but not others (Lin et al., 2008). Candle burning as a source of $PM_{2.5}$ may be less important in terms of respiratory health effects than other sources of indoor $PM_{2.5}$ such as secondhand smoke and cooking with an unvented stove (Lim et al., 2022). Both incense and candle burning are expected to have deleterious effects on the lungs, but their overall public health importance likely varies with degree of exposure and context.

The biologic components of indoor PM also have acute respiratory effects among people with and without asthma. Although the focus of the section is on acute effects, it is notable that—in the case of indoor allergens—acute effects among those who are sensitized to the allergen may be deleterious while their effects on incident asthma (chronic effects) may be beneficial (Behbod et al., 2013).

These bioaerosols—the biologic components of indoor PM—include environmental and food allergens, microbes and their components, infectious agents, and food-derived particles, such as lipids. Indoor allergens are known causes of asthma symptoms, reductions in the quality of life, exacerbations, reductions in lung function, and pulmonary inflammation among those sensitized to the allergens. All of the major indoor allergens have been implicated, including dust mites, cockroaches, furry pets, and mice. There are also emerging data implicating indoor allergens in COPD exacerbations among those sensitized to the allergens (Putcha et al., 2022). Notably, exposure to these allergens is typically estimated by measuring their concentrations in settled dust, and some of these allergens are found on larger particles and so are less likely to be in the $PM_{2.5}$ fraction. A large fraction of airborne furry animal allergens (from cats, dogs, and rodents), however, are found in the $PM_{2.5}$ fraction. Fungal allergens also exert respiratory effects via an allergic mechanism (e.g., by stimulating immunoglobulin E, or IgE, antibody production), although fungi may also exert their effects through non-IgE-dependent mechanisms, such as through innate immune activation. Although the most common route of exposure to food allergens by far is through ingestion or contact, food allergens can be aerosolized during cooking, and foods that are pan-fried are the most commonly aerosolized—eggs and fish, for example. These aerosolized food allergens can lead to respiratory symptoms among those who are allergic to these foods.

Microbes and their components have also been implicated in asthma symptoms and exacerbations. The best studied microbial component may be endotoxin (a lipopolysaccharide), which exerts its effects by activating the innate immune system through the TLR4 receptor (Thorne, 2021). It is found in the fine particle fraction and is a cause of respiratory symptoms, fever, and leukocytosis in occupational settings where there are extremely high concentrations. Human exposure studies using doses (20,000 EU), similar to what might be expected for people living in homes burning biomass (100-1000 EU/m^3), have shown that endotoxin exposure induces pulmonary inflammation, including both eosinophilic and neutrophilic inflammation (Hernandez et al., 2012). In homes, endotoxin concentrations—which are correlated with pets, mice, and young children in the home—can be measured in settled dust or air samples and are associated with asthma symptoms and exacerbations and may interact with indoor pollutants (indoor NO_2, air nicotine, and traffic-related air pollution, specifically outdoor $PM_{2.5}$ and NO_2) to potentiate their effects (Matsui et al., 2013; Mendy et al., 2019; Rosser et al., 2020). However, exposure to microbial components and their sources (animals) during early life may protect against the development of allergy and asthma, highlighting that the effects of these indoor environmental factors vary by stage of life, and may also vary by compartment and genetics (Lynch et al., 2014; Ownby et al., 2002; Sahiner et al., 2014). Importantly, endotoxin in environmental samples co-exists with other microbial components, so some of its effects in epidemiologic studies could be due to other microbial components. There are just a handful of studies of respiratory effects of endotoxin exposure among people with COPD. One study of 84 people with COPD found no associations between home endotoxin and symptoms, rescue medication use, quality of life, or exacerbations (Bose et al., 2016).

Other microbes and components that have been studied are fungal spores and their components and some bacteria-associated molecules, such as *Staphylococcus aureus* enterotoxins (Davis et al., 2018). Most of this body of work has focused on asthmatic populations, so there is scant literature for COPD. Some fungal spores have average aerodynamic diameters in the 2- to 10-micrometer range and thus can penetrate the conducting airways (Secondo et al., 2021). Fungal spores can cause asthma symptoms and exacerbations, and certain fungi have been linked to more severe asthma and even fatal asthma. Fungal exposure has also been linked to decrements in lung function among COPD patients (Fréalle et al., 2021). Although fungi have allergens that exert their effects in an IgE-dependent manner, there are a variety of fungal molecules that can trigger respiratory symptoms in a non-IgE-dependent manner. Specifically, a variety of fungal molecules, such as mannoproteins, glucans, and chitin, have been implicated as causes of acute respiratory symptoms and inflammation, but disentangling the independent effects of these various constituents is difficult (Cope and Lynch, 2015; D'Evelyn et al., 2021). Beyond specific microbes and microbial components, the application of metagenomic methods to environmental samples in the past decade has resulted in a proliferation of research describing microbial communities in environmental samples. Much of this work has focused on the potential impact of the microbial communities on long-term outcomes, such as incident asthma, and there is scant literature on acute health effects. Moreover, these studies have mostly relied on settled dust reservoir samples, and whether the microbial communities identified in this type of sample correlate with microbial communities in indoor airborne $PM_{2.5}$ is unclear.

Infectious microbes have received much more attention because of the COVID-19 pandemic, which has spotlighted airborne transmission of SARS-CoV-2 as the major mode of its transmission. Other infectious microbes found in the $PM_{2.5}$ fraction include other respiratory viruses, such as influenza, measles, and tuberculosis. The supporting evidence comes from animal model studies, aerosol science, and epidemiologic studies and has largely focused on exhaled particles carrying infectious virus, but the results of one animal study suggest that aerosolized fomites could contribute to influenza transmission (Asadi et al., 2020). Airborne infectious microbes are well established causes of acute respiratory effects with particular impact among those with asthma and those with COPD. These observations have important implications for the practical mitigation of $PM_{2.5}$, in that strategies that reduce indoor $PM_{2.5}$ concentrations should also reduce concentrations of these infectious organisms.

Overall, extending the understanding of health effects of mass concentration of $PM_{2.5}$ to include its composition and toxicity will be important for informing practical mitigation strategies as this will lend insight into high-impact targets to intervene. For example, it is possible that targeting particular sources, composition, or biologic activity in $PM_{2.5}$ may result in greater health benefits than targeting overall mass concentration. For instance, there is evidence pointing to oxidative potential as a mechanism of $PM_{2.5}$ health impacts which could help target interventions (Weichenthal et al., 2016; Sarnat et al., 2016; A. Yang et al., 2016). Other approaches have targeted indoor and outdoor PM by analyzing cellular injury or cytokine production in human cell lines (Monn and Becker, 1999) or assays on rat models (Long et al., 2001).

Acute Effects: Respiratory Tract Infection

Aside from $PM_{2.5}$ serving as a vehicle for infectious microbes, $PM_{2.5}$ can also increase susceptibility to respiratory tract infection indirectly, although the exact mechanisms by which it acts are unclear. There is a large body of evidence associating outdoor $PM_{2.5}$ levels with greater risk of respiratory tract infection among children. Much of the literature on indoor $PM_{2.5}$ and respiratory tract infection is from developing countries where biomass burning for cooking and heat has been linked with an increased risk of infection (Simkovich et al., 2019). In the United States, there are a handful of studies that also demonstrate an association between indoor $PM_{2.5}$ in homes with wood stoves and lower respiratory tract infection among young children. For example, two studies found that children living in homes with a wood stove were exposed to higher indoor PM concentrations and a higher risk of lower respiratory tract infection than their counterparts who did not live in homes with a wood stove (Walker et al., 2022). These studies enrolled children from poor rural communities where the use of wood stoves for cooking or heat is more common, and there is scant literature focused on other U.S. populations (Robin et al., 1996).

However, secondhand smoke, a major contributor to indoor PM, has been linked to upper and lower respiratory tract infections in young children (Cao et al., 2015). It has also been implicated in invasive bacterial infections in children, longer hospital length of stay for lower respiratory tract infection among atopic infants (Lemke et al., 2013), and chronic rhinosinusitis among adults (Hoehle et al., 2018). Secondhand smoke and indoor air pollution have also been shown to increase the risk of contracting tuberculosis in international studies (Obore et al., 2020).

Although the mechanisms by which indoor PM may increase respiratory tract infection risk are not clear, outdoor PM has been shown to damage airway epithelium and perturb the immune response, highlighting the biologic plausibility of PM increasing susceptibility to infection. The literature focusing on mechanisms by which indoor PM may act is smaller, but a 2022 in vitro study suggested that indoor PM may impair innate immunity by inhibiting the antiviral activity of airway surface liquid (ASL) (Stapleton et al., 2022). Outdoor PM has also been shown to impair the bactericidal effects of ASL (Stapleton et al., 2020), suggesting that PM may impair immunity against both viral and bacterial respiratory tract infections. The literature examining mechanisms by which outdoor PM may increase susceptibility is larger and points to deleterious effects on the airway epithelium and the immune response (Beentjes et al., 2022).

Chronic Respiratory Health Effects

Although there is a growing body of work demonstrating associations between outdoor $PM_{2.5}$ and long-term respiratory effects, there is, with few exceptions (e.g, Logue et al. 2012), little literature on indoor $PM_{2.5}$. Outdoor $PM_{2.5}$ has been linked to incident asthma and COPD as well as long-term effects on lung function—either more rapid decline among adults or reduced lung function growth among children. However, secondhand smoke—a major contributor to indoor $PM_{2.5}$—has repeatedly been associated with reduced lung function growth among healthy children (Okyere et al., 2021) and those with underlying conditions, such as cystic fibrosis (Oates et al., 2020). An Australian study observed associations between particular indoor $PM_{2.5}$ sources (wood heating, tobacco smoke) and risk of persistent asthma and lung function decline among adults (Dai et al., 2021).

Pulmonary Symptoms in School Environments

While the bulk of the indoor PM literature has focused on homes, children spend a substantial amount of time in schools. The growing body of literature focused on school exposure has identified school buildings being in poor condition as a risk factor for asthma hospitalizations and absenteeism, although these studies did not examine indoor PM directly (Berman et al., 2018; Wu et al., 2023). Schools can have clinically relevant levels of PM and bioaerosols, including fungi and allergens. Although studies examining the health effects of school-based PM exposure are scant, a few studies have reported associations between mouse allergen, fungi, and endotoxin exposures in schools and adverse health effects among children with asthma (Baxi et al., 2019; Lai et al., 2015; Sheehan et al., 2017). $PM_{2.5}$ concentrations can be high in schools, and outdoor sources can be major contributors to classroom $PM_{2.5}$. School factors such as proximity to idling buses, the age and type of buildings, ventilation, and servicing of the furnace also contribute to school $PM_{2.5}$ concentrations (Matthaios et al., 2022). Although there is little literature examining the respiratory effects of school-based $PM_{2.5}$ exposure specifically, the concentrations observed in schools have been linked to a variety of respiratory health effects, suggesting that school-based exposure also has deleterious effects on respiratory health.

Susceptibility Factors for Pulmonary Outcomes

Susceptibility to indoor $PM_{2.5}$ and its different constituents varies. Young age and advanced age are susceptibility factors for the respiratory effects of outdoor $PM_{2.5}$ and are also likely susceptibility factors for indoor $PM_{2.5}$ (Simoni et al., 2015). One study found school-age children at greatest risk for asthma exacerbations in response to exposure to particles of outdoor origin, suggesting that age may also be a susceptibility factor for the respiratory effects of indoor $PM_{2.5}$ exposure (Alhanti et al., 2016), but studies examining age as a modifier of indoor $PM_{2.5}$ respiratory effects are scant. Obesity is a risk factor for indoor and outdoor $PM_{2.5}$ respiratory effects, including on respiratory symptoms and lung function and among asthmatic and healthy populations. Although this result has been found in multiple studies across all ages and several continents, the mechanism by which obesity may confer susceptibility to $PM_{2.5}$ respiratory effects is unclear. Researchers have postulated that the underlying inflammatory state or physiologic changes in lung function associated with obesity may be mechanisms. Diet has also been hypothesized as influencing susceptibility to $PM_{2.5}$ exposure (Brigham et al., 2023). For example, in one study, omega-6 and omega-3 fatty acid intake via diet modified responses to indoor $PM_{2.5}$ exposure among children with asthma (Bose et al., 2019; Brigham et al., 2019). Omega-3 fatty acid intake attenuated the respiratory effects of indoor $PM_{2.5}$ exposure, while omega-6 fatty acid intake amplified its effects. For outdoor PM, genetic polymorphisms in genes that are critical for the oxidative stress response have been established as susceptibility factors (Romieu et al., 2010). Whether these same polymorphisms—or polymorphisms in other oxidative stress genes—confer susceptibility to indoor $PM_{2.5}$ is unknown. Susceptibility factors for biologic constituents of $PM_{2.5}$ are better understood. For example, individuals with IgE sensitization to indoor allergens and foods are susceptible to exposure to these allergens, while those without IgE sensitization are not. For endotoxin, polymorphisms in the CD14/TLR pathway confer susceptibility to its respiratory effects.

CARDIOVASCULAR HEALTH OUTCOMES

There is a robust body of literature providing strong evidence that ambient fine PM is associated with adverse cardiovascular health effects (Brook et al., 2010; Newman et al., 2020; Rajagopalan and Landrigan, 2021; Rajagopalan et al., 2018). Large studies in the United States have demonstrated that short-term increases in PM are associated with an increased risk of heart attacks, heart failure events, and strokes requiring emergency department visits or hospitalizations. Further, increases in both short-term and long-term outdoor PM have been associated with increases in cardiovascular deaths.

Published studies of the health effects of indoor PM exposure have typically focused on short-term health effects. A notable exception is the body of evidence demonstrating the health benefits related to the reduction of secondhand smoke in the context of indoor smoking bans (Meyers et al., 2009; Oliver, 2022). Studies have demonstrated that indoor smoking bans have resulted in reductions in cardiovascular events, such as acute myocardial infarction by up to 40% and acute cerebrovascular disease by up to 29% (Pechacek and Babb, 2004). Studies of the cardiovascular health effects of indoor PM have generally focused on intermediate endpoints that have been conceptualized as mediators of cardiovascular health effects or proposed as clinically relevant. Pathways that may explain the cardiovascular health effects of indoor PM include systemic inflammation and oxidative stress responses; activation of the coagulation cascade; alteration of cardiac autonomic response and conduction; and changes in vasomotor tone of the circulatory system. The clinical endpoints include biomarkers of systemic inflammation and oxidative stress, blood pressure, pulse rate, heart rate variability, and electrocardiogram changes. Outcomes such as acute myocardial infarction and episodes of heart failure were not identified in the studies reviewed, and few (if any) studies examined chronic exposure. The sample sizes of the studies of indoor PM were relatively small, particularly when compared with the population studies that have demonstrated cardiovascular health effects of outdoor air pollution. Most of the studies were observational with sample sizes of less than 100 participants. Although interventions are the focus of Chapter 7, findings from some intervention studies contribute to the evidence base that informs potential causality.

Acute Effects on the Cardiovascular System

Blood Pressure

Blood pressure is a physiologic measurement that is one of the major risk factors for cardiovascular disease. The consequences of higher blood pressure include coronary artery disease, heart failure, and cardiovascular death. Higher blood pressure is also associated with stroke, chronic kidney disease, and diabetes as well as other chronic conditions (Fuchs and Whelton, 2020). Studies of outdoor PM have consistently demonstrated that increases in $PM_{2.5}$ are associated with increases in blood pressure, with increases of 10 $\mu g/m^3$ being associated with changes in the range of 1- to 3-mmHg elevations in systolic and diastolic blood pressure (Cai et al., 2016; Giorgini et al., 2016; Liang et al., 2014; B.-Y. Yang et al., 2018). Controlled chamber studies and experimental models have also demonstrated this association (Cosselman et al., 2012; Hudda et al., 2021; Münzel et al., 2017; Urch et al., 2005, found in Rajagopalan et al., 2018).

Studies that have investigated the association between indoor PM and blood pressure, heart rate, and electrocardiogram (ECG) changes have demonstrated mixed results. For example, several small studies conducted in the United States did not detect an association. Jansen et al. (2005) studied blood pressure and heart rate in 16 individuals with asthma and COPD and did not find an association between indoor PM and pulse or blood pressure. Linn et al. (1999) studied 30 individuals with severe COPD and conducted monitoring near and inside participant homes. Outcomes included lung function, blood pressure, pulse oximeter, and ECG. Indoor PM was not associated with blood pressure or ECG changes. Brook et al. (2011) separately analyzed associations between cardiovascular outcomes and both community-level ambient $PM_{2.5}$ concentrations and personal $PM_{2.5}$ concentration measurements (by vest monitors) of 65 non-smoking subjects, finding that a 10 $\mu g/m^3$ increase in total personal-level $PM_{2.5}$ exposure was associated with systolic blood pressure elevation but that community $PM_{2.5}$ levels were not associated with cardiovascular outcomes. International studies that focus on biomass fuel use, including those conducted in China, Guatemala, and Peru, provide more consistent evidence of the association between indoor particulate matter and increases in blood pressure. One review article found that eight cross-sectional studies reported an association between higher blood pressure or prevalence of hypertension, while two cross sectional studies did not find an association (Fatmi and Coggon, 2016).

Intervention studies also provide evidence of the association between indoor PM and blood pressure, and several studies have demonstrated improvements in blood pressure with reductions in PM concentrations. Morishita et al. (2018) studied 40 non-smoking older adults in an intervention study in economically disadvantaged senior housing and found that the use of indoor portable air filtration for 3 days led to significant reductions in systolic blood pressure and a trend toward reduction in diastolic blood pressure. A crossover study in China of 35 college students living in dormitories detected improvement in blood pressure with an air cleaner intervention for 48 hours that resulted in a 57 percent reduction in $PM_{2.5}$ (96.2 vs 41.3 μg/m^3) (R. Chen et al., 2015). Another air cleaner intervention crossover trial in China demonstrated blood pressure reduction among college students with PM reduction of 54 percent (53.1 vs 24.3 μg/m^3) with use of an air cleaner for 9 days (H. Li et al., 2017). In one of the only longer-term intervention studies of which the committee is aware, Chuang et al. (2017) introduced an air filtration intervention to air conditioners in the homes of 200 participants in Taipei, Taiwan, and found that increased levels of $PM_{2.5}$ were associated with increased blood pressure over the course of the year. However, many of the clinical trials of portable air cleaners have included blood pressure and heart rate and have not found an association between PM reduction and blood pressure improvement. International studies in Guatemala and Bolivia reported a reduction in blood pressure (BP) with the use of improved stoves (Alexander et al., 2015; McCracken et al., 2007).

Vascular Physiology and Function

Vascular physiology and function are often measured with surrogate measures in research studies to assess vascular function. These surrogate measures include the assessment of carotid intimal media thickness, brachial artery diameter, flow mediated dilatation, and endothelial function/microvascular function (reactive hyperemia–peripheral arterial tonometry with EndoPat sensors). In a crossover study of 21 elderly nonsmoking couples in Copenhagen, air filtration with a HEPA filter for 48 hours led to a 62 percent reduction in indoor particulate matter concentrations (12.6 to 4.6 μg/m^3) and an 8 percent improvement in microvascular score (Bräuner et al., 2008). In a study of healthy adults in British Columbia, a HEPA filter intervention for 7 days led to improvement in $PM_{2.5}$ concentrations by 60 percent (11.2 vs 4.6 μg/m^3) and reactive hyperemia index of 9.4 percent (Allen et al., 2011). Other intervention trials did not demonstrate improvement in that index (Kajbafzadeh et al., 2015; Karottki et al., 2013; Weichenthal et al., 2013).

Cardiac Autonomic Dysfunction and Conduction

Cardiac autonomic dysfunction (heart rate variability) and conduction (ECG changes) have been proposed as an effector pathway by which air pollution leads to increased cardiovascular events. Heart rate variability (HRV) reflects the ability to adapt to the body's changing physiologic demands, and greater variability is associated with better outcomes. Several studies examined the association between outdoor PM and HRV. The association was more pronounced among those with pre-existing cardiovascular disease. Raju et al. (2023) studied 85 former smokers with COPD and detected an association between indoor $PM_{2.5}$ and ultrafine particles and HRV among former smokers with a diagnosis of COPD. HRV was assessed using the standard deviation of the average NN intervals and the root mean square of successive differences approaches to measuring the variability between heart beats measured on an ECG. Though the sample size was smaller, the effect sizes were larger for ultrafine particles, which could suggest that these smaller particles are more potent. Liao et al. (1999) studied 26 elderly individuals and found that increases in $PM_{2.5}$ (indoors and immediately outside the home) were associated with lower heart rate variability in the elderly. Zanobetti et al. (2009) studied 48 individuals who were hospitalized for coronary artery disease for 1 year following the hospitalization. Exposures included ambient and in-home $PM_{2.5}$ and black carbon. Indoor black carbon and indoor $PM_{2.5}$ were associated with the ECG finding of t wave alternans, a marker of cardiac electrical instability. An international study demonstrated a benefit of reducing wood smoke exposure (mean 266 to 102 μg/m^3) with reduction in T-wave inversions among women living in Guatemala but did not detect changes in heart rate variability (McCracken et al., 2011).

Biomarkers and Inflammation

Studies of exposure to indoor air pollution have used biomarkers of inflammation in the blood (e.g., C reactive protein [CRP], interleukin-6 [IL-6]) and oxidative stress, as well as endothelial function (e.g., soluble vascular adhesion molecule-1 [sVCAM-1]), and coagulation. Findings may provide insight about to the pathways by which indoor PM exerts health effects. Delfino et al. (2008) studied 29 non-smoking elderly individuals investigating the association between both outdoor and indoor air pollution and systemic inflammation. The investigators reported associations between outdoor air pollution and CRP, IL-6, sTNF-RII, Sp-selectin and noted that associations with indoor pollution were consistent. However, the associations between indoor PM and the biomarker outcomes in isolation were less convincing.

Bose et. Al (2015) studied 50 individuals with COPD and detected an association between indoor PM and elevated white blood cell count, including neutrophils and lymphocytes. Garshick et al. (2018) studied 85 individuals with COPD and found that indoor black carbon was associated with CRP and results suggested a greater effect among those who were not taking statins. Findings were similar for interleukin 6 (IL-6), but there was no association with sVCAM-1. While statin therapy is anti-inflammatory, these results suggest that statin therapy may have the potential to mitigate the inflammatory consequences of indoor pollution exposure and similar findings have been reported in the outdoor PM literature (Ostro et al., 2015). Brugge et al. (2017) studied ultrafine particulate pollution in 23 homes in Massachusetts and evaluated in-home HEPA filtration for 3 weeks compared to sham filtration for 3 weeks with a crossover study design. Despite reducing particle number concentrations by 50–85 percent in most homes, there was no evidence of beneficial effect on biomarkers of inflammation for HEPA as compared to sham filtration periods. The investigators also examined the association between ultrafine particle number concentration and did not find evidence of a positive association.

PM Composition and Cardiovascular Health Effects

Studies have investigated metals as a component of indoor PM and reported health outcomes. Bräuner et al. (2008) conducted a crossover trial of air cleaners among 21 elderly couples. Microvascular function was assessed using reactive hyperemia–peripheral arterial tonometry with EndoPat sensors. Personal exposure to iron, potassium, copper, zinc, arsenic, and lead in the fine particulate fraction was associated with changes in microvascular function. Hsu et al. (2011) reported that nickel in indoor and personal PM samplers was associated with increased heart rate among individuals with COPD, but these findings were representative of only nine participants from New York, and this association was not detected among the 15 individuals with COPD who were enrolled in Seattle. Studies investigating PM measured outdoors have demonstrated an association between a particle radioactivity and cardiac arrhythmias among a high-risk population (Peralta et al., 2020) and studies in populations with COPD have demonstrated associations between in-home gamma radiation PM exposures and systemic inflammation (CRP, IL-6 and sVCAM-1) and oxidative stress (Huang et al., 2020; 2021). These findings may suggest the need to consider activities that generate PM or sources and composition of PM in evaluating health effects.

Hammond et al. (2014) reported findings of the Detroit Exposure and Aerosol Research Study (DEARS) in a subset of 50 nonsmoking adults who underwent cardiovascular assessment in addition to an indoor environment assessment. The indoor environment assessment included continuous PM assessment and completion of household activity diaries. Participants contributed a maximum of 5 days in the summer and 5 days in the winter. Activities that significantly increased PM included cooking, candles, smoking, open windows, and product use. The investigators found heterogeneity in the associations between household activities likely to influence PM source and cardiovascular outcomes, including heart rate, blood pressure, brachial artery diameter, and flow-mediated dilatation. The exploratory nature of the study suggests that future studies that include consideration of source and composition may be informative and advance understanding of the pathways by which PM elicits health effects. The aforementioned long-term filtration study by Chuang et al. (2017) found that long-term (1-year) air-conditioner filter use reduced VOC as well as PM concentrations in homes in Taiwan and that filtration resulted in a reduction in inflammation and oxidative stress and blood pressure.

Susceptibility Factors for Cardiovascular Outcomes

Vulnerable populations at increased risk for the cardiovascular health effects associated with exposure to indoor particulate matter include children with asthma, elderly adults, and adults with asthma, chronic obstructive pulmonary disease (COPD), and heart disease. Studies of air pollution measured outdoors have demonstrated that the adverse impacts of particulate pollution may be amplified among those living in more disadvantaged areas (Hazlehurst et al., 2018; Wing et al., 2017). Some studies specifically enrolled participants who were of lower income (Padró-Martínez et al., 2015).

Individual characteristics may also confer susceptibility, and these characteristics may be differentially distributed among populations. Obesity is such a trait. Raju et al. (2023) described effect modification by body mass, suggesting that obese individuals with COPD may be more susceptible to the cardiovascular effects of indoor PM. The finding that obesity may enhance susceptibility to indoor PM has also been demonstrated in respiratory health effects among both children with asthma and adults with COPD (K. D. Lu et al., 2013; McCormack et al., 2015; Wu et al., 2018). Studies of outdoor pollution have also suggested that diabetes is a susceptibility factor for cardiovascular outcomes associated with PM exposure. Given the overlap between obesity and metabolic dysfunction, it is possible that underlying metabolic dysfunction could be a pathway by which obese individuals are more susceptible to the adverse effects of PM. The findings that statin therapy may mitigate PM health effects may also provide insight as to potential pathways that confer susceptibility and resistance to PM health effects.

Diet has also been identified as a modifiable risk factor that exaggerates or attenuates air pollution health effects in studies of air pollution measured outdoors. For example, in the U.K. Biobank Study, outdoor $PM_{2.5}$ was associated with an increased risk of all-cause mortality as well as of coronary vascular disease and coronary heart disease mortality; a healthy diet and, specifically, vegetable intake attenuated the association between $PM_{2.5}$ and mortality (Wang et al., 2022).

CANCER OUTCOMES

Air pollution has been classified as carcinogenic to humans by the International Agency for Research on Cancer (IARC) based on evidence from both epidemiological and animal studies, although there have been few studies focused on the attributable risk related to the exposures that occur within the indoor environment. There is substantial evidence to support a causal link between levels of outdoor air pollution, and especially PM, with lung cancer incidence and mortality (Turner et al., 2020). In addition to lung cancer, outdoor sources of air pollution have been associated with colorectal, gastric, renal, and bladder cancer (Schraufnagel et al., 2019). Secondhand smoke, exposure to which may occur outdoors or indoors, has long been recognized as carcinogenic (IARC, 2012; NTP, 2016). Much of what is known about the association between indoor air pollution and cancer has been generated from studies of biomass burning in low- and middle- income countries and primarily focused on lung cancer (Lee et al., 2020).

Mechanistic studies have demonstrated that components of air pollution alter the length of telomeres and the expression of genes involved in DNA damage and repair. Chen et al. In a case–control study of patients with lung cancer, K.-C. Chen et al. (2022) analyzed pleural fluid for evidence of internal exposure dose to substances shown to have an association with lung cancer. Excluding current smokers, they found individuals with lung cancer were more likely to report habitual cooking at home and indoor incense burning. Indoor wood-burning fireplaces have also been studied in relation to the risk of breast cancer. In a U.S. study, White et al. (2014) analyzed population-based case–control data and found that synthetic log burning was associated with increased risk of breast cancer, but not wood logs alone. The same investigators in a prospective study of sister study participants found that having an indoor wood-burning stove or fireplace in the longest adult residence was associated with a higher breast cancer risk, and the risk increased with frequency of use (White and Sandler, 2017). A similar increased risk of breast cancer related to indoor biomass cooking was observed in a large study based in the China Kadoorie Biobank (Liu et al., 2021). Compared with long-term clean fuel users, women burning solid biomass fuels to cook had elevated odds of being diagnosed with breast cancer. Those who had switched from solid to clean fuels did not have an excess risk of breast cancer.

NEUROLOGICAL OUTCOMES

With the increasing evidence of the association of ultrafine particle exposure and cardiovascular effects and the physiological interactions between the vascular system and the brain, the possibility of a pathway between vascular changes as risk factors for cognitive decline and psychological conditions (NASEM, 2016) merits attention. In addition to the vascular pathway, multiple studies have demonstrated that solid ultrafine particles are able to penetrate the brain via the nose and olfactory nerve (Oberdörster et al., 2004). Animal models have shown that, within the brain, PM alters neurotransmitter levels, triggering oxidative stress, inflammation, and other biochemical changes (Sirivelu et al., 2006). The link between these neurological effects and health outcomes such as cognitive decline, autism, and depression have been hypothesized. You et al. (2022) published a review of the association of particulate matter and neurological outcomes such as dementia in the elderly and neurological changes across all age groups. They summarized potential neurological mechanisms in human and animal studies that suggest that PM-induced neurodegenerative pathology includes neurotoxicity, neuroinflammation, oxidative stress, and damage to the blood–brain barrier and neurovascular units.

While there is a growing body of evidence of the association between airborne particles and neurological outcomes, it remains unknown which particle components have the most serious neuro-toxicological profiles. The various components of indoor air pollution, such as the particles, gaseous components, organic compounds, and toxic metals, may have different effects on neurological systems. Most of the epidemiological studies of particulate matter and neurological outcome have focused on the link between PM_{10} and $PM_{2.5}$ in air pollution and include studies of adults, pregnant people, and young children. As described in previous chapters, outdoor air pollution is a major component of the indoor air environment in addition to PM being generated by indoor sources. Studies focused on exposures that occur indoors and potential neurobehavioral and cognitive effects such as in offices and schools are increasingly being pursued.

Outdoor Air Pollution and Neurological Outcomes

The research on the association between ambient air pollution and neurological effects is characterized by studies of specific populations such as workers, the elderly, pregnant people, and veterans and an array of different outcomes such as cognition, depression, other psychiatric diagnoses, and admissions. Researchers in the United States conducted a cross-sectional study to determine if $PM_{2.5}$ in air pollution was associated with cognitive function in a national sample of older adults (Ailshire and Clarke, 2015). EPA monitoring data were linked with cognitive function of participants in the 2001/2002 Americans' Changing Lives Study (n = 780). An association was reported between older adults living in areas with high concentrations of $PM_{2.5}$ and error rates on cognitive function tests. Bakolis et al. (2021) conducted a prospective longitudinal population-based mental health survey of 1,698 adults in southeast London from 2008 to 2013. Adjusting for socioeconomic status and exposure to road noise, they found evidence of 18–30 percent increased odds of common mental disorders among the persons with increased exposure to $PM_{2.5}$ along with other air pollutants. However, a study in the United States of 570 participants in the U.S. Veterans Administration Normative Aging Study found no association between $PM_{2.5}$ levels at residential address and Brief Symptom Inventory psychiatric symptom levels, although positive associations were found for other air pollution components (Qiu et al., 2022a). Bastain et al. (2021) published a study of the association between prenatal exposure to ambient air pollution and maternal depression at 12 months after childbirth in a cohort of 180 predominantly economically disadvantaged Hispanic/Latina women. They reported that second-trimester $PM_{2.5}$ exposure was associated with increased depression at 12 months postpartum and exposure to NO_2 was associated with almost a two-fold increase in postpartum depression.

A 2022 study was the first to describe the association of ambient residential long-term average predicted concentrations of particle components with the risk of psychiatric hospitalizations (Qiu et al., 2022). In this study, the Health Cost and Utilization Project's state inpatient databases, which cover residents of eight U.S. states, were used to examine correlations between psychiatric hospitalizations and 14 constituents of $PM_{2.5}$ by the ZIP code of residence. The results found an association with $PM_{2.5}$ constituents such as sulfate, Fe, Pb, and Zn.

Two published reviews have examined the association between ambient air pollution and neurological conditions in adults. In a systematic review Dimakakou et al. (2018) reported a positive association between ambient air pollution, including $PM_{2.5}$, and neurodegeneration risks such as dementia and cognitive decline. They found similar evidence of an association with indoor work-related exposure to $PM_{2.5}$. More recently, Boronni et al. (2022) published a review and meta-analysis of 39 studies on the association between ambient air pollution, including $PM_{2.5}$, and depression. They reported an increased risk of depression associated with long-term ambient $PM_{2.5}$ concentrations and with short-term exposure to other components of air pollution. While they acknowledged the publication bias, they reported that the association between $PM_{2.5}$ and depression was strengthened by the absence of heterogeneity and the inclusion of both long- and short-term exposure studies. The strength of the results of the studies that were being published, led Taylor et al. (2021) to develop a model that estimated the prevalence of expected cases of major depressive disorder in multiple scenarios and concluded that indoor $PM_{2.5}$ might contribute to 476,000 cases of major depressive disorder in the United States (95% confidence interval [CI] = 11,000–1,100,000).

Outdoor Air Pollution and Prenatal and Childhood Neurological Effects

There have been multiple reports of relationships between prenatal and early childhood exposures to ambient air pollution, including $PM_{2.5}$, and neurological outcomes, primarily behavioral effects and school performance. In a study of prenatal and early childhood exposures to traffic-related air pollution and neurobehavioral health outcomes in over 1,000 children, Harris et al. (2016) conducted parental and classroom teacher evaluations of behavioral ratings on executive function. Exposures were estimated using validated spatiotemporal models to predict residential ambient concentrations of $PM_{2.5}$ and black carbon. Only a slight association was found between $PM_{2.5}$ exposures during gestation and early childhood and teacher ratings, and none of the parent-rated outcomes suggested adverse effects. However, another study reported an association between ambient air pollution and academic achievement (W. Lu et al., 2021). Lu et al. examined outdoor $PM_{2.5}$ and other air pollutants and their associations with average academic test scores in third- to eighth-grade students in the United States from 2010 to 2016, controlling for urbanicity, socioeconomic status, and race/ethnicity. The authors found that ambient $PM_{2.5}$ concentration was associated with both lower scores in math and English language/arts test scores.

Several studies focused on outdoor $PM_{2.5}$ exposure during pregnancy and effects on neurobehavioral performance in offspring. Chiu et al. (2016) assessed gestational exposure to ambient $PM_{2.5}$ in 267 full-term urban children and its association with neurobehavioral outcomes. They found a positive association between gestational exposure at different windows of susceptibility and poorer function across memory and attention domains with variable associations based on sex. Ahmed et al. (2022) studied the association between ambient $PM_{2.5}$ and mental and behavioral development in children using data from the Mothers and their Children's Health study in Australia, with ambient $PM_{2.5}$ levels estimated using a land use regression model. Residential proximity to roadways was also studied for early life exposure during pregnancy, the first year of life, and all of the children's lifetime. Children exposed to moderate and high ambient $PM_{2.5}$ exposure had higher odds of emotional and behavioral problems and gross motor delays.

A number of studies have been published on the association between gestational and early life exposures to outdoor $PM_{2.5}$ and autism in children (Becerra et al., 2013; Kalkbrenner et al., 2015; Raz et al., 2015; Talbott et al., 2015; Volk et al., 2013; Weisskopf et al., 2015). Raz et al. (2015) used models of predicted ambient PM_{10} and $PM_{2.5}$ levels from 1988 to 2007 to estimate maternal exposures pre-, during, and 9 months after pregnancy to identify women who had children diagnosed with autism, finding an increased risk of autism in offspring who had higher $PM_{2.5}$ prenatal exposure, particularly during the third trimester. Associations between traffic pollution around schools and direct measures of brain maturation measured with magnetic resonance imaging have also been reported in children aged 8–12 years (Pujol et al., 2016). Air pollution exposure was associated with brain changes of a functional nature, with no evident effect on brain anatomy, structure, or membrane metabolites.

Trombley (2023) published a review of 17 papers to examine the relationship between ambient $PM_{2.5}$ exposure and mental health outcomes (emergent and general psychiatric outcomes, neurodevelopmental disorders, stress and anxiety and depression) in children and adolescents. The author reported that there was evidence supporting a possible correlation between ambient $PM_{2.5}$ exposure and adolescent mental health outcome but that the data were not consistent and that more research is needed.

Indoor Exposure to $PM_{2.5}$ and Neurological Effects

There is a scarcity of population-based studies of indoor air pollution and neurological health effects in adults. A study of 628 households in the United Arab Emirates examined a number of indoor air pollutants, including particulate matter, collecting health information from household members using in-person interviews (Yeatts et al., 2012). Significant associations were reported for health symptoms and pollutants such as SO_2, NO_2, and H_2S, but not for $PM_{2.5}$ specifically. Burning incense daily was associated with an increased likelihood of headaches, difficulty concentrating, and forgetfulness. Cedeño Laurent et al. (2021) reported on declines in neurobehavioral performance in office workers in six countries. They found that higher indoor $PM_{2.5}$ levels were associated with slower response times and reduced accuracy and that the association was evident only at levels above 12 $\mu g/m^3$.

While there is a scarcity of studies reporting associations between indoor air quality and health impacts, studies of neurobehavioral performance in children do exist. Vrijheid et al. (2012) studied the association of gas cooking during pregnancy with infant neurodevelopment in a prospective birth cohort study in Spain. Neurodevelopment was measured at age 11–22 months using the Bayley Scales of Infant Development. Gas cookers, present in 44 percent of homes, were related to a small decrease in the mental development score compared with the use of other cookers. The negative association with gas cooking was relatively consistent across strata defined by social class, education, and other covariates. A similar study was conducted in Sri Lanka assessing indoor air pollution and neurodevelopmental measures at 1.5 and 3.0 years. Two-hour area measures of particulate matter in the home were obtained. They found children in wood-burning households had lower cognitive and motor scores. Unit increases in log-transformed indoor $PM_{2.5}$ were significantly associated with decrements in cognitive function, suggesting potential a neurotoxic impact on child's cognitive scores with the impact continuing through early childhood (Sathiakumar et al., 2019).

The association between indoor air quality in schools and learning outcomes among children has been an area of concern. At the population level, the question has been asked if green schools influence the overall academic performance of the children in those schools (Vakalis et al., 2021). More than 2,000 schools in the U.S. are LEED-certified but have not been evaluated comprehensively for their effect on school performance. A review by Vakalis et al. (2021) synthesized the literature in this area and reported that the building components of LEED certification are associated with positive learning outcomes and improved indoor air quality and acoustic performance appear to have the most effect. This review did not however establish an association between LEED certification and reduction in indoor fine PM. This comprehensive review points to the difficulties in associating specific learning outcomes with the variety of components associated with green buildings, including indoor air quality but also noise, thermal conditions, ambient air pollution and siting of the school, lighting, and other factors. In general, the study design, the academic outcomes measured, and the different LEED components vary greatly in the investigations, but in general green schools are associated with better performance. While these findings are not surprising, there is a need for prospective studies of the health impacts of replacing old structures with renovated or new buildings and the subsequent impact on student learning.

Saenen et al. (2016) measured attention, short-term memory, and visual information processing speed in 310 school age children and monitored $PM_{2.5}$ and PM_{10} exposure with portable monitors both in schools and the child's residence on the same day or up to 2 days before the examination (for recent exposure) and 365 days before the examination (for chronic exposure). They reported that increasing classroom $PM_{2.5}$ exposure was associated with declining performance on two neurobehavioral tests. Other neurobehavioral changes were observed in relation to recent residential outdoor $PM_{2.5}$ exposure and chronic exposure at the residence. Sunyer et al. (2015), conducted a prospective study of 2,715 school aged children in Spain exposed to varying levels of air pollution in close proximity to their schools. Children were tested four times over a year, and air pollution, including ultrafine particle number concentration, was measured twice both outside and inside the classroom. Cognitive development was assessed with neurobehavioral tests, and linear mixed effects models were adjusted for age, sex, maternal education, socioeconomic status, and air pollution exposure at home. Children from highly polluted schools had a smaller growth in cognitive development than children from the paired lowly polluted schools, both in crude and adjusted models. Children attending schools with higher levels of ultrafine particles both indoors and outdoors experienced substantially smaller growth in all the cognitive measurements. These associations remained when controlled for type of school, educational quality, commuting, and smoking at home.

An association between indoor air pollution exposure during pregnancy and autistic-like behavior in offspring has also been reported. Yang et al. (2022) analyzed data from the Longhua Child Cohort Study in China which enrolled 65,317 preschool children. Associations between maternal exposure to four sources of indoor air pollution (e.g., cooking, environmental tobacco smoke, mosquito coils, and home decoration) during pregnancy, and preschool children's autistic traits were analyzed using multivariate logistic regression. The study found that maternal exposure to indoor air pollution from four different sources during pregnancy was associated with the presence of children's autistic-like behaviors, with a suggested dose–response relationship and additive interactions.

REPRODUCTIVE OUTCOMES

In the past two decades, a number of studies have examined the association of exposure to particulate matter and adverse reproductive outcomes (Ghazi et al., 2021; Jo et al., 2020; Saenen et al., 2019). The possible biological mechanism is the impact of fine particulate matter on pulmonary and placental inflammation during pregnancy, subsequently affecting gas and nutrition exchange and reducing the level of oxygen available to the fetus. The large majority of reports have focused on ambient pollution, and in more recent years there have been reports of exposure to particulate matter from wildfires and reproductive effects. There has been to date a scarcity of reports that look specifically at indoor particulate matter exposure and reproductive outcomes.

Outdoor Air Pollution and Reproductive Outcomes

The association between outdoor air pollution and pregnancy outcomes provides some evidence of a potential link between indoor air pollution and these outcomes, though the evidence is not as robust as that found for cardiovascular and respiratory outcomes. Li et al. (2017) published a systematic review and meta-analysis of the association between ambient fine particulate matter and preterm birth or term low birth weight. In a review of studies published prior to July 2016, they found a significantly increased risk of preterm birth with an interquartile increase in ambient $PM_{2.5}$ concentrations throughout pregnancy (odds ratio [OR] = 1.03; CI = 1.01–1.05) but stressed the need for prospective cohort studies and personal exposure measurements to better characterize the observed relationship. An ongoing prospective cohort study of pregnancy, MADRES, suggested that there appears to be critical windows of exposure to ambient air pollution and effects on in utero fetal growth (Peterson et al., 2022). Participants had daily ambient air pollutant concentrations measured including $PM_{2.5}$. A significant sensitive window of susceptibility during the gestational weeks 4–16 was associated with $PM_{2.5}$ and fetal weight. Weeks 1–23 exposure to $PM_{2.5}$ was also associated with smaller fetal abdominal circumference, suggesting that exposure to particulate matter in early to mid-pregnancy, but not preconception or late pregnancy, may have critical implications on fetal growth.

In a review of ambient air pollution and pregnancy outcomes, Klepac et al. (2018) identified several environmental public health challenges inherent in current investigations, noting that inconsistent findings have been reported, perhaps due to the different outcomes studied, the observed gestational windows of exposure, exposure assessment methods, and statistical methods. In their review of 96 studies, they reported that particulate matter and ozone over the entire pregnancy were significantly associated with a higher risk for preterm birth and that most studies have been retrospective, linking routine ambient air monitoring and birth records data. Their meta-analysis of the pooled effect estimates of the 28 studies reviewed indicated that exposure to particulate matter in entire pregnancy was significantly associated with a higher risk for preterm birth (1.09; CI = 1.3–1.16) for PM_{10} and 1.24 (CI = 1.08–1.41) for $PM_{2.5}$. More recent studies have been published that add additional evidence of a link between ambient $PM_{2.5}$ and pregnancy outcomes. Singleton births occurring in 2004 in metropolitan counties of Atlanta, Georgia, were compared to county-level daily air quality index controlling for potential pregnancy confounders (Zhu et al., 2019). County-level daily Air Quality Index (AQI) was used to estimate individual exposure levels of $PM_{2.5}$ for each study participant. A higher rate of preterm birth was observed in the offspring whose mothers were exposed to ambient $PM_{2.5}$ with an average air quality index values (AQI) greater than 50 during pregnancy compared with AQI less than 50. Mothers with exposure to ambient $PM_{2.5}$ greater than 50 during the entire pregnancy were at increased risk of preterm birth (OR = l.15; CI = 1.07–1.25).

Wildfire Exposure and Reproductive Outcomes

Recent studies of health outcomes from wildfire exposure are particularly relevant to the link of reproductive outcomes with indoor air exposure, given the propensity for wildfire smoke to encroach into the home environment. $PM_{2.5}$ is a major constituent of wildfire smoke and is hypothesized to be associated with harmful reproductive effects, including preterm birth.

Heft-Neal et al. (2022) investigated the link between preterm births in California from 2006 to 2012 and satellite-based estimates of wildfire plume boundaries and high-resolution gridded estimates of surface $PM_{2.5}$ concentrations. They reported that each additional day of exposure to any wildfire smoke during pregnancy was associated with an 0.49 percent (95% CI = 0.41–0.59%) increase in risk of preterm birth (<37 weeks). The increased risk suggested stronger associations with exposure later in pregnancy. Surprisingly, the health impact differed greatly by baseline smoke exposure, with mothers in regions with infrequent smoke exposure experiencing substantially larger impacts than mothers in regions where smoke is more common. Wildfire exposure and adverse pregnancy outcomes were also investigated by Abdo et al. (2019) using ground-based monitors and remote sensing data stratified by ZIP code. Exposure to wildfire smoke $PM_{2.5}$ over the full gestation and exposure during the second trimester were associated with pre-term birth (OR = 1.076; CI = 1.016–1.139). Exposure during the first trimester was associated with decreased birth rate (−5.7 g/(μg/m^3)).

Amjad et al. (2021) conducted a review of eight published studies from four countries that included almost 2 million births. Exposure was determined by multiple methods, including measurement of $PM_{2.5}$, PM_{10}, ozone, and hot spots. Overall, the results of this review have little utility for $PM_{2.5}$ given the inclusion of multiple exposures associated with wildfires. An integrative review of 16 studies between 2012 and 2022 of wildfire exposure and birth outcomes has been published. Eleven studies reported an association between in utero exposure and impacts on birth weight and length of gestation. A small number of studies focused on gestational diabetes and gestational blood pressure, differences in sex ratio, birth defects, and mental health morbidity (Evans et al., 2022).

Indoor Exposure to $PM_{2.5}$ and Reproductive Outcomes

The committee's review of indoor exposure to $PM_{2.5}$ and reproductive outcomes identified only one study, which was inconclusive. Shezi et al. (2022) reported on maternal exposure to indoor $PM_{2.5}$ and adverse birth outcomes in Durban, South Africa. They assessed several birth outcomes among 800 women, including birthweight, gestational age, low birth weight, and preterm delivery in this prospective study. The homes of 300 of the 800 pregnant people were monitored, with repeated sampling done in 30 homes. A predictive model was used to estimate $PM_{2.5}$ levels in unmeasured homes. The mean (SD) indoor $PM_{2.5}$ concentration was 37 (29) μg/m^3. The exposures in the indoor environment were attributed to a combination of 168 variables assessed during walkthroughs such as type of house, wall, roof and floor, number of residents, smoking, cooking, cleaning and candle use, mold and dampness, heating and ventilation characteristics, presence of windows, and nearby outdoor pollution generating activities. The odds ratio of low birth weight and preterm delivery was 1.75 (95% CI = 1.47–2.09) and 1.21 (95% CI = 1.06–1.39), respectively, per interquartile increase (18 μg/m^3) in indoor $PM_{2.5}$ exposure. Infant sex was found to be an effect modifier for both birthweight and gestational age.

DIABETES AND METABOLIC SYNDROME

Increasing attention has been directed to understanding how particulate matter inhaled by the lung induces effects in distant organs (Snow et al., 2018). The potential association between exposure to $PM_{2.5}$ and the metabolic syndrome is hypothesized to be linked to the neuroendocrine sympathetic–adrenal–medullary and hypothalamic–pituitary–adrenal stress axes. Animal models are being used to examine the effects of the neuroendocrine system associated with air pollution components, suggesting that chronic exposure to physiological stressors associated with air pollution may lead to increases in allostatic load, or the cumulative burden of exposure to chronic stressors. To date the studies have focused on outdoor air pollution, and reviews point to compelling evidence of a link between metabolic syndrome and exposure to air pollution. In a systematic review and meta-analysis of the association between long-term ambient PM exposure and metabolic syndrome risk, Ning et al. (2021) found that an increase of 5 $\mu g/m^3$ in annual average ambient $PM_{2.5}$ and PM_{10} concentration was associated with, respectively, a 14 percent and 9 percent increase in metabolic syndrome risk, and they suggested that approximately 12 percent of metabolic syndrome risk could be attributable to ambient $PM_{2.5}$ exposure.

Zheng et al. (2022) looked specifically at long-term exposure to $PM_{2.5}$ and the components of metabolic syndrome in over 6,000 adults and elderly in 14 districts in south China. They reported that a 10 $\mu g/m^3$ increase in the 2-year mean $PM_{2.5}$ exposure was associated with a higher risk of developing metabolic syndrome, elevated blood glucose level, and hypertriglyceridemia. More recent studies have attempted to partition the effects of exposure to particulate matter and the effects associated with lifestyle factors on the risk of diabetes or metabolic syndrome. For example, Li et al. (2022) conducted an analysis of the interplay between physical activity and air pollution in a large population-based cohort. UK Biobank participants ($n = 359{,}153$) without diabetes at baseline were followed for approximately 9 years, and type 2 diabetes was associated with increasing level of ambient $PM_{2.5}$. As expected, physical activity was associated with the likelihood of developing type 2 diabetes. There was no effect modification of the associations between physical activity and diabetes by air pollution, indicating that the beneficial effects of physical activity on type 2 diabetes remained stable regardless of the air pollution exposure levels. While the evidence of the link between exposure to $PM_{2.5}$ in outdoor air pollution is growing, to date there have been no studies of the link between $PM_{2.5}$ in indoor environments and the risk of diabetes or metabolic syndrome.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

While the literature varies in scope and depth, overall **the committee concludes that there is strong evidence that exposure to indoor $PM_{2.5}$ has adverse effects on the respiratory and cardiovascular systems and likely other organ systems**. Specifically, the epidemiologic evidence points to consistent dose–response relationships between indoor $PM_{2.5}$ exposure and respiratory and cardiovascular outcomes, and this evidence combined with toxicologic evidence and bolstered by the vast outdoor $PM_{2.5}$ literature directly implicates indoor $PM_{2.5}$ as a cause of adverse respiratory and cardiovascular effects. Furthermore, e**vidence for a role of indoor $PM_{2.5}$ in neurologic, metabolic, and reproductive outcomes is less well developed but emerging.** The absence of evidence should not be interpreted as indoor $PM_{2.5}$ not exerting adverse effects on other organ systems, and instead this gap in knowledge underscores the urgent need for more research. It can thus be concluded that **reducing $PM_{2.5}$ exposure would have a significant public health benefit.**

Compared with the evidence supporting the adverse health consequences of PM measured outdoors, there are fewer studies of health effects of PM measured indoors, and these have substantially smaller sample sizes. Indoor PM health studies are expensive and resource- and labor-intensive. Studies of outdoor PM often assign exposure from national air quality monitoring networks, sometimes adding granularity by spatiotemporal models, and link this to health claims data. These approaches take advantage of the investment that has been made in these data sources and allow studies that include larger sample sizes. This provides the ability to study relatively infrequent events, such as heart attacks and stroke, at the population level. The studies of indoor PM health effects have smaller sample sizes. This is expected, given the complexity of health studies of indoor PM, which require an assessment of exposures that are typically at the household, workplace, or individual level. These studies also require simultaneous evaluation of health outcomes. Given the smaller sample sizes and relatively short duration of follow-up of most studies, the health outcomes are usually ascertained at the individual level using questionnaires, physiologic measures, or biospecimens. As discussed in Chapter 5, recent advances in lower-cost air monitoring equipment have provided the opportunity to increase the scale of indoor PM studies. Studies are still relatively small and often lack statistical power to detect clinical events within a given individual, such as heart attacks or strokes.

Even though indoor PM studies are less common than outdoor PM investigations, outdoor air pollution studies are useful in understanding indoor health effects, because of the significant encroachment of outdoor pollution into indoor spaces, as described in Chapters 4 and 5. To date, studies of indoor $PM_{2.5}$ effects on less common health outcomes have been limited. Indoor studies are also limited in examining the relative importance of particular sources and composition and in identifying individual characteristics that confer susceptibility to indoor $PM_{2.5}$. Indeed, $PM_{2.5}$ mass concentration is a crude measure of airborne particles as it does not capture the multidimensional heterogeneity of fine particles, which includes attributes such as size, shape, composition, source (including particles of outdoor origin), and toxicity, as discussed in Chapter 5. Each of these attributes may influence where particles deposit, the dose of particles, and the biologic effects of the particles. Furthermore, certain characteristics may be more harmful to some people than others, depending on the nature of the particle characteristic and the susceptibility of the person to that characteristic (i.e., allergen containing particle). There is also a limited understanding of two other important topics: the contribution of inequities in indoor PM exposure (in terms of concentration as well as other particle characteristics) to health disparities and susceptible populations, and the health effects of $PM_{2.5}$ exposure at school, where a susceptible population (children) spend a significant amount of time. These knowledge gaps are important to address as they have direct implications for practical approaches to mitigating adverse health effects, including health disparities, of indoor PM, the subject of Chapter 7.

Recommendations

The recommendations offered by the committee are directly informed by the knowledge gaps described above. They are directed both to indoor air and particulate matter researchers and to EPA and other funders of such research.

The indoor environment research community should use emerging consumer-grade sensors and statistical modeling to estimate indoor and personal PM exposure at a larger scale to facilitate the conduct of large-scale population-based epidemiologic studies. Such studies are critical to advancing the understanding of (1) the effects of indoor PM on less common health outcomes and on health disparities; (2) the effects of particle characteristics—beyond mass concentration and including composition, size, shape, and sources—on health; (3) individual and population characteristics that confer susceptibility to indoor PM exposure or to certain "types" of indoor PM; and (4) the relative contribution of particles of indoor and outdoor origin to the health effects of PM exposure.

Relatedly, **the indoor environment research community should take better advantage of observational field studies that directly evaluate the effects of reducing $PM_{2.5}$ exposure on health.** Studies conducted under controlled circumstances offer great advantages to researchers in terms of time, effort, and the ability to manage the myriad potential influences on outcomes, but they yield an incomplete answer to what is perhaps the most salient issue for policy makers: does this resolve what happens in the real world? Advances in technology now permit investigators to gather information at a scale and with a degree of accuracy that was unthinkable only a few years ago. These advances need to be exploited, along with improved measurements to ascertain building and behavioral differences between settings that can affect the effectiveness of interventions.

The indoor environment research community should explicitly incorporate social science and behavioral health science perspectives and expertise in studies of the health impacts of indoor $PM_{2.5}$ to better understand how social, cultural, and behavioral factors may influence $PM_{2.5}$ exposure and health effects and the implementation of practical mitigation strategies. As this report makes clear, there are systematic differences in exposure to indoor PM and in susceptibility to adverse effects of that exposure that result in disparate health outcome risks for different populations. The research in this area is still relatively sparse, however, and much more needs to be done in order to formulate effective interventions. One straightforward way to address this gap would be to make consideration of social, cultural, and behavioral factors a standard element of studies by including people with such expertise in research teams.

EPA, in collaboration with other governmental entities and private funders, should incentivize schools to partner with the scientific community to conduct school-based prospective cohort studies. There is a glaring need for research that examines the indoor environment where children, adolescents, and young adults spend considerable amounts of their time. Such work will help advance the currently inadequate understanding of the sources and other attributes of school exposure to $PM_{2.5}$; its effects on health, learning, and school performance effects; and inequities in that exposure. The work will also help inform practical mitigation targets in school settings.

EPA, in collaboration with other governmental entities and private funders, should prioritize the funding of studies designed to characterize differences in indoor $PM_{2.5}$ exposure—including differences in $PM_{2.5}$ characteristics—in home and school settings across communities and their contribution to health disparities. As already noted, significant disparities exist in $PM_{2.5}$ exposures and exposure impacts. It will not be possible to identify and to formulate practical mitigation strategies for disproportionately affected populations until there is a clear understanding of who is affected by them and how their circumstances shape the determination of effective interventions.

The indoor air research community should support the conduct of studies that evaluate the full impact of policies on $PM_{2.5}$ exposure and health, including cost–benefit analyses that incorporate an estimate of the economic and public health costs of <u>not</u> implementing interventions. Governments must balance competing priorities when making policy determinations. Understanding the costs associated with inaction will allow for better informed decisions on the need for interventions regarding indoor $PM_{2.5}$ exposure and mitigation.

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7
Practical Mitigation Solutions for Indoor PM

Given the importance of fine particulate matter (PM) to human health (Chapter 6), and the exposures that occur in homes and schools (Chapter 5), there is a compelling need to develop approaches to reduce that exposure. Such mitigation must recognize the multitude of indoor and outdoor sources of fine PM (Chapter 3) and the building and occupants and other factors that affect the transport and removal of fine PM in indoor environments (Chapter 4). It must consider exposure disparities to fine PM and the resulting criticality of targeting mitigation to communities and individuals that are exposed to high levels of indoor fine PM or that have disproportionate negative health impacts from these exposures. And, important questions about availability, accessibility, and sustainability of fine PM mitigation measures for communities must be addressed.

This culminating chapter presents the results of the committee's consideration of these complex issues. It does not provide a how-to guide for practical mitigation, nor does it call for specific interventions to be implemented. Instead, it offers a critical review of the existing literature on the effects and effectiveness of various strategies, benchmarking what is and is not known today and offering recommendations regarding the way forward. The review is focused on indoor PM exposures commonly found in U.S. and does not address the mitigation of such sources as unvented biomass fuel burning for cooking or heating, which is a major source for some people living in low- and middle-income countries (EPA, 2023; WHO, 2022).

INTRODUCTION

Mitigation—as the term is used in this report—is not just the removal of fine PM from indoor air or the limiting or elimination of exposure to that PM. The committee's definition is broader, including considerations about the practicality of the mitigation measure such as its cost, feasibility, persistence, availability, co-benefits, negative secondary consequences and side-effects, barriers to implementation, and opportunities to address equity. The committee is critically concerned with questions of effectiveness that go beyond questions of concentration reduction to necessarily include those related to health effects.

The intent is to provide as complete a view as possible on the evidence basis for practical fine PM mitigation approaches. The specific process for locating and categorizing evidence is set forth below; the standard of evidence was high-quality investigations published in peer-reviewed journals. To be sure, there are limitations to this approach, including (1) the many practical fine PM mitigation approaches that have not been evaluated or were not part of a peer-reviewed journal article or else that have been evaluated for their impact on emissions, concentration, or exposure reduction but not health effects, (2) the large differences in the quantities of published papers on different practical mitigation approaches, (3) the large variation in the quality of investigations in the peer-reviewed literature, and (4) disparities in the populations and communities that have been part of mitigation investigations. These limitations are part of a much broader limitation: the overall small number of high-quality investigations of practical mitigation measures and the absence of any large-sample-size longitudinal investigations.

A key subtlety is inherent in this definition of mitigation. There is overwhelming evidence in the literature that a wide variety of mitigation approaches can reduce indoor concentrations of fine PM. There is also a clear logical chain that goes from reduced indoor concentrations as a result of mitigation (Chapter 4) to reduced exposure (Chapter 5) and to improved health outcomes (Chapter 6). There are two primary reasons why reduced concentrations are not used as the standard in this chapter. The first is that there are incomplete data that specifically link reduced indoor concentrations to specific health outcomes. The committee has a high degree of confidence when stating that reducing indoor fine PM concentrations is beneficial for a wide variety of health outcomes. It has a much lower degree of confidence in explicitly quantifying this effect. There are important nuances concerning particle size distribution and composition that are addressed elsewhere in this report (Chapter 5 in particular) that are almost always not characterized in the literature included in this chapter. The second reason is that the context for mitigation is often as important as the mitigation measure itself. The context here means the details of the environment or system in which the measure is used (Chapter 4 has considerable detail here), the population or community that uses that measure, and the practical details of implementation. As is the case with the first reason, the literature often incompletely characterizes this context. It is for these reasons that the major recommendations of this chapter are both (1) more complete research is needed that addresses contextual factors and (2) the need for this research should not prevent the application of fine PM mitigation measures.

This chapter addresses building- and individual-level fine PM mitigation measures. It explicitly excludes from its scope any measures to address outdoor fine PM sources (e.g., reducing traffic, mitigating industrial sources). Voluntary labeling programs and interventions based on building code changes are not addressed. While programs and codes that specified the installation of high-efficiency air filtering would help to signal the importance of this intervention, there is little evidence in the published literature regarding the effectiveness of such measures for particle reduction or the generation of health benefits, along with the challenges associated with their enforcement beyond their initial application at the time of construction or certification. Although some mitigation literature suggests that the primary health benefit of any mitigation measure comes from reducing indoor exposure to outdoor fine PM (e.g., Fisk, 2013), this may arise from the vast imbalance between the amount of literature and attention on outdoor versus indoor fine PM.

Furthermore, mitigation of outdoor PM tends to occur at a political and economic scale that is much larger than the scale considered here; this chapter focuses on mitigation at the building and personal level. It needs to be pointed out that although approaches to reducing outdoor PM should be part of any overall strategy to reduce indoor PM exposure, the cost and benefits of such approaches should always be considered in the context of the building- and individual-level mitigation measures discussed in this chapter. Although the committee is not aware of such analyses, a reasonable hypothesis is that smaller-scale measures are more likely to result in health benefits at a lower cost and may allow more targeting of measures for equity and other purposes. Further, the mitigation measures discussed here are practical in the sense that they are achievable by individuals or communities.

FRAMEWORK

Four specific practical mitigation measure categories are considered in this chapter, organized according to the hierarchy of controls:

1. Source control
2. Ventilation
3. Filtration and air cleaning
4. Personal protective equipment (PPE)

Source control measures either eliminate indoor sources (e.g., avoiding the use of candles, incense, fireplaces, etc.) or reduce the emissions of indoor sources or their toxicity (e.g., replacing unvented combustion with electrical heat sources). Ventilation measures include measures that dilute indoor air with outdoor air (e.g., natural or mechanical ventilation) and localized exhausts (e.g., kitchen range hood) that remove fine PM and other indoor air pollutants to outside. Air cleaning measures are those that remove fine PM from recirculated indoor air (e.g., central or portable filtration). PPE, in the context of airborne exposure, refers to clothing, equipment, or devices designed to be worn and reduce the intake of pollutants, such as masks and respirators. These categories are not always mutually exclusive (e.g., kitchen range hood ventilation primarily removes particles from a specific source, and ventilation systems often have integrated filtration, while mask or respirator use can also have an infectious disease source control benefit). So, although useful as a framework for considering the evidence for different mitigation approaches, a meaningful approach to practical mitigation will likely involve multiple intervention measures.

Each of these categories has a combination of inherent, building, and behavioral factors that influence their impact as a mitigation on fine PM (Table 7-1). Inherent factors are those that are intrinsic to the particular measure itself in terms of effectiveness for reducing $PM_{2.5}$ exposure. Building factors are those contextual factors from the indoor environment that influence the effectiveness of the measure. Behavioral factors arise from individual and building operator decisions about the use of such measures as well as from broad economic and social contexts. A central challenge that arises from much of the literature on fine PM mitigation interventions is that these contextual factors are often not assessed, and thus findings cannot always be generalized to other environments with different contexts.

TABLE 7-1 Mitigation Measures and the Contextual Factors that Influence Their Impact

Measure	Inherent Factors	Building Factors	Behavioral Factors
Source Control	• Emission rate • Emissions profile	• Energy availability and need • Indoor location of source	• Selection of emitting appliances • Activity/use
Ventilation	• Flow rate • Outdoor air fraction • Efficiency of filtration on ventilation air	• Proximity to sources • Air mixing in the building • Ambient fine PM (and other pollutant) concentration • Building/system capabilities • Operational timing	• User operation (e.g., range hood fans, open windows) • Maintenance of fans and other equipment
Filtration and Air Cleaning	• Filter efficiency • Flow rate	• Magnitude of other loss processes • Runtime (central)	• User operation and placement (portable) • Filter replacement and maintenance
Personal Protective Equipment (PPE)	• Efficiency • Fit	(not applicable)	• Use/compliance • Replacement • Time spent in proximity to source

LITERATURE REVIEW METHODOLOGY

The committee was charged to focus on practical intervention approaches for $PM_{2.5}$ indoors. As this topic has not been addressed in detail in previous National Academies reports on the indoor environment and health, the methodology underlying the literature search is presented here.

The search was conducted in Fall 2022 in the Science Citation Index using the set of terms listed in Table 7-2. These terms were established using an iterative process that was designed to be broad and inclusive of all relevant articles for which the committee was aware. In addition, a separate search was conducted in PubMed to capture additional articles, and committee members consulted their personal libraries to ensure as thorough an examination as possible. No strict date limitation was placed on the search, but the committee focused on the most recent work (generally speaking, papers published from 2010 onward) addressing the range of mitigation measures under consideration.

TABLE 7-2 Search Terms Used in the Review of Practical Mitigation Measures

(personal protective equipment OR PPE OR mask OR respirator) OR (source control OR source removal OR emissions reduction) OR (rangehood OR kitchen OR Ventilation OR ventilated OR air exchange rate OR air change rate OR airflow OR exhaust OR window OR HVAC OR mechanical ventilation) OR (filter OR filtration OR air cleaning)
(intervention OR trial)
(cardiovascular OR respiratory OR cognitive OR asthma)
(fine PM OR PM2.5 OR particulate OR ultrafine)
(indoor OR home OR school)

This process identified 471 articles. From this master list, the committee conducted a relevance assessment and classified papers into five categories:

1. Papers that addressed PM mitigation and a health outcome and that were relevant to one or more of the four mitigation measure categories (source control, ventilation, PPE, or filtration/air cleaning).[11] Owing to its charge and the guidance provided by the sponsor, the committee excluded papers that addressed cookstove combustion source control and direct assessments of environmental tobacco smoke (ETS) source control (e.g., smoking cessation), although a small number of papers that investigated reducing ETS through ventilation or filtration were assessed. Investigations from global environments with much higher ambient PM than is typically found in U.S. locations were included with the location of the investigation noted.
2. Papers that otherwise fit Category 1 but that did not address health effects (e.g., they focused on characterizing concentration or on exposure reduction).
3. Papers that otherwise fit Category 1 but that did not fit into one of the mitigation measure categories (e.g., they examine cookstove emissions but not emission mitigation).
4. Papers that addressed indoor PM but did not examine a health outcome or a mitigation strategy.
5. Papers that did not fit into an above category, such as, for example, a paper that was intended for a specific audience (e.g., clinicians) that addressed mitigation of fine PM but did not report research results.

For the first 100 papers, two committee members completed the categorization, and any differences were resolved and the approach standardized. The remaining 371 papers were categorized by at least one committee member. The primary focus was placed on Category 1 papers, but papers in categories 2–5 were included where they offer insight on topics not addressed in the Category 1 literature.

Following the categorization process, all Category 1 papers were identified by their primary (and secondary, if relevant) mitigation measure, and a committee member was assigned to each category to collect data on Category 1 papers including sample size, study population, study duration, building type, location, health outcomes considered, and findings. Following this

[11] As noted in Table 7-1, behavioral interventions are a part of all of these mitigation strategies and thus are not called out separately.

categorization, a committee member with health expertise separated the papers into different health endpoints to correspond with the discussion in Chapter 6.

An obvious initial finding is that there is a wide variation in the number of articles that address the different framework measures, with fewer than 10 articles on PPE, source control, and ventilation and (by far) the largest number of articles on filtration and air cleaning and specifically on portable filtration. Similarly, some populations and health effects have received disproportionate attention relative to others. As would be anticipated, there is a wide variety in quality metrics and study approaches, with almost all investigations being very short term. A consistent theme through most of the investigations is that the broader context is often not considered with much depth, which complicates assessments of measurement effectiveness and the generalizability of findings.

The literature search also identified a number of review papers (R. W. Allen and Barn, 2020; Cheek et al., 2021; Fisk, 2013; Kelly and Fussell, 2019; Morishita et al., 2015; H. Park et al., 2021; Rajagopalan et al., 2020; Sandel et al., 2010; Sublett, 2011; Walzer et al., 2020; Warner, 2017; Xia et al., 2021) that met the criteria for inclusion in Category 1. These papers were evaluated and included in the discussion where warranted. They were useful for identifying issues that arose in previous reviews as well as informing the recommendations from this chapter.

LITERATURE REVIEW RESULTS

This section discusses the literature examining mitigation of indoor PM exposure and health outcomes. It focuses on the most recently published papers and reports but reviews older research where relevant. Findings are grouped by practical mitigation measure category. The purpose of this examination is to highlight what is known about the effectiveness of various mitigation approaches along with the broad themes and gaps found in the course of the literature review. Mitigation efforts focused on limiting exposures to toxic substances are not addressed here; such interventions are examined in the National Academies' *Why Indoor Chemistry Matters* report (NASEM, 2022).

Table 7-3 summarizes the results of a selection of the studies considered by the committee, some of which are not otherwise addressed in the text. This table is grouped by health outcome. It is intended to illustrate the state of the literature and to summarize the findings of representative research efforts.

TABLE 7-3 Summary of Selected Studies Addressing Mitigation of Indoor PM Exposure, Grouped by Health Outcomes

Study	Location	Study Population and Sample Size	Mitigation Approach	Health Outcome[s] Resulting from Mitigation Approach
Children—General respiratory focus				
Singleton et al. (2018)	US: AK; homes	214 children ages 0–12	Source control and ventilation	Home remediation and education reduced respiratory symptoms, low respiratory tract infection visits, and school absenteeism in children with lung conditions.
Walker et al. (2022)	US & Navajo Nation: AK, AZ, MT, NM; homes	461 children ages 0–5	Filtration and air cleaning	No significant difference with education or HEPA air cleaner intervention on lower respiratory tract infections.
Children and young adults with asthma				
Noonan et al. (2017)	US: AK, ID, MT; homes	114 rural children ages 6–18	Filtration and air cleaning	Filter use resulted in $PM_{2.5}$ reduction: no treatment effect on Pediatric Asthma Quality of Life Questionnaire or other outcomes.
Phipatanakul et al. (2021)	US: Northeast; schools	236 elementary school age children	Filtration and air cleaning	No statistically significant improvement in asthma symptom days from HEPA filters.
Lee et al. (2020)	South Korea: Incheon and Gyeonggi-do; homes	30 elementary school age children	Filtration and air cleaning	Air cleaners associated with less frequent use of asthma medications. Asthma severity assessed by symptoms and medication use, lung function, airway inflammatory, and urine microbiome.
Kim et al. (2020)	South Korea: homes	26 children ages 6–11	Filtration and air cleaning	HEPA air filters reduced $PM_{2.5}$; lower $PM_{2.5}$ associated with reduction in peak expiratory flow rate, but no significant difference between filter and control groups.
H.-K. Park et al. (2017)	US: Fresno, CA; homes	16 children ages 6–18	Filtration and air cleaning	Improvement in childhood asthma control test scores, peak flow rates, nasal symptoms, but only statistically significant for self-reported nasal symptoms.
Cui et al. (2020)	China: Shanghai; homes	43 children ages 5–13	Filtration and air cleaning	Improvements in total airway resistance, small airway resistance, resonant frequency, small airway reactance, fractional exhaled nitric oxide, peak expiratory flow.

Study	Location	Study Population and Sample Size	Mitigation Approach	Health Outcome[s] Resulting from Mitigation Approach
Antonicelli et al. (1991)	Italy; homes	9 children and adults ages 10–28	Filtration and air cleaning	No improvements in symptom score or bronchial hyperresponsiveness with intervention. Dust mites may have been a factor as all participants were allergic to house dust mites.
James et al. (2020)	US: Cincinnati, OH; homes	43 children ages 5–13	Filtration and air cleaning	Asthma control and quality-of-life scores significantly improved following HEPA filter intervention.
Eggleston et al. (2005)	US: “inner-city” homes	100 children ages 6–12	Source control and filtration and air cleaning	Asthma daytime symptoms significantly increased in the control group and decreased in the treatment group. Other measures of morbidity, such as spirometry, nighttime symptoms, and emergency department use, were not significantly changed.
Moreno-Rangel et al. (2020)	US: McAllen, TX; homes	13 children ages 7–12	Filtration and air cleaning	Four survey tools used, including Home Environmental Personal Well-Being Survey, Pediatric Quality of Life Inventory Asthma Module (PedsQL), the Asthma Control Test, and Healthy Homes and Asthma Test. All surveys showed better health outcomes after intervention, but only the PedsQL showed a statistically significant improvement.
Sulser et al. (2008)	UK: homes	36 children ages 6–17	Filtration and air cleaning	No significant change in forced expiratory volume in 1 second (FEV_1) after cold air challenge or in the use of medication and serum eosinophil cationic protein levels. Trend observed in the active group towards an improvement of bronchial hyperresponsiveness (BHR), whereas the sham filter group showed a deterioration of BHR.
Jhun et al. (2017)	US: school	25 children ages 6–10	Filtration and air cleaning	Classroom $PM_{2.5}$ levels reduced compared to intervention control group; modest improvement in peak flow, but no significant changes in FEV_1 and asthma symptoms.
Thiam et al. (1999)	Singapore: homes	24 children ages 6–14 with asthma/dust mite sensitivity	Source control and filtration and air cleaning	Mattress covers improved FEV_1 and reduced diurnal peak expiratory flow rate; both mattress covers and HEPA filters improved mean symptom scores.

Study	Location	Study Population and Sample Size	Mitigation Approach	Health Outcome[s] Resulting from Mitigation Approach
Xu et al. (2010)	China: Beijing; homes	30 children ages 5–16	Filtration and air cleaning	As a measure of pulmonary inflammation, the exhaled breath condensate (EBC) nitrate concentrations decreased significantly, and the EBC pH and PEF values increased significantly with operation of the filtration and air cleaning unit.
Butz et al. (2011)	US: MD; homes	126 children ages 6–12	Filtration and air cleaning	Air cleaner intervention group experienced fewer days of asthma symptoms in homes that were in an inner-city and included a household smoker.
Grant et al. (2023)	US: MD; homes	155 children ages 5–17	Filtration and air cleaning	Multifaceted intervention, including air purifiers, did not change asthma medication use. Indoor PM concentrations were not significantly reduced with the intervention.
Lajoie et al. (2015)	Canada; homes	83 children	Ventilation	Intervention group showed significant decrease in average levels of formaldehyde, airborne mold spores, toluene, styrene, limonene, and α-pinene concentrations. There was no significant change in number of symptoms days/2-week period. However, there was a significant decrease in number of children experiencing wheezing episodes over 12-month period.
Kile et al. (2014)	US; homes	12,570 children ages 2–16	Ventilation	Found that children whose parents reported using ventilation when operating their stove had higher lung function and lower odds of asthma, wheeze, and bronchitis; it is not clear if the health benefits were due to fine PM reduction or other indoor air pollutants, such as NO_2.
Adults—General respiratory focus				
Yoda et al. (2020)	Japan: homes	32 healthy adults	Filtration and air cleaning	No statistically significant findings on respiratory or pulmonary function or fractional exhaled nitric oxide (FeNO), but indoor PM was not reduced with filtration.
Hansel et al. (2022)	US: homes	94 adults, former smokers	Filtration and air cleaning	Air cleaners improved respiratory symptoms: lower rate of moderate exacerbations and lower rescue medication use. Adherence to intervention was associated with greater magnitude of improvement. Air cleaner intervention did not significantly improve primary outcome of respiratory status, measured by St. George's Respiratory Questionnaire.

Study	Location	Study Population and Sample Size	Mitigation Approach	Health Outcome[s] Resulting from Mitigation Approach
Cui et al. (2018)	China: Shanghai; homes	70 non-smoking healthy adults	Filtration and air cleaning	Filtration significantly lowered airway impedance, airway resistance, and small airway resistance, reflecting improved airway mechanics especially for the small airways. However, no significant improvements for spirometry indicators (FEV_1, FVC) were observed. Filtration also significantly lowered von Willebrand factor (VWF) 24 h after the end of filtration, indicating reduced risk for thrombosis.
Francis et al. (2003)	UK: homes	30 adults with asthma + pets	Filtration and air cleaning	Beneficial clinical response observed in reduction in asthma treatment in 10/15 subjects in the active group compared with 3/15 in the control group after 12 months of intervention. No significant differences between the active and control groups were detected for changes in measures of lung function, reservoir pet allergen, or airborne pet allergen during the study.
Warburton et al. (1994)	UK: homes	12 adults with asthma	Filtration and air cleaning	No difference in subjective symptom scoring, spirometry, or bronchial reactivity demonstrated.
Skulberg et al. (2005)	Norway: offices	80 adults with airway symptoms	Filtration and air cleaning	Irritation and general symptom indices (acoustic rhinometry and peak expiratory flow) decreased in both groups, but there was no improvement in the intervention group compared with the control group.
van der Heide et al. (1997)	The Netherlands: homes	45 adults with asthma/allergies	Source control and filtration and air cleaning	Statistically significant improvement of provocative concentration of histamine only in group with both mattress cover and filter. Dust and dust-mite allergen collected in filter was significantly correlated with improvement in peak flow variation.
Allergic diseases				
K. H. Park et al. (2020)	South Korea: homes	44 adults with house dust mite–induced allergic rhinitis	Filtration and air cleaning	For allergic rhinitis, medication scores improved significantly, while subjective measures (symptoms, visual analog scale, and quality-of-life scores) did not differ.
Stillerman et al. (2010)	US: homes	35 adults with perennial allergic rhinoconjunctivitis	Source control and filtration and air cleaning	Significant improvements in nocturnal nasal and ocular allergy symptoms and quality of life for the active vs. placebo device.

Study	Location	Study Population and Sample Size	Mitigation Approach	Health Outcome[s] Resulting from Mitigation Approach
		(dog, cat, or dust mite sensitivity)		
Jia-Ying et al. (2018)	China: Guangzhou; homes	32 children and adults with allergic rhinitis	Filtration and air cleaning	HEPA filtration was associated with improvements in activity limitation, non-nasal-eye symptoms, practical problems, and nasal symptoms via the Rhinitis Quality of Life Questionnaire.
Wood et al. (1998)	US: homes	35 adults (cat-allergic)	Filtration and air cleaning	No differences in morning, afternoon, or nighttime nasal-symptom scores, chest-symptom scores, sleep disturbance, morning or afternoon peak-flow rates, or rescue medication use.
Reisman et al. (1990)	US: homes	32 adults with perennial rhinitis and/or asthma + dust-mite-positive skin test	Filtration and air cleaning	No difference in the total symptom/medication scores or individual symptom scores during the placebo and active-filter periods over the full study period. Analysis of the last 2 weeks of each filter period in which respiratory infection was absent demonstrated definite differences in total and individual symptoms, suggesting active-filter benefit. Patients' subjective responses also suggested benefit from the filter.
Adults—Cardiovascular diseases				
Day et al. (2018)	China: Hunan Province; offices and dormitories	89 healthy adults	Filtration and air cleaning	No statistically significant findings from electrostatic precipitator (ESP) alone. ESP+ HEPA: change in plasma-soluble P-selectin and a −3.0% change in systolic blood pressure, suggesting reduced cardiovascular risks.
Padró-Martínez et al. (2015)	US: MA; homes	20 adults living near highway	Filtration and air cleaning	Blood pressure, high sensitivity C-reactive protein (hsCRP), interleukin-6 (IL-6), tumor necrosis factor alpha-receptor II (TNF-RII) and fibrinogen levels assessed. Il-6 concentration higher; no statistically significant change in all other tested parameters.
L.-Y. Lin et al. (2011)	Taiwan: homes	60 young healthy university students	Filtration and air cleaning	Blood pressure and heart rate elevated in subjects with no filter.

Study	Location	Study Population and Sample Size	Mitigation Approach	Health Outcome[s] Resulting from Mitigation Approach
Karottki et al. (2013)	Denmark: Copenhagen; homes	48 non-smoking senior adults, some taking vasoactive drugs	Filtration and air cleaning	No statistically significant effects of filtration as category were observed on microvascular and lung function or the biomarkers of systemic inflammation.
S. Liu et al. (2018)	China: Beijing; homes	35 non-smoking senior adults	Filtration and air cleaning	Benefits of cardiovascular of short-term air filtration intervention included reduction in SDNN[12] during filtration, further effects of black carbon, 12-hour daytime ambulatory heart rate variability and blood pressure.
Chuang et al. (2017)	Taiwan: Taipei; homes	200 adult "homemakers"	Filtration and air cleaning	Improvements in systemic inflammation, oxidative stress and elevated blood pressure.
Bräuner et al. (2008)	Denmark: Copenhagen; homes	42 adults living in proximity to major roads	Filtration and air cleaning	Indoor air filtration significantly improved microvascular function (MVF–biomarker of inflammation). MVF was significantly associated with personal exposure to iron, potassium, copper, zinc, arsenic, and lead in $PM_{2.5}$.
Eom et al. (2022)	South Korea: homes	38 adults with coronary artery disease	Filtration and air cleaning	Improved baroreflex sensitivity, and decrease in the indicator of oxidative stress represented as 8-hydroxy-2′-deoxyguanosine. Blood pressure, heart rate variability, baroreflex sensitivity, autonomic function test results, and endothelial function tested.
Morishita et al. (2018)	US: Detroit; homes	40 non-smoking elderly adults in low-income housing	Filtration and air cleaning	Decreased brachial systolic and diastolic blood pressure; improvements in aortic hemodynamics, pulse-wave velocity, and heart rate variability measures.
Langrish et al. (2012)	China: Beijing; walking outdoors	98 adults with coronary artery disease	Personal protective equipment (PPE)	12-lead electrocardiography for 24-hour period showed reduced symptoms, reduced maximal ST depression, reduced blood pressure and improvement in heart rate variability.
Vieira et al. (2016)	Brazil: São Paulo;	26 adults with heart failure and	Filtration and air cleaning	In patients with heart failure, diesel exhaust (DE) adversely affected reactive hyperemia index; 6-minute walking test; O_2 pulse; and arterial stiffness. Compared

[12] Standard deviation of NN intervals

Study	Location	Study Population and Sample Size	Mitigation Approach	Health Outcome[s] Resulting from Mitigation Approach
	exposure chamber	15 control adults		with DE exposure, filtration reduced particulate concentration, and was associated with an increase in VO_2 and O_2, an improvement in reactive hyperemia index, and a decrease in B-type natriuretic peptide. In both groups, DE decreased the 6-min walking distance and arterial stiffness, although filter did not change these responses. DE had no effect on heart rate variability or exercise testing.
Han et al. (2021)	China: Tianjin; walking outdoors	39 healthy university students	PPE	Short-term exposure to traffic acutely affected blood pressure, heart rate, and heart rate variability, but N95 mask and powered air-purifying respirator interventions generally showed little efficacy in reducing these effects.
Shi et al. (2017)	China: Shanghai; respirator use	24 healthy young adults	PPE	48-hour respirator use resulted in lower blood pressure and increases in heart rate variability parameters.
Liu et al. (2021)	China: Beijing; college dormitories	56 healthy college students	Filtration and air cleaning	Increases in $PM_{2.5}$ and negative ion exposure independently associated with increased urinary concentration of malondialdehyde, a biomarker of systemic oxidative stress, resulting in a null net effect of negative ion air purifier (NIAP) on malondialdehyde. No significant net effects of NIAPs observed for other outcomes indicative of lung function, vascular tone, arterial stiffness, and inflammation.
Lin et al. (2013)	Taiwan: Taipei; homes	300 healthy adults	Ventilation	Increases in cardiovascular endpoints and decreases in heart rate variability were associated with increased indoor particle concentration and window opening, while no significant changes in cardiovascular endpoints were observed when windows were closed and AC was on.
Biomarker studies				
Brugge et al. (2017)	US: Boston & Chelsea, MA; homes	23 low-income Puerto Rican adults; skewed female and elderly	Filtration and air cleaning	No intervention benefit in terms of reduced inflammation; associations between inflammation biomarkers hsCRP, IL-6, or TNFRII in blood samples, and associations with indoor particle number concentrations (PNC) were inverse and not statistically significant.

Study	Location	Study Population and Sample Size	Mitigation Approach	Health Outcome[s] Resulting from Mitigation Approach
Kajbafzadeh et al. (2015)	Canada: British Columbia; homes	83 healthy adults in traffic- or woodsmoke-affected areas	Filtration and air cleaning	Endothelial function and biomarkers of systematic inflammation showed an increase in C reactive protein per interquartile range increase in indoor $PM_{2.5}$, only in traffic-affected locations, not woodsmoke-affected locations.
R. W. Allen et al. (2011)	Canada: British Columbia; homes	45 healthy adults	Filtration and air cleaning	Air filtration associated with improved endothelial function and decreased concentrations of inflammatory biomarkers but not markers of oxidative stress.
Li et al. (2017)	China: Shanghai; dormitories	55 healthy college students	Filtration and air cleaning	Significant increases in cortisol, cortisone, epinephrine, and norepinephrine. Between-treatment differences were also observed for glucose, amino acids, fatty acids, and lipids.
Chen et al. (2018)	China: Shanghai; dormitories	55 healthy college students	Filtration and air cleaning	Randomized crossover trial of a sham versus true air filtration intervention and estimated associations with time-weighted $PM_{2.5}$ indoor and outdoor exposures. Higher $PM_{2.5}$ exposure positively associated with the expression interleukin-1 (IL1), IL6, tumor necrosis factor (TNF), toll-like receptor 2 (TLR2), coagulation factor 3, and endothelin 1 (EDN1), and negatively associated with miRNAs (miR-21-5p, miR-187-3p, miR-146a-5p, miR-1-3p, and miR-199a-5p) predicted to target mRNAs of IL1, TNF, TLR2, and EDN1.
Yang et al. (2022)	China: Beijing; schools	125 children ages 9–12	Filtration and air cleaning	27 biomarkers tested. Air cleaner intervention associated with decreases in fractional exhaled nitric oxide, exhaled breath condensate IL-1β, and IL-6.
Wen et al. (2022)	China: Beijing; dormitories	54 healthy college students	Filtration and air cleaning	38 inflammatory cytokines tested. No significant alteration in cytokines observed under air filtration intervention.
Cognitive function				
Gignac et al. (2021)	Spain: Barcelona; schools	2,123 high school students ages 13–16	Filtration and air cleaning	No differences found in the median of cognitive attention test (Flanker task) hit reaction time standard error (HRT-SE) between classrooms with cleaned air and normal air.

Study	Location	Study Population and Sample Size	Mitigation Approach	Health Outcome[s] Resulting from Mitigation Approach
B. Du et al. (2022)	Canada: Toronto; simulated office	59 healthy university students	Source control	Exposure to essential oil emissions caused shortened reaction time at the cost of significantly worse response inhibition control and memory sensitivity, indicating potentially more impulsive decision making. Effect of scented lemon-oil and non-scented grapeseed oil were similar.
More than one category of health outcome				
Guo et al. (2021)	China: Chongqing; nursing home	24 healthy older adults	Filtration and air cleaning	Air filtration associated with significantly decreased concentrations of inflammatory and coagulation biomarkers, but not of biomarkers of oxidative stress and lung function.
Zhao et al. (2020)	China: Beijing; homes	29 healthy young adults	Filtration and air cleaning	Blood pressure, pulmonary function, fractional exhaled nitric oxide, circulating biomarkers tested. Statistically significant improvements in most measured effects.
Shao et al. (2017)	China: Beijing; homes	35 non-smoking senior adults	Filtration and air cleaning	Filtration lowered PM and systemic inflammation (IL-8); no other demonstrable changes in the cardio-respiratory outcomes of study interest.
Wang et al. (2021)	China: Beijing; dormitories	57 healthy students	Filtration and air cleaning	Increased blood pressure and airway inflammation, and decreased lung function associated with specific phthalic acid esters. Compared with sham air purification, average diastolic blood pressure, fractional exhaled nitric oxide, and 8-isoprostane (8-isoPGF2α) levels decreased significantly in the real purification. The effects of indoor air purification on lung function indicators including forced expiratory volume in one second (FEV_1), peak expiratory flow (PEF), and forced expiratory flow were also significant.
Chen et al. (2015)	China: Shanghai; dormitories	35 healthy college students	Filtration and air cleaning	Air purification significantly associated with decreases in geometric means of several circulating inflammatory and thrombogenic biomarkers. Furthermore, systolic blood pressure (BP), diastolic BP, and fractional exhaled nitrous oxide were significantly decreased. The impacts on lung function and vasoconstriction biomarkers were beneficial but not statistically significant.
Weichenthal et al. (2013)	Canada: southern Manitoba; homes	37 First Nations adults	Filtration and air cleaning	Lung function, blood pressure, and endothelial functions measured. Air filter use was associated with an increase in forced expiratory volume in 1 s, a decrease in systolic blood pressure, and a decrease in diastolic blood pressure.

Study	Location	Study Population and Sample Size	Mitigation Approach	Health Outcome[s] Resulting from Mitigation Approach
Dong et al. (2019)	China: Beijing; schools	44 children ages 11–14	Filtration and air cleaning	Cardiorespiratory metrics showed an increase in forced exhaled volume in 1 s and a decrease in fractional exhaled nitrogen oxide. However, heart rate variability was altered negatively.
Johnston et al. (2013)	Australia: Launceston & Hobart; ambient	67,000 Launceston residents, intervention, & 148,000 Hobart residents, controls	Source control	Before and after intervention, PM_{10} levels dropped in intervention city, with small, non-significant reductions in annual mortality. In males, mortality reduction significant for all-cause, cardiovascular, and respiratory.
Karottki et al. (2013)	Denmark: Copenhagen; homes	48 non-smoking senior adults, some taking vasoactive drugs	Filtration and air cleaning	No statistically significant effects of filtration were observed on microvascular and lung function or the biomarkers of systemic inflammation among all subjects or in the subgroups taking or not taking vasoactive drugs. However, the filtration efficacy was variable and microvascular function was significantly increased within 2 days with the actual $PM_{2.5}$ decrease in the bedroom, especially among subjects not taking any drugs.
Jiang et al. (2021)	China: Beijing; walking outdoors	52 healthy college students	PPE	N95 use while walking outdoors improved lung function, reduced nitrate in exhaled breath condensate (reduced respiratory oxidative stress), and reduced serum inflammation biomarkers; effect was stronger during higher pollution conditions.

Source Control

Source control via elimination or substitution is, when feasible, the best line of defense against exposure, following recommendations on the hierarchy of controls. Elimination may be accomplished by removing a source or relocating the exposed people. As demonstrated in Figure 5-1, mitigating at the source prevents the downstream transport, transformation, and contact processes that result in exposures and health effects. The co-benefits typically extend beyond fine particle reduction, by including the removal of other gaseous and particle components emitted by the source.

Examples of source-control measures at the policy and behavior level are siting a school away from busy roadways, providing residents with access to clean air shelters during wildfires, electrifying heating and cooking in homes, electrifying school buses, banning the use of candles in schools, and enacting regulatory bans or incentives to reduce the use of high-emitting materials or devices (details about these sources are in Chapter 3), along with the banning of smoking in indoor environments (e.g., Repace, 2004). Examples of programs that incentivize innovation and behavior change are the Biden-Harris administration Net-Zero Game Changers initiative (OSTP, 2022), Green Building certifications that address fine PM or programs to educate consumers to drive the use of cleaner options and discourage the use of elective or recreational sources such as candles and incense.

Another class of solutions involves engineering a product or appliance to have a lower emission rate or less toxic emissions (as described in Chapter 3). Either primary or secondary emissions may be targeted. For instance, secondary sources are targeted by designing cleaning products without terpenes or vacuum cleaners that reduce the reservoir of dust and allergens available for resuspension or by using hard flooring instead of carpet. Disinfectants or materials that suppress the growth of dust mites or other allergens can reduce the bioactivity of a source, rather than targeting emissions on a bulk quantitative basis. However, safety regulations mandating limits on or disclosures for particle or precursor emissions from (or amounts of toxic chemicals contained in) consumer equipment are limited. When they exist, the onus is on the consumer to demonstrate harm.

Policy-level measures have the advantage of influencing large populations in a cost-effective manner. They can be targeted to address equity considerations or specifically to address marginalized and susceptible populations, and they can have benefits that persist over time. However, while individuals and communities can advocate for them, they require a political and budgetary coordination that typically takes time, and they are vulnerable to being influenced by special interest groups and systemic bias. Measures relying on individual behavior change have the advantage of being immediately available. Their accessibility depends on cost, and the persistence of benefits relies on continued use. A practical barrier is access to reliable data and recommendations to guide behavior and purchasing decisions, especially in cases where a decision involves a comfort or aesthetic trade-off.

The design and selection of a source-control strategy is dependent primarily on the type of source it is directed toward. The range of sources and their characteristics were reviewed in Chapter 3. The attributes considered were: Are the emissions continuous or intermittent? Is the source primary or secondary? Is it bioactive or biologically inert? How toxic are the emitted particles? Are marginalized and susceptible populations disproportionately exposed?

The practicality of a source-control measure depends on how readily it can be deployed, whether it is feasible for an individual or requires collective action or product reengineering, and also on the relative effort that would be needed to employ downstream measures such as ventilation and filtration to mitigate the resulting exposures and health effects.

The evidence base for source-control measures that demonstrably reduce adverse health impacts is slim for the range of sources that are within the scope of this review. The vast majority of papers in the literature review that presented a source-control strategy addressed either biomass cookstoves used in rural settings in lower- or middle-income countries or environmental tobacco smoke. The single study (Noonan et al., 2017) that met the review criteria had inconclusive findings. The authors evaluated asthma-related outcomes among children in homes using biomass combustion for residential home heating in rural and periurban areas in the United States. The effects of replacing a wood stove with an Environmental Protection Agency (EPA)-certified, improved-technology wood-burning appliance and of implementing an air filter were evaluated. The results indicated that the air filters, but not the improved stoves, resulted in lowered $PM_{2.5}$ and an improvement in one of the secondary health outcomes tested. Neither intervention resulted in improved quality-of-life measures. Johnston et al. (2013) also evaluated the effect of a wood heater replacement program on multiple health outcomes, but the relevance of their findings is limited because of the lack of indoor air quality data.

A related evidence-base that was not systematically reviewed but that indirectly points at the benefits of source control includes studies on source-specific health effects. Chapters 3 and 6 present studies where the existence of a source was strongly associated with specific health effects, so that it is reasonable to conclude that removing those sources would mitigate the adverse outcomes. As an example, in a controlled exposure study with 34 female and 25 male adults in a simulated office, B. Du et al. (2022) presented evidence of the cognitive impacts of essential oil emissions. Outcomes studied included reasoning, response inhibition, memory, risk taking, and decision making. Essential oil diffuser particle emissions caused shortened reaction time at the cost of significantly worse response inhibition and memory sensitivity, indicating potentially more impulsive decision making. The effects of scented lemon-oil and unscented grapeseed oil were similar. Studies of this nature can be used to infer the health benefits anticipated from eliminating or replacing specific sources.

A challenge associated with this review is that it excluded studies describing exposures that were not clearly attributed to the fine particle fraction as well as nonspecific interventions that included source control among a range of other measures. As a result, hygiene measures such as integrated pest management to reduce exposures to pests, pest control agents, and microbial products and efforts to reduce the use and generation of toxic chemicals such as phthalates and metals for which inhalation of airborne fine particles is one of the exposure routes are not reviewed in depth, in spite of their importance. Though excluded from the literature review on these grounds, studies showing the improvement of symptoms from the reduction of allergens do translate to broad-scale recommendations for household behaviors.

Ventilation

Improving building ventilation has been a component of healthy home and other building interventions. Lajoie et al. (2015) found that installing of mechanical ventilation in homes of children with asthma significantly reduced their symptoms. A 2017 literature review by Fisk and Chan found that increased ventilation rates were associated with reduced respiratory health effects and student absences. Review studies (Jacobs et al., 2010; Sandel et al., 2010) generally found evidence to indicate that some measures of interventions have health benefits through reducing occupant exposures to indoor air pollutants. However, the measures that are most likely to affect indoor fine PM exposures, such as building ventilation and envelope sealing, require more field evaluation and research to show their effectiveness. Similarly, a review by Fisk et al. (2020) on the impacts of residential energy efficiency retrofits with IEQ, comfort, and health found that there are too few studies (only three were identified that met the inclusion criteria) that measured changes in indoor particle concentrations pre and post retrofits.

Some studies have reported on the impacts of building ventilation on indoor concentrations of fine PM (Kang et al., 2022; Singer et al., 2017; H. Zhao et al., 2021). However, the committee's review identified only one U.S. study that evaluated the health outcomes. Singleton et al. (2018) studied the impact of home remediation and household education on indoor air quality, respiratory visits, and symptoms in Alaska Native children. The home remediation included improving ventilation (passive vents, bathroom fans, or range hoods in 98 percent of homes) and other measures: replace old leaky woodstoves with more efficient, EPA-certified models (47 percent), fixing or replacing oil-fired furnaces (23 percent), and addressing moisture issues (10 percent). Environmental health professionals provided home-based education about indoor air quality (IAQ) using discussions and informational pamphlets about the proper use of home ventilation systems, burning dry wood, gasoline storage, using best household cleaning practices, and smoking outside the home. Three months after the interventions, a respiratory therapist or case manager made an in-home visit to provide education on respiratory triggers, asthma medication use, and medication compliance. Overall, parents reported decreases in symptoms after remediation. Children had an age-adjusted decrease in lower respiratory tract infection (LRTI) visits. Singleton et al. (2018) concluded that home remediation and education reduced respiratory symptoms, LRTI visits, and school absenteeism in children with lung conditions. However, short-term IAQ monitoring (1 to 4 consecutive days) that was repeated three times (2 weeks before, 2 weeks after, and 12 months after the remediation) found decreases in total volatile organic compounds (VOCs) and benzene, toluene, ethylbenzene, and xylenes, but no changes in $PM_{2.5}$.

One study in Taipei focused solely on ventilation as the mitigation strategy (L.-Y. Lin et al., 2013). It recruited 300 healthy subjects, and their exposures to PM and total VOCs were monitored under three conditions: windows open, windows closed, and windows closed with air conditioning on. During each of the 24-hour monitoring periods, participants stayed home and refrained from combustion activities. Under these prescribed experimental conditions, the study found that in-home exposure was associated with inflammation, oxidative stress, blood coagulation, and autonomic dysfunction. By closing windows and turning on air conditioning (and under the case where there was no combustion indoors), this study concluded that improvements in cardiovascular health could be expected. However, findings from this study may not apply in conditions where the mixture of indoor and outdoor sources of PM is different and, in particular, in locations with low ambient PM.

Because ventilation will not only alter indoor exposure to fine PM but also change the concentrations of other indoor air pollutants (such as VOCs), intervention studies cannot easily pinpoint the observed health outcomes with fine PM alone. For example, Kile et al. (2014) evaluated the association between ventilation of gas stoves and chronic respiratory illness in U.S. children enrolled in NHANES III. Even though the study found that children whose parents reported using ventilation when operating their stove had higher lung function and lower odds of asthma, wheeze, and bronchitis, it was not clear if the health benefits were due to reductions in fine PM or in other indoor air pollutants, such as NO_2.

The role of ventilation in mitigating the risk of airborne infectious transmission has recently been reviewed (Allen et al., 2021; Fox et al., 2021). Several studies point to the potential effectiveness of ventilation (and filtration) in reducing infection risk in classrooms (Buonanno et al., 2022; Gettings, 2021; Muecke et al., 2006). Despite the general consensus that more ventilation is beneficial for infectious disease outcomes, there is a need for more deliberate considerations on ventilation metrics and acceptable risk for different building types and their occupants. Studies that gather sufficiently detailed data about ventilation and other building factors when testing the effectiveness of mitigation could also help inform this discussion. The 2023 recommendations from the Centers for Disease Control and Prevention (CDC, 2023) to aim for at least effective five air changes per hour and in ASHRAE Standard 241(ASHRAE, 2023) are based on the principle that more ventilation will lower infection risk from reducing exposure to potentially infectious respiratory aerosols, though in practice the effectiveness of increasing ventilation will depend greatly on the existing conditions of a given building. Further, increasing ventilation in the absence of filtration or available thermal conditioning will increase the indoor exposure to fine PM of outdoor origin as well as increase the risk of overheating during extreme heat events. The intersection between ventilation and energy use is particularly important as conditioning of ventilation air often drives building energy use.

Filtration and Air Cleaning

Air cleaning as a mitigation measure for fine PM has a relatively short history (less than 70 years) for use with fine PM (Burroughs, 2020), and the formal study of the health effects of air cleaning measures has an even shorter history. There are a variety of scales for air cleaning of fine PM (e.g., central, room, personal) and a variety of technologies (e.g., media filtration, ionization, electrostatic) which are summarized elsewhere (e.g., Siegel, 2016); however, almost all of the published literature that met the criteria for inclusion in this review focused on room filters that use media filtration (e.g., HEPA filters). Background and contextual information on other scales of air cleaning and other technologies are included here for completeness and to guide their potential inclusion in fine PM mitigation efforts in the future.

Room air cleaners for fine PM are devices that have two general mechanisms: something that moves air (usually a fan) and something that removes fine PM from the air. By far the most common instantiation is a portable unit that contains a high-efficiency particulate air (HEPA) filter and a fan. Room air cleaner performance is best described by a clean air delivery rate (CADR, often standardized according to the American National Standards Institute/Association of Home Appliance Manufacturers AC-1 standard), which is the product of the filter efficiency for fine PM and the air flow rate through the filter. Both of these parameters are independently important. An air cleaner that has a small flow rate cannot be an effective air cleaner, even if it has a high single-pass removal efficiency, simply because it does not treat enough air to compete with other loss mechanisms (namely deposition and ventilation, see Chapter 4). Similarly, an air cleaner that has a low efficiency for fine PM will not provide a competitive removal sink. A room air cleaner will be less effective for removal of fine PM in a larger room and will also be less effective in a room with more ventilation because of competition with other loss processes for fine PM. There are a variety of sizing practices for room air cleaners, including an effective floor area defined in the Association of Home Appliance Manufacturers standard (AHAM, 2020) and a total removal from all loss mechanisms, including room filtration, for reducing risk of transmission of infectious disease (e.g., the recommendation of five effective air changes per hour to reduce transmission of COVID-19 from the Centers for Disease Control and Prevention (CDC, 2023)).

How well a room air cleaner performs at removing fine PM is highly variable between environments (because of building contextual factors described above) and over time for the same air cleaner (e.g., Barkjohn et al., 2021; Pei et al., 2020). Some of the major factors behind this variability are declines in efficiency or flow rate owing to particle loading (e.g., Pei et al., 2020), placement especially relative to source (e.g., Dai and Zhao, 2022; He et al., 2021; Novoselac and Siegel, 2009), short circuiting and room mixing issues (locally cleaning the air near the air cleaner more than the broader room), user behavior (turning air cleaner to a lower speed, turning off, or moving to edge of room, especially in response to noise) (e.g., L. Du et al., 2011), and the dynamic nature of indoor sources and indoor penetration of outdoor particles (Chapter 3). Importantly, the CADR of room air cleaners is generally highest on the highest fan speed setting, which is also generally when the air cleaner produces the most noise (Peck et al., 2016). A critical consideration of almost all of the articles about portable air cleaners in this review is that this context is not assessed and therefore the results often reflect the unknown context of the research setting and time of experiments.

Fundamentally, the fine PM removal performance of air cleaning installed in a central system is the product of flow rate and removal efficiency and is subject to the same building contextual factors as room air cleaning (namely, competition with background loss rates; see, for example, Alavy and Siegel, 2020). Also, similar to room air cleaners, many charged media central air cleaning filters change in performance over time because of loading (Lehtimaki et al., 1994; Li and Siegel, 2020a) or because of declines in flow (Alavy and Siegal, 2019). There are also some fundamental differences from room air cleaners, factors such as bypass related to gaps around the filter (Li and Siegel, 2020a,b), interactions between air face velocity and efficiency (Hanley et al., 1994), and air flow control for conditioning and ventilation in variable air volume and multiple-speed systems.

Both room and central air cleaners can use other cleaning strategies besides media filtration. Generally, the most common class includes electrically connected air cleaners, which include a variety of technologies (often inconsistently named between manufacturers) including bipolar and unipolar ionization, plasma, and polarized media, among other technologies. Ionization is the most common, with some devices intentionally releasing ions into the air for a purported perception benefit or to increase deposition onto room surfaces, others charging particles and removing them to oppositely charged plates in the device (often called an electrostatic precipitator or electronic air cleaner), and others using ions to enhance removal to a conventional media filter. Many of these approaches have a variety of performance issues ranging from low CADRs (e.g., Waring et al., 2008), degradation in performance over time due to loading (e.g., Zuraimi et al., 2017), as well as the potential negative health effects associated with ions (W. Liu et al., 2021). Some electrically connected air cleaners also emit ozone, a respiratory hazard and chemical oxidant which can lead to a variety of compounds with potentially negative health outcomes, increased concentrations of odorous or irritating compounds, and increased concentrations of fine PM through secondary organic aerosol (SOA) formation. Although in general there are very few studies in the literature review that evaluated these technologies in the context of specific health effects, the precautionary principle should be followed. In particular, the production of primary (e.g., ions or ozone) or secondary (e.g., SOA or gas-phase byproducts) emissions should be avoided until deemed safe.

No matter the scale or type of air cleaning, there are common factors that affect that practicality of air cleaning measures. Common issues include cost (both initial cost as well as replacement filter costs), electricity use/cost (and specifically, the perception of high energy use), noise, negative outcomes from loading or the lack of maintenance (e.g., increased emissions from used/dirty air cleaners, diminished performance because of flow or efficiency degradations), and aesthetics, among other factors. Many of these issues translate to phenomena and behaviors that diminish the effectiveness of air cleaners over time, and this points to a potential bias that results from short study periods in many of the investigations in the literature review because air cleaners likely have a high initial effectiveness and also points to the importance of the messaging for study participants concerning the benefits of air cleaning and effective air cleaner use. Such messaging is rarely described and is an important area for future efforts (see recommendations). Given the importance of these contextual factors, it is unclear whether the generalizability of the findings of any individual investigation on the health effects of air cleaning apply to any other application, particularly if the results are not contextualized with metadata on the air cleaner, building, and behavioral aspects of the air cleaner's use. However, the existing literature is worth exploring for the identification of general benefits of air cleaning and benefits for specific populations as well as specific opportunities for application and needs for future research.

Of the four areas considered in this review, air cleaning as a mitigation measure has by far the most research. This review identified 55 articles that met the criteria for inclusion in the literature review (Table 7-3) and addressed air cleaning. The very big picture of this literature is that there is clear evidence that air cleaning is an effective mitigation measure for fine PM. However, there is also considerable variation in findings between studies and within studies for multiple health outcomes. Much of the inconsistency arises from the consideration of different health outcomes, variations in study designs, variations in study populations, and, critically, the often unassessed contextual factors described above. Each of these larger categories is discussed below, with a broader view towards practical guidance on air cleaning mitigation for fine PM that can be made based on available evidence as well as towards identifying areas for future research.

Table 7-3 divides health outcomes into broad groupings. One of the largest health outcomes investigated in the literature in response to an air cleaning intervention is childhood asthma. All investigations consider portable air cleaning generally with HEPA filters. Although there is encouraging evidence that filters improve at least one of the studied parameters, in all but two (Antonicelli et al., 1991; Phipatanakul et al., 2021) of the 16 included investigations have decidedly mixed evidence, with over half showing no improvement for at least one of the considered outcomes. Many of the investigations are a few weeks in total length, which may limit the ability to observe an impact. Although many of the included investigations measured fine PM, only some make specific measurements of likely asthma triggers. Notably, Antonicelli et al. (1991)—an investigation that found no significant benefit for the use of portable filters on any of the considered symptoms—also found no change in dust mite concentrations between operating and sham air cleaners. This may point to a particle size interaction (e.g., dust mites may be associated with larger particles which are already effectively removed by other loss processes) or to an unmeasured contextual factor. Fine particle concentrations are actually measured in only some of the studies, and none of the included studies measured exposure. Thus, it is unclear if the measure was appropriate for the space (e.g., undersized or poorly placed air cleaner) or whether the air cleaner was actually used.

These same patterns exist for the other health outcomes in Table 7-3. Although there is considerable evidence that filters improve health outcomes, the majority of investigations found significant improvement in at least one measured health outcome. Similarly, most investigations also found no significant improvement in at least one measured health outcome. Taken together, these findings suggest that the use of filters is likely beneficial for some health outcomes but a consistent finding beyond this is challenged by the wide variety of study methodologies, health outcome assessments, and (often unmeasured) contextual factors that change the performance of filters. Of note, many articles in Table 7-3 associate beneficial health outcomes related to reductions in $PM_{2.5}$, but it is unclear how much of the particle reduction was due to the filters used versus changes in contextual factors.

Personal Protective Equipment

Global interest in the efficacy of personal protective equipment (PPE) to filter particles and protect human health dramatically increased during the COVID-19 pandemic. This also influenced cultural norms related to masking, which could create opportunities to expand PPE use. There is a robust literature on PPE and protection from infection, particularly with a focus on COVID-19. Particles of different sizes are relevant for unique infectious diseases. The review did not explicitly include this literature but rather focused on the role of PPE in protecting from fine particulate matter exposure. Although PPE has been studied in occupational settings, that is also beyond the scope of this document.

Studies investigating PPE and protection from the risk of PM exposure are challenging from a design standpoint. It is difficult to measure the exposure reduction aspect as this occurs at the level of the individual, as opposed to source reduction, ventilation, or air cleaning, which can be assessed by measuring airborne particles in the relevant space. Efficacy measurements are also confounded by the amount of time used and by the fit of the mask, which can be influenced by PPE characteristics, individual characteristics, and behavior.

There are few studies of PPE use in residential or other indoor spaces that do not pose an occupational hazard related to exposure. Studies that have investigated PPE as an intervention have included chamber studies as well as experimental designs in which PPE is used while walking outdoors or during a prespecified amount of time. These have often been conducted in international settings in countries that have higher ambient concentrations of PM than the United States. Study populations range from younger healthy populations to elderly populations with specific chronic medical conditions.

Shi et al. (2017) designed a study to measure the effect of wearing masks in which they randomized 24 healthy young adult participants to wearing particulate respirators for 48 hours versus no respirator, with a 3-week washout period in between. The investigators noted the need for practical approaches to protect individuals from particulate exposure in developing countries and conducted this study in Shanghai. Participants were instructed to use the respirators when spending time outdoors, including a 1-hour walk outdoors, and as much as possible indoors. Respirator use resulted in lower blood pressure and improved heart rate variability parameters (high-frequency power, RSSD, pNN50).

Other studies in international settings used an experimental design of exercising outdoors to evaluate the health benefits of PPE. Jiang et al. (2021) used a randomized crossover trial to assess the effect of wearing N95 face masks versus sham masks among 52 college students in Beijing, China. The participants had lung function and cardiopulmonary blood biomarker assessment at baseline and after a 2-hour walk. The analyses compared the differences on high-pollution versus lower-pollution days ($PM_{2.5} > 75$ μg/m^3 versus $PM_{2.5} < 75$ μg/m^3). The N95 mask was associated with lower cytokine concentrations post-exposure for IL-6, IL-10, IL13, IL-17A, IFN-γ, and TNF-α. Lung function improved in the N95 group and did not change in the sham group. Beneficial effects of N95 were more pronounced on high-pollution days.

Han et al. (2021) also studied university students in China using a study design of walking outdoors near a busy road for 2 hours. Participants were assigned PPE interventions in a crossover design with powered air-purifying respiratory (PAPR) placebo, PAPR with PM filter, PAPR with PM and VOC filter, and an N95 respirator. The researchers demonstrated that short-term exposure to traffic acutely affects heart rate variability, blood pressure, and heart rate, but that N95 mask and PAPR interventions generally show little efficacy in reducing these effects. Langrish et al. (2010) applied a similar study design to investigate 98 individuals with coronary heart disease. Participants were randomised in an open crossover trial to a highly efficient mask versus no mask. The use of the mask was associated with a reduction in symptoms, reduction in blood pressure, and improvement in heart rate variability. These studies provide examples of attempts to study the health benefits of PPE in typical settings but have limited or no representation of the indoor environment.

Exposure chamber studies have evaluated the impact of air filtration through a polypropylene filter face mask. The FILTER-HR trial (a double-blind, randomized to order controlled, crossover trial) examined the effects of clean air, unfiltered diesel exhaust, and filtered diesel exhaust exposure in 26 individuals with heart failure and 15 control volunteers (Vieira et al., 2016). The filtration was implemented at the level of the chamber rather than the individual in the experimental design and demonstrated that filtration attenuated the adverse effect of diesel exhaust with respect to reactive hyperemia index and B-type natriuretic peptide. Filtration did not improve the effect of diesel exhaust (DE) on reduced 6-minute walk distance or arterial stiffness. DE has no effect on heart rate variability. The filtration of particles was associated with an increase in maximal oxygen consumption (VO_2 max, maximal oxygen consumption) and O_2 pulse during exercise testing compared with DE exposure. While this study examined the potential benefit of an air filter, the filter was not applied to the face, so extrapolation of findings is limited.

CONSIDERATIONS ACROSS ALL MITIGATION MEASURES

Despite differences between the intrinsic, building, and behavioral factors that make up the details of various mitigation measures, there are some common considerations. The first is that the effectiveness of a mitigation measure is often determined by the quality of the implementation guidance that accompanies it. Educational efforts—including those about important sources of fine PM, the effective use of user-controlled ventilation systems (such as rangehood fans), the placement and operation of portable filters, and the use of PPE—are often lacking and likely account for some of the variation observed in study outcomes. Although educational interventions themselves are not always effective in reducing adverse health outcomes (e.g., Walker et al., 2022), there have been few efforts to develop and test educational interventions that are responsive to building and behavioral contexts. Practical considerations associated with the use of mitigation measures, including when to change central or room filters and how to maintain ventilation and filtration systems, are often not well known by building occupants, and there are thus substantial opportunities for initiatives such as community-sourced and innovative educational materials and approaches to improve outcomes (for example, see Burke, 2020).

A second issue entails the disparities in which communities have been a part of mitigation research investigations. These disparities lead to results that cannot be generalized to different populations and contexts. There are disparities in the ability to implement mitigation measures, including cost, maintenance requirements, and appropriate training on effective use, and in the building factors that interact with mitigation measures, such as the inter-apartment transport of fine PM in multi-unit residential buildings, the availability of effective kitchen exhaust fans, and the presence of HVAC systems that use central air cleaning or mechanical ventilation. There are mitigation approaches (such as the banning of smudging, incense, or cannabis) that have important cultural implications for some groups and the historical use of source control to target specific groups (e.g., messaging about the harms of menthol cigarettes to African American communities). A robust approach to the practical mitigation of fine PM should not increase disparities and instead should be designed to prioritize reducing fine PM exposure for racialized, marginalized, and susceptible communities.

Finally, fine PM mitigation has historically been considered through the lens of cost. Capital and operating costs are often real or perceived barriers to specific mitigation measures. However, mitigation benefits are much larger than mitigation costs (Bekö et al., 2008; Fisk and Chan, 2017; Montgomery et al., 2015; Zuraimi and Tan, 2015), with avoided health care costs making up a large and often unaccounted portion of benefits. The cost of not mitigating fine PM includes these health care costs as well as the likely negative impacts of exposure on productivity, decision making, student learning, and cognitive performance. There is limited research estimating such costs, making this an important area for future efforts.

CONCLUSIONS AND RECOMMENDATIONS

The information reviewed by the committee in the course of their work leads them to conclude that **effective and practical mitigation of exposure to fine particulate matter in homes and schools is currently possible.** Such mitigation is possible with a proper combination of source reduction, ventilation, central or in-room filtration, and PPE. It is reasonable to assume that reductions in indoor $PM_{2.5}$ concentration will have health benefits, even if based solely on reduction in exposure to $PM_{2.5}$ of outdoor origin, although the literature related to the specific health benefits of such mitigation is sparse and sometimes mixed owing to the numerous confounding and limiting factors described in this and preceding chapters.

It is not possible to offer generic observations regarding which specific mitigation measures will be most practical to implement because, as this report has made clear, there are myriad variables characterizing the sources of indoor $PM_{2.5}$ and UFPs; their fate, transport, and transformations indoors; the circumstances and level of exposure to them; the health effects associated with that exposure; and the context and details of how mitigation measures are used. Different circumstances will necessarily dictate different choices. Generally speaking, though, the hierarchy of controls explored by the committee—again, indoor source control, ventilation, filtration and air cleaning, and personal protective equipment—provides a guideline for determining the order in which alternatives should be pursued, and consideration should be given to layered or combined approaches.

The following recommendations flow from the chapter's analysis:

Public health professionals should prioritize the implementation of immediate, multilevel interventions to mitigate exposure, relying on currently available evidence and tools, for economically disadvantaged, historically marginalized, underserved, and disproportionately exposed populations. These prioritized and community focused efforts should form the basis for the studies of effectiveness and cost–benefit needed to expand exposure mitigation efforts to the general public.

Federal and regional agencies should fund large-scale, population-level clinical trials to build the evidence base concerning the health impacts of indoor PM mitigation measures. A standard of evidence for the effectiveness of PM control technologies and strategies should be created, based on positive health outcomes. The trials need to consider exposure scenarios related to indoor versus outdoor sources and acute versus chronic effects as well as a range of interventions, including filtration, ventilation, source control, and personal protective equipment.

Researchers should characterize building factors in studies of PM mitigation to appropriately contextualize findings and add to the existing knowledge on strategies to mitigate adverse effects. These factors should include ventilation rate, air infiltration, particle loss rates, portable filter clean air delivery rate and location, and such parameters as runtime, flow rate, and in-situ efficiency for central systems.

Public health professionals and researchers should consider behavioral factors in their development of control strategies to assure effective implementation and to maximize impact. Examples of behaviors that can mitigate or exacerbate exposure include adjusting air cleaner speed and operation to control noise levels or electricity use, adjusting HVAC or furnace runtime, using range hood fans, opening and closing windows, using primary and secondary sources such as candles or terpenes in cleaning products, and selecting electric or gas appliances for cooking and heating.

Environmental health researchers should consider the effects of composition and other particle attributes and use this knowledge to harness mitigation options that may be more practical in some settings than reduction of $PM_{2.5}$ defined in conventional, mass terms.

Engineering and technology researchers and industry should endeavor to optimize existing air cleaning and ventilation technologies and also develop new one that are more effective, energy-efficient, quieter, easier to maintain, and more intuitive to operate. Special attention should be paid to lower-cost solutions that are more accessible and likely to be used by marginalized and susceptible individuals and communities. Additionally, in-situ air cleaning test approaches should be developed and promulgated that capture contextual factors as well as assess primary and secondary byproducts of air cleaning.

Coalitions of public health, engineering, and social science and public policy researchers should partner with community-based organizations to better characterize and address potential non-technical components of a successful PM mitigation implementation effort, such as messaging, education, and community engagement. Efforts should be made to better understand implementation strategies that can bring the most benefits to vulnerable, underserved, or disproportionately exposed populations.

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8
Key Findings, Conclusions, and Recommendations

This final chapter of the report builds on the preceding text, recapitulating the elements of the committee's work, identifying the major themes, and highlighting the key findings, conclusions, and recommendations.

OVERVIEW OF THE COMMITTEE'S WORK

The committee's statement of task charged it to consider the state of the science on the health risks of exposure to fine particulate matter ($PM_{2.5}$) indoors and engineering solutions and interventions to reduce the risks of exposure to this particulate matter indoors, including practical mitigation solutions to reduce exposure in residential settings. The U.S. Environmental Protection Agency (EPA), the report's sponsor, identified two areas of emphasis in this work:

- synthesizing and summarizing recent scientific literature to assess the health risks of indoor exposure to $PM_{2.5}$; and
- identifying and analyzing practical intervention approaches for $PM_{2.5}$ indoors.

The committee was further directed to develop findings and recommendations regarding the key implications of the scientific research for public health, including potential near-term opportunities for incorporating what is known into public health practice, and to identify where additional research would be most critical to understanding indoor exposure to $PM_{2.5}$ and the effectiveness of interventions. Opportunities for advancing such research by addressing methodological or technological barriers or enhancing coordination or collaboration among governmental bodies and organizations were also to be noted.

The committee approached the task by conducting a wide-ranging review of the available science, focused on the literature it deemed to have been influential in shaping understanding at the time it completed its task in summer 2023. It divided its review into five major categories: analyses of the published research on the sources of indoor fine PM; particle dynamics and building characteristics that influence indoor PM; building occupant exposures and the means of characterizing them; the health effects associated with that exposure; and practical approaches to mitigating it. So vast is the topic that, with even with the limitations it imposed on the scope of the review, the committee cites over 800 papers and reports.

Key conclusions and overarching recommendations resulting from this effort and the findings that underlie them are summarized below. Box 8-1 contains a synopsis of what is and isn't known about the health risks of indoor exposure to fine particulate matter and practical mitigation solutions. Citations to the literature supporting this information may be found in Chapters 3–7.

Box 8-1

Synopsis – What Is and Isn't Known about the Health Risks of Indoor Exposure to Fine Particulate Matter and Practical Mitigation Solutions

Despite the relatively large base of peer-reviewed literature on the topic, there remain significant limitations to the existing knowledge on indoor fine particulate matter and the health effects associated with exposure to it. It's well known from epidemiological studies involving outdoor measurements of $PM_{2.5}$ that fine particulate matter of outdoor origin causes a wide range of acute and chronic health effects. Given that outdoor air and associated PM penetrate indoors and the fact that Americans spend the vast majority of their time inside buildings, it is reasonable to infer that indoor exposure to fine particles of outdoor origin causes health effects. However, PM undergoes physical and chemical transformations in indoor environments and the effects of such transformations on health are not well understood. Indoor fine particles of outdoor origin are mixed with fine PM associated with indoor sources. Major indoor sources of fine particulate matter are reasonably well understood. While there have been epidemiological and toxicological studies related to particle emissions from some sources, much is still unknown regarding both acute and chronic health effects associated with fine PM emissions from most indoor sources.

It is possible to significantly reduce indoor concentrations and exposure to fine particulate matter of both outdoor and indoor origin through a combination of source control, filtration and air cleaning, and personal protective equipment. Increased ventilation can also be effective at reducing exposure to fine particulate matter originating from indoor sources, but without proper filtration, inlet air can significantly increase exposure to fine particulate matter of outdoor origin. Importantly, while it is reasonable to infer health benefits from the lowering of exposure to indoor fine PM, the literature related to such health benefits remains sparse. We have an incomplete understanding of how much indoor PM reduction is needed to achieve meaningful health benefits generally, for specific health conditions, for specific types of individuals and communities, and for PM from different sources.

Practical mitigation of fine PM is possible today, but it isn't possible to offer generic advice on what steps should be taken to implement it because the myriad variables that characterize PM sources, levels, dynamics, exposures, exposure vulnerabilities, health effects, and the means available to limit exposures will necessitate different choices in different circumstances. More research is needed to understand how best to effectively implement practical mitigation strategies in different indoor environments and diverse communities.

Given that practical mitigation is possible and has beneficial effects, it is important that such mitigation be a priority—in particular, for schools and economically-disadvantaged households, where there may be concentrations of people who are susceptible to adverse health effects and who have limited ability to ameliorate exposure. This will require concerted action from government at all levels and non-governmental entities interested in public health. Research will also be needed to close the many knowledge gaps identified.

KEY CONCLUSIONS

Five overarching conclusions stem from the committee's literature review.

There is ample evidence that exposure to indoor fine particulate matter causes adverse health effects.

The epidemiologic literature strongly supports the conclusion that exposure to indoor $PM_{2.5}$ has adverse effects on the respiratory and cardiovascular systems and likely other organ systems. Evidence for a role of indoor $PM_{2.5}$ in neurologic, metabolic, and reproductive outcomes is less well developed but emerging. There is, however, only a limited understanding of how inequities in indoor PM exposure (in terms of concentration as well as other particle characteristics) contribute to health disparities; and of the health effects of $PM_{2.5}$ exposure at school, where children—a cohort that is more vulnerable to adverse effects—spend a significant amount of time.

This understanding stems in part from the knowledge that $PM_{2.5}$ of outdoor origin generally makes up a large fraction of indoor $PM_{2.5}$ and that a greater amount of $PM_{2.5}$ of outdoor origin is inhaled indoors than outdoors as well as from the wealth of literature that associates outdoor $PM_{2.5}$ with adverse health outcomes. Compared with the evidence supporting the adverse health consequences of PM measured outdoors, there are fewer studies of the health effects of PM measured indoors, and these have substantially smaller sample sizes.

People report spending nearly 90 percent of their time indoors, on average, including nearly 70 percent in residences and approximately 10 percent in other indoor environments, including schools. Estimates vary widely, but, generally speaking, indoor sources account for approximately half of total indoor $PM_{2.5}$ concentrations in homes, with the remainder originating from outdoors. Because outdoor $PM_{2.5}$ infiltrates and persists indoors, the bulk of human exposure to PM of outdoor origin is likely to take place indoors.

Disparities exist in population exposure to indoor fine particulate matter of both outdoor and indoor origin.

Exposure to $PM_{2.5}$ and related health impacts may be greater for people living in economically disadvantaged circumstances and marginalized communities near heavy industry or busy highways, along with populations such as seniors, children, those with underlying chronic diseases, those living in older and smaller homes, and those lacking resources to purchase lower-emitting appliances or to maintain air cleaning technologies.

While there is a knowledge base addressing socioeconomic and cultural disparities in ambient $PM_{2.5}$ sources, concentrations, and compositions, less is known about how such differences manifest in differences in indoor $PM_{2.5}$ Moreover, while it is expected that there is high variability in the types and magnitudes of indoor $PM_{2.5}$ sources that is likely attributable to socioeconomic and cultural differences, robust characterizations of the presence, types, and frequency of indoor emission sources—as well as technologies to mitigate exposures—for specific populations do not readily exist.

Technological advances have great potential for quantifying and reducing exposures to fine particulate matter.

There has been great progress in recent years in the development of small, easy-to-use, and relatively inexpensive devices for measuring airborne PM levels and in the capacity to share such information over the web. Consumer-grade sensors that can be used by non-technical people to measure $PM_{2.5}$ and track location, and also be used in environmental data management, analysis, and modeling, enable new approaches to exposure assessment and control. These technologies—which will continue to evolve in accuracy, capabilities, and lower cost—permit community-based participatory research that can build awareness and address critical data gaps, especially in communities that are disproportionately exposed and under-examined, and also make it possible to provide real-time alerts to inform exposure-avoiding behavior. There is a specific need for such monitoring approaches to identify and quantify important parameters that potentially affect the effectiveness of practical mitigation measures.

Effective and practical mitigation of exposure to fine particulate matter in homes and schools is currently possible.

Truly practical mitigation strategies must be affordable, available, feasible to implement, perform consistently over product life, and be devoid of adverse secondary consequences. As the report details, there are several actions that can be taken immediately. Generally speaking, PM exposure mitigation may be implemented with a combination of source reduction, ventilation, central or in-room filtration, and personal protective equipment (PPE). It is reasonable to assume that reductions in indoor $PM_{2.5}$ concentration will have health benefits, even if based solely on reducing exposures to $PM_{2.5}$ of outdoor origin, although the literature related to the specific health benefits of such mitigation is sparse and mixed owing to the numerous confounding and limiting factors.

However, it is not possible to offer generic observations regarding which specific mitigation measures will be most practical to implement because there are myriad variables characterizing the sources of indoor $PM_{2.5}$ and ultrafine particles (UFPs); their fate, transport, and transformations indoors; the circumstances and level of exposure to them; and the health effects associated with that exposure. Different circumstances will necessarily dictate different choices. The hierarchy of controls identified by the committee provides a guideline for determining the order in which alternatives should be pursued.

The lack of centralized responsibility for indoor fine PM policy is hindering reductions in population exposure at scale.

There are many factors that influence population exposure to indoor $PM_{2.5}$, including indoor and ambient sources, air handling and cleaning technologies, building-related features, and occupant behaviors. Currently, though, there is no single entity with the authority to apply an integrated system approach toward lowering population exposure to $PM_{2.5}$.

While EPA exercises considerable responsibility for conducting and sponsoring research on the indoor environment and communicating the results of that work to the public, it has no regulatory authority regarding indoor particulate matter. Other federal agencies also have interests. The Department of Energy promotes energy efficiency and sustainability, which has material impacts on indoor environmental quality through guidance in such areas as energy-efficient building design and, heating, ventilation, and air conditioning (HVAC) systems. The Centers for Disease Control and Prevention focuses on public health issues, including those related to indoor environments. That agency provides provide guidance on preventing and addressing issues like mold, respiratory diseases, and exposure to environmental hazards in indoor spaces. The Department of Housing and Urban Development and the Department of Defense, among others, manage huge portfolios of building stock and are generally responsible for the health of the people who live in them. The Consumer Product Safety Commission investigates safety issues regarding and develops standards for products that include those that generate indoor PM and develops standards for such products. And the Occupational Safety and Health Administration and the National Institute for Occupational Safety and Health deal with indoor exposures and health in occupational environments. Most of these federal agencies have their state and sometimes tribal, territorial, and local counterparts. They are joined in responsibility by those public and private entities that develop and, in some cases, enforce building codes, standards, and guidelines.

Consequently, the opportunities to implement mitigation strategies where most needed and to support related research are fragmented. There has thus been limited progress to reduce exposure to indoor fine PM, even though effective and practical mitigation approaches exist.

OVERARCHING RECOMMENDATIONS

Four primary recommendations are offered to advance reductions in population exposure to $PM_{2.5}$ to lessen health impacts on susceptible populations including the elderly, young children, and those with pre-existing conditions; and to address important knowledge gaps.

Prioritize the mitigation of PM exposures among susceptible populations and do so with urgency.

Disparities exist in population exposure to indoor fine particulate matter of both outdoor and indoor origin. These occur not only because of higher indoor exposure concentrations due to more activities happening in smaller, densely occupied, and interconnected (multi-family) homes, or outdated appliances that have higher emissions or ventilation equipment that are less effective at removing PM, but also because of the greater susceptibility of the exposed populations leading to excess health burdens. Settings where indoor PM exposures and their associated health impacts are enhanced and mitigation opportunities are limited include schools and early childhood education facilities, and institutional housing such as homeless shelters, transitional homes, skilled nursing facilities, and prisons.

Public health professionals and federal, state, local, tribal, and territorial agencies should thus prioritize immediate, multilevel, easily implementable, cost-accessible, and effective interventions relying on currently available evidence and tools to address this situation. In doing so, collaboration with community-based organizations and communication professionals to address the non-technical aspects of fine and ultrafine particle mitigation, including messaging, education, and public engagement, will be important, as will a consideration of the factors that drive user behaviors related to air cleaners, HVAC systems, range hood fans, window use, source usage and frequency, choice of appliances, and more.

While education of stakeholders is insufficient in and of itself to significantly reduce exposure of susceptible populations to $PM_{2.5}$, it is important to provide informative and understandable outreach materials through trusted sources as a means of modifying possible behavior and decision making in order to reduce exposures, particularly in residences where individuals or families have some control over their exposure.

Reduce exposure to fine PM in schools.

School is a unique indoor environment where children and young adults spend considerable time. Reducing exposures to fine PM, including infectious aerosols, in schools has the potential to improve acute and chronic health impacts, reduce absences, and improve student performance. An immediate and highly visible program, perhaps analogous to "Green School" designations, could, for example, spur improvements in indoor air quality in schools with opt-in by school districts and assistance from federal and state governments for impoverished school districts. Clear goals should be established and effectively communicated with guidance on source reduction, ventilation, central filtration, effective and right-sized air cleaning, fine PM monitoring, and frequency of monitoring. District or school-specific improvements in measured fine PM and health outcomes, including reductions in absences, should be monitored for schools that implement the guidance and compared against national averages.

As part of this effort, the committee recommends that EPA, in collaboration with other governmental entities and private funders, should prioritize the support of studies designed to characterize differences in indoor $PM_{2.5}$ exposure—including differences in $PM_{2.5}$ characteristics—in home and school settings across communities and also characterize their contribution to health disparities. As already noted, significant disparities exist in $PM_{2.5}$ exposures and exposure impacts. It will not be possible to identify and to formulate practical mitigation strategies for disproportionately affected populations or to assess the efficacy of their implementation until there is a clear understanding of who is affected by the disparate exposures and how these individuals' circumstances shape the effectiveness of interventions.

Continue to support research necessary to fill important knowledge gaps.

While the existing knowledge base is sufficient to draw conclusions about some health outcomes related to indoor PM exposure and to recommend practical mitigation strategies for lowering exposure to $PM_{2.5}$, significant gaps in knowledge remain and should be prioritized for future research. Several important knowledge gaps and research needs were noted by the committee. Some of these are highlighted below; additional observations are offered in chapters 3–7.

There are a few general efforts that would greatly advance knowledge and provide the groundwork for advances in the understanding of adverse health impacts from indoor PM exposures and interventions that would ameliorate them.

Toward this end, the committee recommends that EPA, in collaboration with other governmental entities, private funders, and standards and professional organizations, foster additional research on methods for measuring PM in the indoor environment. Studies of indoor sources of PM may take place in controlled laboratory chambers or actual indoor spaces. Both environments present research challenges and limitations. The deployment of large, research-grade instrumentation into occupied indoor spaces offers some of the greatest exposure assessment challenges because of such factors as noise, space requirements, and safety limitations. Recent advances in lower-cost, consumer-grade sensors have made it possible to deploy sensors effectively in a wide variety of indoor environments. However, to capture the true diversity of indoor sources and indoor environments, advances must be made in miniaturized research-grade instrumentation that can characterize PM in terms of size, concentration, chemical composition, and the like at the large scales needed to advance our understanding of health effects of indoor $PM_{2.5}$. In concert with this, the indoor air research community should continue to build and maintain capacity for identifying, quantifying, and measuring new mechanisms for sources, sinks, and transformations of indoor PM as they arise and to subsequently understand the potential impacts of such mechanisms on the toxicity of indoor PM.

A national effort is needed to measure and report indoor exposure to PM using validated methods and sufficient characterization of the built environment, occupancy, and activity patterns to identify key determinants of indoor exposure to fine particles (and other indoor air pollutants) so that source-specific exposure can be assessed, which can in turn help guide mitigation efforts for subpopulations overburdened with exposure to fine particles in homes, schools, and other building types. The data would greatly improve our understanding of the exposure and potential health impacts of indoor PM on the U.S. population in key indoor environments: homes, schools, and other vulnerable settings.

The committee also offers recommendations aimed at creating baseline standards for information gathering in some critical areas. The first of these is the fostering of additional research on establishing uniform criteria for the information needed on indoor sources to inform the assessment of exposure, health effects, and mitigation. It is impractical to address all indoor sources of $PM_{2.5}$ because they continually evolve and change along with the consumer market. If uniform criteria existed for characterizing indoor sources, it could provide a pathway for harmonizing future studies in indoor particle physics and chemistry as well as helping with the development of mitigation strategies and associated communications to the public. As an initial step in this process, compiling a comprehensive indoor emissions inventory (including outdoor sources) across a wide range of particle sizes, mass and number concentrations, and compositions would help researchers and policy makers to better evaluate data regarding different source categories and their exposures. This recommendation would be best carried out by EPA in collaboration with other governmental entities, private funders, and standards and professional organizations.

Relatedly, the indoor air research community should come to a consensus on what minimal information on indoor PM dynamics is needed to meaningfully improve understanding of the health effects of indoor PM exposure, for example, by modeling exposures across the building stock for use in epidemiology studies. This community should also explore what minimal information is needed to meaningfully improve understanding of practical mitigation measures for indoor PM by, for example, adopting a more "building-aware" epidemiology approach whereby research characterizing the effects of a practical mitigation measure would also provide the context of mechanisms that affect the fate, transport, and transformations of indoor PM. In order to enable this contextualization, there is a specific need for clear, practical, and relatively low-cost monitoring approaches to identify and quantify important parameters that potentially affect the effectiveness of practical mitigation strategies.

The committee additionally recommends that indoor air research community should take better advantage of observational field studies to conduct studies that can directly evaluate the effects of reducing $PM_{2.5}$ exposure on health. Studies conducted under controlled circumstances offer great advantages to researchers in terms of time, effort, and the ability to manage the myriad potential influences on outcomes, but they yield an incomplete answer to what is perhaps the most salient issue for policy makers: Does this provide information about what happens in the real world? Advances in technology now permit investigators to gather information at a scale and with a degree of accuracy that was unthinkable only a few years ago. These advances need to be exploited.

The committee identified five specific areas where additional research would materially advance knowledge: studies related to mitigation and health improvements, studies of indoor aerosol characteristics, studies on the effects of particle origin on health effects, new technologies for real-time indoor particle monitoring, and social and behavioral influences. These are elaborated on below.

Mitigation and health improvements. Research is needed to quantify the efficacy of mitigation efforts to reduce exposure and the health benefits of practical mitigation strategies. Large-scale intervention studies are needed to establish an evidence base for the health impacts of indoor fine particulate matter exposure and of mitigation measures, including different exposure scenarios, a range of interventions, and multiple health endpoints. Such studies should include acute exposures such as wildfire smoke. They should evaluate co-benefits such as reductions in airborne infectious agent exposures, which may require different target air exchange rates than those focused on reducing PM of other sources. The inclusion of economically disadvantaged and marginalized communities in these studies is critical, as is the appropriate characterization of building factors such as indoor space geometry, ventilation, recirculated air flows, use of local exhaust, nature of filtration, indoor sources, proximity to outdoor sources, and the like.

As part of the effort to address knowledge gaps, the committee recommends that federal and regional agencies fund large-scale, population-level clinical trials to build the evidence-base for the health impacts of indoor PM mitigation measures. A standard of evidence for the effectiveness of PM control technologies and strategies should be created, based on the health evidence base. The trials need to consider exposure scenarios related to indoor versus outdoor sources, and acute versus chronic effects as well as a range of interventions, including filtration, ventilation, source control, and personal protective equipment. Researchers should characterize building factors to appropriately contextualize their findings and add to our knowledge base on strategies to mitigate the adverse effects. The building factors that should be characterized include ventilation rate, air infiltration, particle loss rates, portable filter clean air delivery rate and location, and parameters such as runtime, flow rate, and in-situ efficiency for central systems.

The committee also recommends that EPA, in collaboration with other governmental entities and private funders, support the conduct of studies to evaluate the impacts of policies on $PM_{2.5}$ exposure and health, including cost–benefit analyses that incorporate an estimate of the economic and public health costs of not implementing the policy. Governments must balance competing priorities when making policy determinations. Understanding the costs associated with action—and inaction—will allow for better informed decisions on the need for interventions regarding indoor $PM_{2.5}$ exposure and mitigation.

Indoor aerosol characteristics. Additional research needs to be conducted to identify and understand the variations in aerosol characteristics, including size (particularly, UFPs), concentrations, sources, and compositions in different indoor residential and school environments. Such research could be a component of intervention studies to better understand the role of aerosol characteristics on health endpoints. Environmental health researchers need to consider the effects of composition and other particle attributes and use this knowledge to harness mitigation options that may be more practical in some settings than reduction of PM.

Ultrafine particles deserve special attention because they are the predominant component of many indoor sources of $PM_{2.5}$. While they usually contribute a very small portion of the total $PM_{2.5}$ mass, they but represent a large portion in terms of particle number concentrations. Information on indoor ultrafine particles, especially their composition and health effects, is currently limited.

The committee therefore recommends that EPA, in collaboration with other governmental entities, private funders, and standards and professional organizations, foster additional research on the composition of ultrafine particles from indoor sources. With this knowledge, researchers and the public could prioritize actions where there is greater potential for impact. Mitigation strategies could be developed along with education initiatives to minimize people's exposure to those indoor sources that lead to worse health outcomes. There is an opportunity to educate the general public about the indoor sources of fine particulate matter to assist decision making when choosing indoor products and activities to minimize exposure.

Furthermore, EPA, in collaboration with other governmental entities, private funders, and standards and professional organizations, should foster additional research on spatiotemporal $PM_{2.5}$ variability indoors. This variability, which results from the everchanging nature of indoor sources in indoor environments—particularly residences and schools—may significantly affect the exposure of indoor occupants. Specifically, questions remain on how acute exposures (high concentrations, short time periods) cause health effects and can be influenced by practical mitigation choices. This knowledge could help inform the type and location of mitigation strategies contextually. In other words, not all mitigation strategies may work for all indoor $PM_{2.5}$ sources, but if there is an understanding of which sources play a larger role in the exposure of indoor occupants, decisions can be made to optimize mitigation strategies.

Effects of particle origin on health effects. While understanding the relative health effects of indoor fine particulate matter of both outdoor origin and indoor origin is important for defining appropriate mitigation strategies, research in this area is still lacking. Advancing understanding of the source[s] associated with specific health effects is also important for informing source control measures.

EPA, in collaboration with other governmental entities, private funders, and standards and professional organizations, should thus foster additional research on ambient air pollution as a source of indoor particles. Although the penetration of outdoor air pollutants into the indoor environments is relatively well understood, knowledge gaps remain in terms of the health effects of ambient particles that infiltrate and persist indoors. Particularly, questions remain on how to contextualize the evidence linking exposure to ambient $PM_{2.5}$ levels and their health outcomes given that people in many societies spend the majority of their time indoors, so they are likely to be predominantly exposed to ambient particles indoors.

New technologies for real-time indoor particle monitoring. New technologies—particularly low-cost and real-time sensors that capture key aerosol characteristics—would benefit future exposure and health studies as well as serve as sentinels for mitigation feedback systems or actions by building occupants to reduce exposure. Research and development are needed to expand features and improve quality control and consistency, both at the single-sensor level and in relation to installation, maintenance, and data interpretation from networks of sensors.

Such research is needed because, while consumer-grade sensors and personal monitoring are advancing abilities to measure exposure, important limitations remain. The accessibility of these lower-cost sensors has greatly expanded monitoring capabilities, but the efforts have been mainly outdoors. Beyond improving instrument accuracy, cost, form factor (ease of use, connectivity), and other performance aspects, it is critically important to advance our understanding of how measured values are useful for determining the health impacts from exposure to fine particles or mitigation effectiveness. While indoor PM is generally expected to contribute to excess morbidity and mortality, the lack of a standardized approach to readily obtain indoor fine PM exposure levels, especially in historically marginalized communities, limits the advancement of our understanding of the connection between exposure and disease.

Furthermore, our understanding of the acute exposure to indoor PM, while improving, is still limited. There are emerging concerns about new sources, such as vaping, as well as about more frequent cleaning and disinfection, and electronic air cleaners. Very high exposure to indoor fine PM is occurring in some microenvironments. Many indoor sources are intermittent and can lead to localized, short-lived, and high concentrations of UFPs and $PM_{2.5}$. Indoor sources of particles, such as cooking, personal care products, and some office products, can emit copious amounts of UFPs and $PM_{2.5}$ for the duration of the emitting activity, leading to high, sometimes short-lived, PM concentrations in the vicinity of the activity. This can lead to elevated exposure to the people performing the activity.

Circumstances are complicated by the fact that indoor sources of $PM_{2.5}$ change continually with the development of new products and activities. The indoor environment changes as society and the consumer market change over time. New products are always entering our lives, homes, and schools, creating the need for a continuous reevaluation of indoor $PM_{2.5}$ sources and associated exposures. Examples at the time of writing included electronic cigarettes, air fryers, and an abundance of air cleaning devices created or reintroduced during the COVID-19 pandemic that did not exist or were not as prevalent in decades prior.

Our understanding of the potential health impacts of these indoor sources in different built environments is partly restricted by the available instrumentation used to characterize exposure. In particular, the understanding of indoor exposure to some specific types of PM, such as UFPs and specific PM compositional constituents, remains poor. Beyond exposure concentrations, intake from all routes (inhalation, ingestion, and dermal), lung deposition, and dose are also highly variable and difficult to quantify, and they add to the uncertainty in characterizations of health impacts. Studies point to a need for innovation to improve measurement techniques and study methods and thus to enable better characterization of the total exposure and health impacts to fine particles in indoor environments.

Researchers should therefore use emerging consumer-grade sensors and statistical modeling to estimate indoor PM exposure at a larger scale to facilitate the conduct of large-scale population-based epidemiologic studies. Such studies are critical to advancing the understanding of (1) the effects of indoor PM on less common health outcomes and on health disparities; (2) the effects of particle characteristics—beyond mass concentration and including composition, size, shape, and sources—on health; (3) individual and population characteristics that confer susceptibility to indoor PM exposure or certain "types" of indoor PM; and (4) the contribution of particles of outdoor origin to the health effects of indoor PM.

Affordable, quiet, and effective air cleaning technologies. While there are standalone air cleaners based on media filtration that lower indoor fine PM concentrations, research is still needed to develop cleaners that are priced in a range that allows for their widespread use; are effective at lowering exposure to, and health effects of, indoor aerosols; are easier to maintain; are more intuitive to operate; and have features like quiet operation that make them convenient and comfortable to use. This has become especially important in recent times as exposures to emissions from indoor appliances and from wildfire smoke penetrating the indoor environment have reached the public consciousness.

Accordingly, engineering and technology researchers and industry should endeavor to optimize existing and develop new air cleaning and ventilation technologies that have these health-conscious, consumer-friendly attributes. Special attention should be paid to lower-cost solutions that are more accessible and likely to be used by marginalized and susceptible individuals and communities. Additionally, in-situ air cleaning test approaches should be developed and promulgated that capture contextual factors in addition to assessing primary and secondary byproducts of air cleaning.

Social and behavioral influences. The indoor air research community should explicitly incorporate social science and behavioral health science perspectives and expertise into studies of the health impacts of indoor $PM_{2.5}$ to better understand how social, cultural, and behavioral factors may influence $PM_{2.5}$ exposure and health effects and the implementation of practical mitigation strategies. As this report makes clear, there are systematic differences in exposure to indoor PM and in susceptibility to adverse effects of that exposure that result in disparate health outcome risks for different populations. The research in this area is still relatively sparse, however, and much more needs to be done in order to formulate effective interventions. One straightforward way to address this gap would be to make consideration of social, cultural, and behavioral factors a standard element of studies by including people with such expertise in research teams.

Furthermore, public health professionals and researchers should consider behavioral factors in their development of control strategies in order to ensure effective implementation and maximize impact. Examples of behaviors that can mitigate or exacerbate exposure include adjusting air cleaner speed and operation to control noise levels or electricity use, HVAC or furnace runtime, the use of range hood fans, window use, the use of primary and secondary sources such as candles or terpenes in cleaning products, and the choice of electric or gas appliances for cooking and heating.

Magnify and unify efforts to reduce population exposure to indoor fine particulate matter.

The literature review presented in this report establishes that reducing $PM_{2.5}$ exposure would have a significant public health benefit. The three broad recommendations offered above would have a material effect in realizing that benefit, but they cannot be effectively enacted without coordinated support and action. However, as already noted, the lack of centralized responsibility for indoor air quality hinders the ability to take the steps that would result in a significant reduction in population exposure to indoor fine PM at scale. Such a reduction will require a unification and integration of efforts across federal, state, local, tribal, and territorial entities. A concerted effort will be needed that spans environmental, building code, public health, and social service agencies, in collaboration with community, school-based, and other organizations that can aid with implementation. The form and details of this effort will need to be worked out among the involved parties and might include such interventions as woodstove replacement, healthy home retrofits, school HVAC upgrades, and portable air cleaner deployments. Another effort could involve changes to building standards and practices, which have the potential to bring about wide-ranging and long-lasting benefits. And effective communication with the public will be required. In the end, the effectiveness of a mitigation measure is often determined by the quality of the implementation guidance that accompanies it. There is a need to make indoor exposure to fine PM more "visible," in the sense of raising awareness of its importance to health and well-being. This can motivate people to take actions that reduce indoor sources and increase the use of mitigation measures.

Programs such as these will require evaluation of the outcomes achieved in order to identify best practices and motivate their funding and continued support. Guidance on how to measure the potential reduction in indoor fine PM exposure and what metrics to use is needed so that these programs can adjust and improve over time to bring more benefits to communities.

Collaborations to study indoor PM exposure and implement interventions in susceptible, underserved, and disproportionately exposed communities should be particularly encouraged. Indoor environments and the people who live in them are diverse. They have unique characteristics that may lead to high indoor fine PM exposures that require focused attention. More targeted data on such exposures are necessary to improve our understanding of them and, ultimately, to protect susceptible populations. Indoor environment researchers need to collaborate with community- based organizations and community members if they are to conduct the kinds of culturally sensitive studies that will produce information relevant to these populations and develop effective messaging on PM exposure issues to help motivate practical mitigation.

While it might not be simple to bring these measures about, the rewards in terms of improved population health will be great.

Appendix A
Agendas – 2021 Workshop Series on Indoor Exposure to Fine Particulate Matter and Practical Mitigation Approaches

April 14 Webinar – Sources of Indoor Fine Particulate Matter

11:00 am	**Welcome; Workshop and Session Goals** *Richard Corsi, PhD, PE – Planning Committee Chair*
11:10 am	**Sponsor remarks** *Jonathan Edwards* Director, Office of Radiation and Indoor Air, U.S. Environmental Protection Agency
SESSION I: OUTDOOR SOURCES OF INDOOR PARTICULATE MATTER	
11:15 am	**Introduction of session speakers** *Kimberly Prather, PhD – Session Moderator and Planning Committee Member*
11:20 am	**Indoor Particulate Matter of Outdoor Origin and the Disparities in Sources and Exposures Across Communities** *Cesunica Ivey, PhD* Assistant Professor, Chemical/Environmental Engineering, University of California, Riverside
11:40 am	**Outdoor-to-Indoor Transport Mechanisms and Particle Penetration for Fine Particulate Matter** *Brent Stephens, PhD* Professor and Department Chair, Department of Civil, Architectural, and Environmental Engineering, Illinois Institute of Technology
12:00 pm	**Outdoor Particulate Matter Sources and the Chemical Transformations that Take Place When They Interact with the Indoor Environment** *Delphine Farmer, PhD* Associate Professor, Department of Chemistry, Colorado State University
12:20 am	**Roundtable Discussion** Session speakers and Planning Committee Members
12:45 am	**Break**

SESSION II: INDOOR SOURCES OF INDOOR PARTICULATE MATTER	
12:55 pm	**Introduction of session speakers** *Kimberly Prather, PhD – Session Moderator and Planning Committee Member*
1:00 pm	**Fine Particulate Matter Emissions From Cooking** *Marina E. Vance, PhD* Assistant Professor and McLagan Family Faculty Fellow, Department of Mechanical Engineering, University of Colorado Boulder
1:20 pm	**Secondary Aerosol Formation of Fine Particulate Matter in the Indoor Environment** *Michael Waring, PhD* Department Head and Professor, Department of Civil, Architectural and Environmental Engineering, Drexel University College of Engineering
1:40 pm	**The Effect of Humidity on the Chemistry and Biology of Indoor Air** *Linsey Marr, PhD* Charles P. Lunsford Professor of Civil and Environmental Engineering, Virginia Tech
2:00 pm	**The Influence of Sources of Indoor Fine Particulate Matter on the Characterization of Exposure and Evaluation of Health Effects** *Andrea Ferro, PhD* Professor / ISE Associate Director for Research, Department of Civil & Environmental Engineering, Clarkson University
2:20 pm	**Roundtable Discussion** Session speakers and Planning Committee Members
2:50 pm	**Session wrap-up and preview of upcoming webinars** *Kimberly Prather, PhD – Session Moderator and Planning Committee Member*
3:00 pm	**Session adjourns**

April 21 Webinar – Indoor Exposure to Fine Particulate Matter: Health, Metrics, And Assessment

11:00 am	**Welcome; workshop and session goals** *Richard Corsi, PhD, PE – Planning Committee Chair*
11:10 am	**Brief summary of the previous workshop session**
SESSION I: HEALTH EFFECTS OF EXPOSURE TO INDOOR PARTICULATE MATTER	
11:15 am	**Introduction of session speakers** *Elizabeth Matsui, MD, MHS – Session Moderator and Planning Committee member*
11:20 am	**The Overall (Mostly Cardiovascular) Health Burden of Indoor $PM_{2.5}$ Exposure** *Howard Kipen MD, MPH* Professor, Department of Occupational and Environmental Health, Rutgers University – School of Public Health
11:45 am	**Pulmonary Disease Associated with Fine Particulate Matter Exposure in Indoor Environments and Disparities in Economically Challenged Communities** *Meredith McCormack, MD, MHS* Medical Director, Pulmonary Function Laboratory and Associate Professor of Medicine, John Hopkins University School of Medicine
12:05 pm	**Wildfire Smoke and Other Ambient Air Pollution Comes Indoors: Health Effects and the Building Characteristics that Mitigate Them** *Stephanie Holm, MD, MPH* Co-director, Western States Pediatric Environmental Health Specialty Unit, University of California, San Francisco
12:25 pm	**Moderated roundtable discussion** Session speakers and Planning Committee members *Elizabeth Matsui, MD, MHS and Linda A. McCauley, PhD, RN, FAAN, FAAOHN – Comoderators*
12:50 pm	**Break**
SESSION II: INDOOR EXPOSURE TO PARTICULATE MATTER: METRICS AND ASSESSMENT	
1:00 pm	**Introduction of session speakers** *Elizabeth Matsui, MD, MHS – Session Moderator and Planning Committee member*

1:05 pm	**Transcending Complexity: Indoor Fine Particulate Matter Measurement, Exposure, and Control** *William W Nazaroff, PhD* Daniel Tellep Distinguished Professor Emeritus, Department of Civil and Environmental Engineering, University of California, Berkeley
1:30 pm	**The Challenge of Moving from the Measurement of Fine Indoor Particulate Matter to Evaluating Occupant Exposure** *Kirsten Koehler, PhD* Associate Professor, Johns Hopkins Bloomberg School of Public Health
1:50 pm	**The Utility, Use, and Misuse of Low-Cost Consumer Indoor Particulate Matter Sensors** *Dusan Licina, PhD* Assistant Professor, Indoor Environmental Quality, School for Architecture, Civil, and Environmental Engineering, Swiss Federal Institute of Technology, Lausanne
2:10 pm	**Moderated roundtable discussion** Session speakers and Planning Committee members *Elizabeth Matsui, MD, MHS and Linda A. McCauley, PhD, RN, FAAN, FAAOHN – Co-moderators*
2:50 pm	**Session wrap-up and preview of upcoming webinar** *Seema Bhangar, PhD – Session Moderator and Planning Committee member*
3:00 pm	**Session adjourns**

April 28 Webinar – Mitigation of Indoor Exposure to Fine Particulate Matter

11:00 am	**Welcome; workshop & session goals; summary of the previous workshop sessions** *Richard Corsi, PhD, PE – Planning Committee Chair*
SESSION I: INDOOR PARTICULATE MATTER EXPOSURE CONTROL AND MITIGATION	
11:10 am	**Introduction of session speakers** *Wanyu (Rengie) Chan, PhD – Session Moderator and Planning Committee member*
11:15 am	**Fine Particulate Matter Filtration and Air Cleaning in Residential Environments** *Jeffrey Siegel, PhD* Professor of Civil Engineering, University of Toronto
11:35 am	**Fine Particulate Matter Exposure Control in Schools** *Elliott Gall, PhD*

	Assistant Professor, Department of Mechanical and Materials Engineering, Maseeh College of Engineering and Computer Science, Portland State University
11:55 am	**Mitigation of Fine Particulate Matter Exposures Associated with Cooking** *Brett Singer, PhD* Staff Scientist and Principal Investigator, Energy Technologies Area, Lawrence Berkeley National Laboratory
12:15 pm	**Moderated roundtable discussion** Session speakers and Planning Committee members *Wanyu (Rengie) Chan, PhD and Seema Bhangar, PhD – Comoderators*
12:50 pm	**Break**

SESSION II: OCCUPANT RESPONSES TO INDOOR PARTICULATE MATTER	
1:00 pm	**Introduction of session speakers** *Wanyu (Rengie) Chan, PhD – Session Moderator and Planning Committee member*
1:05 pm	**Portable Indoor Air Cleaners and Human Behavior** *Stuart Batterman, PhD* Professor, Environmental Health Sciences and Global Public Health, University of Michigan School of Public Health
1:25 pm	**How Building Occupants Interpret and Respond to Indoor Air Quality Sensor Data** *Lindsay Graham, PhD* Research Specialist, Center for the Built Environment, University of California, Berkeley
1:45 pm	**Public Health Responses to Reduce Community Exposure to Indoor Fine Particulate Matter** *Sarah Coefield, MS, MA* Air Quality Specialist, Missoula City-County Health Department
2:05 pm	**Moderated roundtable discussion** Session speakers and Planning Committee members *Wanyu (Rengie) Chan, PhD and Seema Bhangar, PhD – Comoderators*
2:40 pm	**Workshop summary and closing reflections** *Richard Corsi, PhD, PE – Planning Committee Chair*
2:55 pm	**Workshop concludes**

REFERENCE

National Academies of Sciences, Engineering, and Medicine and National Academy of Engineering. 2022. *Indoor exposure to fine particulate matter and practical mitigation approaches: Proceedings of a workshop.* Washington, DC: The National Academies Press. https://doi.org/10.17226/26331.

Appendix B
Biographic Sketches of Committee Members and Project Staff

COMMITTEE MEMBERS

Richard L. Corsi, Ph.D., PE *(Chair),* was appointed the dean of engineering of the University of California, Davis, in July 2021. He was formerly the H. Chik M. Erzurulu Dean of the Maseeh College of Engineering and Computer Science at Portland State University (PSU). Prior to joining PSU, Dr. Corsi was a faculty member, department chair, and endowed research chair at the University of Texas at Austin in the Department of Civil, Architectural, and Environmental Engineering. Dr. Corsi is an internationally recognized expert in the field of indoor air quality, with a specific interest in physical and chemical interactions between pollutants and indoor materials. He and his colleagues have published nearly 270 peer-reviewed papers stemming from 70 funded research projects and supervision of over 120 students in research. He was inducted into the International Society of Indoor Air Quality and Climates' Academy of Fellows in 2008 and is a past president of that Academy. Dr. Corsi was a member of the planning committee responsible for the 2016 National Academies report *Health Risks of Indoor Exposure to Particulate Matter: Workshop Summary*. He received his B.S. degree in environmental resources engineering from Humboldt State University, where he was honored as a Distinguished Alumnus in 2006, and his M.S. and Ph.D. degrees in civil engineering from the University of California, Davis, where he was honored with a Distinguished Engineering Alumni Medal from the College of Engineering in 2016.

Lilia A. Abron, Ph.D., PE, BCEE (NAE), is the president and chief executive officer of PEER Consultants, P.C. (PEER). She was the first African American woman in the nation to earn a Ph.D. in chemical engineering. Dr. Abron has built one of the largest black, female-owned and operated environmental engineering firms in the United States. PEER provides services to clients in environmental engineering and sciences; field services; energy and environmental sustainability; and water and wastewater engineering. Her experience spans more than 45 years in planning, managing, and directing environmental engineering programs for the improvement, maintenance, and enhancement of the natural and built environments. She is also the president and founder of PEER Africa (Pty) Ltd., an innovative design-build, sustainable development company with offices in Johannesburg and Cape Town, South Africa. Dr. Abron earned her Ph.D. in chemical engineering from the University of Iowa, an M.S. in sanitary science from Washington University, and a B.S. in chemistry from Lemoyne-Owen College. She was elected a member of the National Academy of Engineering in 2020, is a board-certified environmental engineer, and was the 2021 president of the American Academy of Environmental Engineers and Scientists.

Seema Bhangar, Ph.D., serves as the principal of healthy buildings and communities for innovation and research at the U.S. Green Building Council. She previously held program manager and technical lead roles at the commercial real estate firm WeWork. Dr. Bhangar specializes in indoor air quality research projects with a focus on applying human-centric approaches to environmental sensing in buildings and transportation systems. Earlier in her career, she was a technical lead and product manager for the design and development of next-generation indoor sensing devices for Aclima, Inc. She is a regular peer reviewer for journals including *Indoor Air*, *Building and Environment*, and *Environmental Science & Technology*. Dr. Bhangar earned a B.A.S. from Stanford University and an M.S. and Ph.D. in environmental engineering from the University of California, Berkeley.

Wanyu (Rengie) Chan, Ph.D., is a staff scientist and the deputy indoor environment group leader in the Energy Analysis and Environmental Impact Division at Lawrence Berkeley National Laboratory. Her work focuses on characterizing indoor air quality and implications of human exposures in residential and commercial buildings. Dr. Chan led a recent field study to evaluate the role of mechanical ventilation on indoor air quality in new California homes. She is part of an ongoing project funded by Department of Energy's Building America Program to study indoor air quality in new homes across different U.S. regions. Dr. Chan has also modeled the health benefits from filtration of ambient $PM_{2.5}$ and during wildfire smoke. She joined the Lawrence Berkeley lab as a graduate student and worked on the evaluation of shelter-in-place effectiveness. Dr. Chan earned her B.S. in chemical engineering from Carnegie Mellon University and her M.S. and Ph.D. in civil and environmental engineering from the University of California, Berkeley, in 2006.

Elizabeth C. Matsui, M.D., M.H.S., is a professor of population health and pediatrics at the Dell Medical School at the University of Texas at Austin, where she is also the director of clinical and translational research. She is a leading international expert on environmental allergies and asthma. Her research focuses on examining the impact of allergen exposure on allergic disease. She serves on the editorial board of the *Journal of Allergy and Clinical Immunology* and is a member of the American College of Asthma, Allergy, and Immunology and of the American Academy of Allergy, Asthma, and Immunology. Dr. Matsui serves on the National Academies Standing Committee on Medical and Epidemiological Aspects of Air Pollution on U.S. Government Employees and Their Families. She received her undergraduate degree in molecular biology and her M.D. from Vanderbilt University. Dr. Matsui also completed a master of health science in epidemiology at the Johns Hopkins Bloomberg School of Public Health.

Linda A. McCauley, Ph.D., RN, FAAN, FAAOHN (NAM), is a professor in and the dean of Emory University's Nell Hodgson Woodruff School of Nursing. Dean McCauley has special knowledge in the design of epidemiological investigations of environmental hazards and is nationally recognized for her expertise in occupational and environmental health nursing. Her work aims to identify culturally appropriate interventions to decrease the impact of environmental and occupational health hazards in vulnerable populations, including workers and young children. Dr. McCauley was previously the associate dean for research and the Nightingale Professor in Nursing at the University of Pennsylvania School of Nursing. She received a bachelor of nursing degree from the University of North Carolina, a masters in nursing from Emory, and a doctorate degree in environmental health and epidemiology from the University of Cincinnati. She was elected a member of the Institute of Medicine (now the National Academy of Medicine) in 2008 and has served on numerous National Academies committees.

Meredith C. McCormack M.D., M.H.S., is an associate professor of medicine at the Johns Hopkins University School of Medicine with a joint appointment in environmental health and engineering at the Johns Hopkins Bloomberg School of Public Health. Dr. McCormack is a physician–scientist with a research focus on the effect of environmental influences on underlying obstructive lung disease—specifically air pollution, diet, and obesity influences on chronic obstructive pulmonary disease and asthma. She has conducted environmental cohort studies to understand the effects of indoor and outdoor air pollution on children and adults with underlying respiratory disease. She earned her M.D. from Jefferson Medical College of Thomas Jefferson University and her M.H.S. from the Johns Hopkins Bloomberg School of Public Health.

Kimberly A. Prather, Ph.D. (NAE, NAS), holds a joint appointment as a professor in chemistry and biochemistry at Scripps Institution of Oceanography at the University of California San Diego. Her research involves the development and application in field and lab studies of real-time measurements of size-resolved chemistry of aerosols. Dr. Prather is involved in aerosol source apportionment studies and her group is working to better understand the impact of specific aerosol sources on health and climate. She was formerly a member of the Fine Particle Monitoring Subcommittee of the Environmental Protection Agency's Clean Air Scientific Advisory Committee. Dr. Prather is on several editorial boards for journals including *Aerosol Science and Technology* and is a member of a number of professional societies including the American Association for Aerosol Research, the American Chemical Society, and the American Geophysical Union. She received her B.S. and Ph.D. in chemistry from the University of California, Davis. Dr. Prather was elected a member of the National Academy of Engineering in 2019 and of the National Academy of Sciences in 2020.

Jeffrey A. Siegel, Ph.D., is a professor of civil engineering at the University of Toronto and a member of the university's Building Engineering Research Group. He holds joint appointments at the Dalla Lana School of Public Health and the Department of Physical and Environmental Sciences. Dr. Siegel is a fellow of the American Society of Heating, Refrigerating and Air-Conditioning Engineers and a member of the Academy of Fellows of the International Society of Indoor Air Quality and Climate. His research interests including healthy and sustainable buildings, ventilation and indoor air quality in residential and commercial buildings, control of indoor particulate matter, the indoor microbiome, and moisture interactions with indoor chemistry and biology. He holds a B.Sc. from Swarthmore College and an M.S. and Ph.D. in mechanical engineering from the University of California, Berkeley.

Brent Stephens, Ph.D., is a professor of architectural engineering, Arthur W. Hill Endowed Chair in Sustainability, and department chair in the Department of Civil, Architectural, and Environmental Engineering at the Illinois Institute of Technology (IIT). He is a specialist in the fate and transport of indoor pollutants, building energy and environmental measurements and models, HVAC filtration, and human exposure assessment. Dr. Stephens co-directs the Built

Environment Research Group at IIT, which consists of undergraduate students, graduate students, and postdoctoral researchers conducting research on energy efficiency and indoor air quality in buildings. His research projects have included improving and applying methods to measure the infiltration of outdoor particulate matter and reactive gases into homes; measuring gas and particle emissions and evaluating emission control devices; measuring the in-situ particle removal efficiency of HVAC filters in real environments; developing inexpensive, open-source devices for measuring and recording long-term indoor environmental and building operational data; and characterizing the energy, air quality, and health impacts of ventilation and air cleaning interventions. Dr. Stephens holds a B.S. in civil engineering from Tennessee Technological University and an M.S.E. in environmental and water resources engineering and Ph.D. in civil engineering from The University of Texas at Austin.

Marina E. Vance, Ph.D., is an associate professor and McLagan Family Faculty Fellow in the Department of Mechanical Engineering at University of Colorado Boulder, and she holds a courtesy appointment in the university's environmental engineering program. Her research is focused on air quality, specifically on measuring emissions and understanding the dynamics of aerosols in the context of ambient and indoor air quality. She is one of the principal investigators of the HOMEChem (House Observations of Microbial and Environmental Chemistry) and CASA (Chemical Assessments of Surfaces and Air) research initiatives, which were large indoor chemistry field campaigns incorporating measurements from several research groups. Dr. Vance earned B.S. (sanitation and environmental engineering) and M.S. (environmental engineering) degrees from the Universidade Federal de Santa Catarina (Brazil) and a Ph.D. (civil and environmental engineering) from Virginia Tech.

PROJECT STAFF

David A. Butler, Ph.D., is the J. Herbert Hollomon Scholar of the National Academy of Engineering (NAE). He also serves as the director of NAE's Cultural, Ethical, Social, and Environmental Responsibility in Engineering program. Before joining the National Academies, Dr. Butler served as an analyst for the U.S. Congress Office of Technology Assessment, was a research associate in the Department of Environmental Health of the Harvard T.H. Chan School of Public Health, conducted research at Harvard's John F. Kennedy School of Government and practiced as a product safety engineer at Xerox Corporation. He has directed numerous National Academies studies on environmental health and technology policy topics, including ones that produced the reports *Climate Change, the Indoor Environment, and Health*; *Damp Indoor Spaces and Health*; and *Clearing the Air: Asthma and Indoor Air Exposures*. Dr. Butler earned his B.S. and M.S. degrees in electrical engineering from the University of Rochester and his Ph.D. in public policy analysis from Carnegie Mellon University. He is a recipient of the National Academies' Cecil Medal for Research.

Courtney Hill, Ph.D., was formerly a program officer at the National Academy of Engineering working within the Cultural, Ethical, Social, and Environmental Responsibility in Engineering Program. Prior to joining the National Academy of Engineering, Dr. Hill was a Mirzayan Science and Technology Policy Fellow at the InterAcademy Partnership where she coordinated international meetings addressing how academies across the globe could work together to support the United Nations' Sustainable Development Goals. In addition, Dr. Hill has also taught

English at a magnet high school in South Korea as a Fulbright Scholar. Dr. Hill earned her B.S. degree in civil engineering from the University of Arkansas and her M.E. and Ph.D. degrees in civil engineering from the University Virginia. Her doctoral research investigated the relationship between human health and access to silver-embedded ceramics as well as other mechanisms by which silver can be used to treat water in low-income areas.

Maiya Spell, B.S., was formerly a senior program assistant in the Program Office of the National Academy of Engineering. Ms. Spell graduated from the University of Maryland, College Park, in 2021, where she received a B.S. in public health science and certificate in Black women's studies. During her undergraduate career, she worked across a variety of fields, including interning in the cardiology department at the University of Maryland Medical Center; interning at Time Organization Inc., a mental health clinic for kids and adolescents; and working in property management for Morgan Properties.

Casey Gibson, M.S. E.I.T, is an associate program officer at the National Academy of Engineering where she focuses on projects related to cultural, ethical, social, and environmental responsibility. In 2022 Ms. Gibson earned her M.S. degree in humanitarian engineering and science with a focus in environmental engineering from the Colorado School of Mines. During her master's degree work, she developed, taught, and implemented a participatory methodology for sociotechnical analysis in engineering projects and focused her fieldwork in rural Colombian communities. She holds dual undergraduate degrees in biological/agricultural engineering and Spanish with a minor in sustainability from the University of Arkansas. Additionally, she was a Fulbright Scholar in Mexico from 2018 to 2020.

Chessie Briggs, B.A., is a senior program assistant in the Program Office of the National Academy of Engineering. Ms. Briggs graduated from the University of Redlands in 2022, where she received a B.A. in both public policy and political science. During her undergraduate career, she worked for an international nonprofit organization, traveling to China to help implement a new program in a local orphanage, and worked for the (Washington State) City of Federal Way's Economic Development Director, assessing the city's capabilities to host a large-scale event. Additionally, she has recently worked as a legislative intern on Capitol Hill.