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Predicting and Measuring the Effect of Indoor Air Quality Interventions in Representative Real World Use Cases

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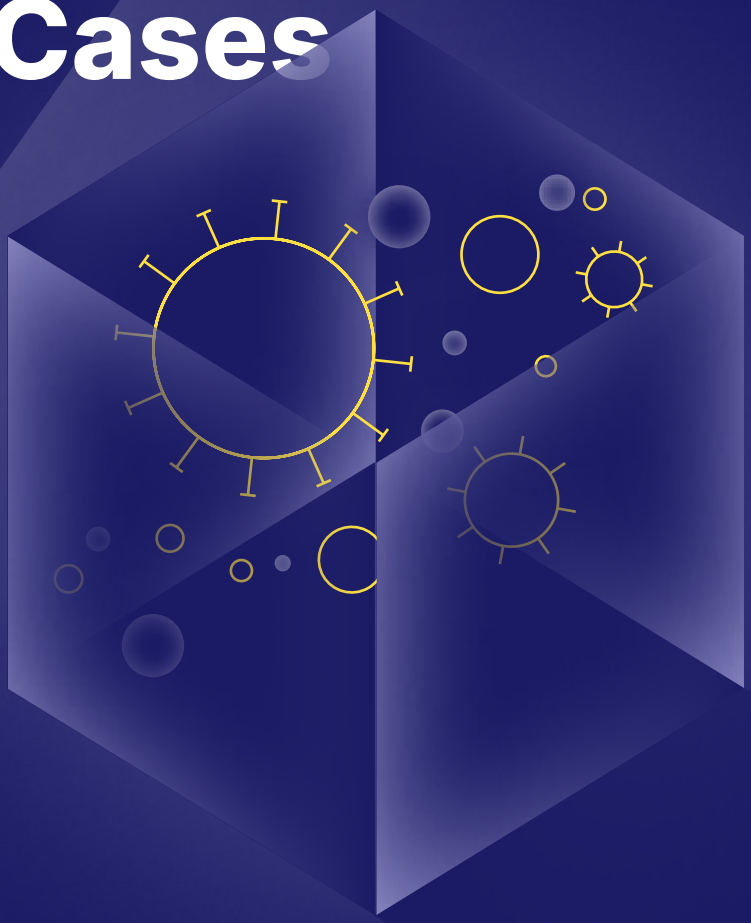

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Executive Summary

Indoor air quality (IAQ) shapes our health wherever we breathe — at work, at school, or at home — which matters considerably given that Americans spend roughly 90% of their time indoors. Several states and cities have begun to act. Boston has a district-wide sensor dashboard tracking real-time air quality in classrooms, while Colorado and Rhode Island have launched statewide programs to improve school ventilation. Such measures have become easier to implement and evaluate as international engineering standards, including the American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE) new Standard 241 (2023), now establish quantifiable targets for controlling infectious aerosols.

This paper estimates the impacts of IAQ interventions in representative real-world settings and proposes appropriate measures of success. It synthesizes the literature linking IAQ to disease and related outcomes such as school performance; reviews the costs and benefits of ventilation, filtration, germicidal ultraviolet light (GUV), and source control; catalogues the passively generated datasets and other real-world evidence streams that can capture these impacts; and outlines biostatistical designs for detecting effects in that data. It then models representative use cases for schools and nursing homes to identify likely effects and appropriate measurement strategies.

We recommend a limited set of interventions in contexts where they are most likely to be cost-effective and impactful. Because average outdoor air pollution in the United States is relatively low (1–5 $\mu g/m^3$), the benefits of $PM_{2.5}$ reduction are real but modest and strongly context-dependent. $PM_{2.5}$ reduction in higher-pollution settings, by contrast, can deliver substantial gains and in some contexts prove robustly cost-saving when funded by the government. Schools, where educational outcomes are both valuable and measurable, emerge as a particularly attractive opportunity.

The broader argument is that air quality improvements should be tied to monitoring and evidence generation so as to improve the ability to reliably forecast the impact of IAQ interventions in new spaces. Embedding evidence generation into real-world deployments creates a feedback loop between evidence, prediction, and impact, enabling more cost-effective interventions over time.

Diseases and Outcomes Affected by Indoor Air Quality

This section synthesizes the existing literature on the effects of indoor air quality (IAQ) on health and educational outcomes. Each disease or condition is introduced with relevant background, followed by estimates of its overall burden and associated unit costs (such as cost per hospitalization). We then examine the evidence linking IAQ to disease risk and severity, concluding each subsection with a table of key studies quantifying IAQ's contribution to disease burden. Taken together, these summaries aim to provide researchers, policymakers, and practitioners with a clear, evidence-based understanding of how indoor air quality shapes health.

Chronic Obstructive Pulmonary Disease

General Background

Chronic obstructive pulmonary disease (COPD) is a progressive, inflammatory lung disorder characterized by persistent airflow limitation and tissue destruction It is primarily linked to long-term exposure to noxious particles or gases, including those produced by cigarette smoke While smoking remains the dominant risk factor, growing epidemiological and toxicological evidence indicates that ambient and indoor fine $PM_{2.5}$ is a significant contributor to both the development and exacerbation of COPD. Indoor environments, particularly in high-occupancy and poorly ventilated settings, can present substantial chronic exposures to $PM_{2.5}$.

$PM_{2.5}$ (particles with an aerodynamic diameter of 2.5 micrometers or less) penetrate deeply into the respiratory tract and evade mucociliary clearance. This can lead to oxidative stress, inflammation, and structural remodeling of the airways. At a biological level, exposure to $PM_{2.5}$ triggers inflammation in the body. It increases the release of chemical signals that drive inflammation and causes immune cells to accumulate in the airways, which can damage lung tissue and worsen respiratory health. Longitudinal cohort studies have demonstrated that long-term exposure to elevated $PM_{2.5}$ concentrations is associated with accelerated lung function decline and increased incidence of COPD.

Overall Disease Burden

COPD is a major cause of morbidity and mortality in the United States. Based on recent national health interview data, approximately 3.8% of U.S. adults aged 18 and older report a diagnosis of COPD. Prevalence rises from less than 1% in early adulthood to more than 10% among those over 75 years. COPD is consistently ranked among the top five leading causes of death in the United States, with more than 120,000 deaths annually attributed to the disease.

There are also hundreds of thousands of hospitalizations due to acute COPD exacerbations in the U.S. annually. These hospitalizations are the largest driver of COPD-related healthcare costs. Inpatient stays cost roughly US $20,000 per admission. When combined with outpatient care, medications, home oxygen, and pulmonary rehabilitation, direct medical costs exceed US $20 billion annually and are projected to rise to more than US $60 billion by 2029.

Disease Burden Attributable to Indoor Air Quality

Large cohort studies show that each additional 5 $\mu g/m^3$ long-term $PM_{2.5}$ exposure increases COPD risk by 17%. This means that a typical increase 2–3 $\mu g/m^3$ above background found in US buildings increases COPD risk by 6–9%. However, this risk is likely not evenly distributed, because older cohorts are at higher risk.

Incidents that create higher $PM_{2.5}$ concentrations increase these baseline risks. A study conducted during U.S. wildfire seasons estimated that each 10 $\mu g/m^3$ increase in wildfire-related $PM_{2.5}$ resulted in a 2.5% increase in COPD (potato) hospital admissions. As an example of extent, another study found an 18% rise in COPD emergency-department visits during wildfire periods in California. These findings suggest that episodic as well as sustained $PM_{2.5}$ exposure contributes substantially to acute exacerbations requiring medical intervention.

Related Studies

Author	Date	Title	Study type	Description	Link
Zhu	2020	Relationship Between Particulate Matter ($PM_{2.5}$) and Hospitalizations and Mortality of Chronic Obstructive Pulmonary Disease Patients: A Meta-Analysis	Meta-analysis	Meta-analysis including 18 studies, finding that a 10-µg/m³ increase in $PM_{2.5}$ was associated with a 2.5% (95% confidence interval [CI]: 1.8-3.2%) increase in COPD hospitalization	https://www.sciencedirect.com/science/article/pii/S0002962920301087
Liu	2024	Long-term exposure to low-level air pollution and incidence of chronic obstructive pulmonary disease: The ELAPSE project	Cohort	Pooled data from three cohorts in Denmark and Sweden, tracking 4,928 new COPD cases. Ambient pollution was assessed using postcode level data for each participant's address. Increasing ambient $PM_{2.5}$ by 5 µg/m³ led to a 1.17HR for COPD risk	https://www.sciencedirect.com/science/article/pii/S0160412020322224
Horne	2024	Association of Short-Term Increases in Ambient Fine Particulate Matter With Hospitalization for Asthma or COPD During Wildfire Season and Other Time Periods	Case-crossover population	Large case-crossover study investigating how short-term increases in fine particulate matter ($PM_{2.5}$) and ozone were associated with hospitalizations for asthma and COPD in Utah's Wasatch Front between 1999 and 2022. The analysis covered 63,976 asthma and 18,514 COPD hospitalization events. $PM_{2.5}$ showed only modest links with COPD risk, but stronger with asthma	https://pubmed.ncbi.nlm.nih.gov/38993972/
Delavar	2023	Relationship between fine particulate matter ($PM_{2.5}$) concentration and risk of hospitalization due to chronic obstructive pulmonary disease: a systematic review and meta-analysis	Meta-analysis	A 19-study meta analysis (10 time-series and 9 case-crossover) to examine the association between short-term increases in ambient $PM_{2.5}$ and hospitalization for COPD, finding a 10µg/m³ increase in daily $PM_{2.5}$ was associated with a 1.6% increase in COPD hospitalizations (95% CI: 0.4% to 2.9%) across all included studies.	https://link.springer.com/article/10.1186/s12889-023-17093-6
Bai	2018	Long-Term Exposure to Air Pollution and the Incidence of Chronic Obstructive Pulmonary Disease (COPD) and Asthma: A Population-Based Cohort Study in Ontario, Canada	Population-based cohort	Followed 5.1 million adults aged 35 years and older, all initially free of asthma and COPD, from 2001 to 2015. 340,733 individuals developed COPD and 218,005 developed asthma. Each interquartile range increase in $PM_{2.5}$ was associated with a 7% higher incidence of COPD, even at lower levels of exposure. Adjusting for deprivation lowered the effect size to 1.04.	https://www.researchgate.net/publication/337525879_Long-Term_Exposure_to_Air_Pollution_and_the_Incidence_of_Chronic_Obstructive_Pulmonary_Disease_COPD_and_Asthma_A_Population-Based_Cohort_Study_in_Ontario_Canada
Ried	2016	Differential respiratory health effects from the 2008 northern California wildfires: A spatiotemporal approach	Population-based cohort	Investigates emergency department admissions following a wildfire event in California, finding a RR of 1.02 for COPD ED visit per 5 µg/m³ increase in $PM_{2.5}$	https://www.sciencedirect.com/science/article/pii/S001393511630247X
Alman	2016	The association of wildfire smoke with respiratory and cardiovascular emergency department visits in Colorado in 2012: a case crossover study	Case-crossover	Case-crossover study following $PM_{2.5}$ increases after wildfires in Colorado, finding a OR of 1.01 for ED visits per 10 µg/m³ increase in $PM_{2.5}$	https://pubmed.ncbi.nlm.nih.gov/27259511/
Cowan	2023	Effect measure modification of the association between short-term exposures to $PM_{2.5}$ and hospitalizations by long-term $PM_{2.5}$ exposure among a cohort of people with Chronic Obstructive Pulmonary Disease (COPD) in North Carolina, 2002–2015	Case-crossover	Randomly selected individuals with COPD from electronic health records. Ensemble modelling was used to estimate $PM_{2.5}$ concentrations in the local area, finding a null effect of short-term $PM_{2.5}$ increases on COPD admissions	https://ehjournal.biomedcentral.com/articles/10.1186/s12940-023-00999-4
Park	2025	Ambient Air Pollution and Chronic Obstructive Pulmonary Disease: The Multiethnic Cohort Study	Cohort	In the Medicare data of 38,000 participants, chronic $PM_{2.5}$ exposure was associated with higher COPD incidence risk in models with multiple pollutants (HR 1.06 per 10 µg/m³) but individually showed no significant result	https://doi.org/10.1513/AnnalsATS.202404-387OC
Xu	2025	Long-term exposure to smoke $PM_{2.5}$ and COPD caused mortality for elderly people in the contiguous United States	Cohort	Used Medicare data to study the effect of smoke $PM_{2.5}$ from wildfire events in an elderly cohort (65-100), finding a 9.2% increase in COPD mortality per 1 µg/m³ increase	https://www.sciencedirect.com/science/article/pii/S0160412025002648

Asthma

General Background

Asthma is a chronic inflammatory disease of the airways that causes variable airflow limitation and recurrent symptoms such as wheezing, breathlessness, and cough. While genetic disposition and allergies are key factors, environmental exposures also contribute to asthma development and exacerbations. Indoor sources such as cooking, heating, and smoking generate $PM_{2.5}$ that reach the lower airways, trigger oxidative stress, and precipitate asthma attacks.

Overall Disease Burden

Asthma affects approximately 25 million Americans (7.7% of the population) and causes thousands of deaths annually. While prevalence has risen modestly in recent decades, other measures of burden have improved. Asthma-related hospitalizations fell from roughly 13.0 per 10,000 people in 2001 to 2.9 per 10,000 in 2020, and emergency department visits have roughly halved. The economic burden nonetheless remains substantial. A CDC analysis of 2008–2013 data estimated the total U.S. cost of asthma at $81.9 billion per year, comprising $50.3 billion in direct medical costs, $29 billion in mortality-related losses, and $3 billion from missed school and work days.

Disease Burden Attributable to Indoor Air Quality

Data on the impacts of IAQ improvement that are specific to U.S. indoor settings are still limited. However, we can make tentative estimates based on extant systematic reviews. Long-term exposure to $PM_{2.5}$ is associated with increased risk of developing asthma, while short-term exposure can cause exacerbation. A major meta-analysis found that up to ⅓ of asthma cases worldwide in 2019 were associated with $PM_{2.5}$. In adults, a marginal increase of 5 $\mu g/m^3$ $PM_{2.5}$ causes approximately a 7% increase in the incidence of asthma.

However, the evidence specifically isolating indoor $PM_{2.5}$ (versus ambient/outdoor or mixed sources) in U.S. settings is more limited and, in many cases, lacks sufficient data to confidently attribute the fraction of burden. However, assuming a 1 $\mu g/m^3$ reduction in $PM_{2.5}$ in office buildings, we could assume a 1.2% reduction in asthma incidence in US adults. Assuming a similar decrease in schools, we could expect a 4.2% reduction in asthma incidence, based on a HR of 1.23.

Related Studies

Author	Date	Title	Study type	Description	Link
Lee	2024	Ambient air pollution exposure and adult asthma incidence: a systematic review and meta-analysis	Meta-analysis	Meta-analysis of 25 studies, finding that risk ratio of adult-onset asthma is 1.07 (95% CI 1·01 to 1·13) per 5 µg/m³ increase in $PM_{2.5}$	https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(24)00279-1/fulltext
Zanobetti	2024	Early-Life Exposure to Air Pollution and Childhood Asthma Cumulative Incidence in the ECHO CREW Consortium	Cohort	Cohort of 5279 children recruited and followed up until 11 years old, with $PM_{2.5}$ levels estimated using participant's birth address. A 3.4 µg/m³ (1 IQR) increase in ambient $PM_{2.5}$ caused a HR of 1.31 (95% CI, 1.04-1.66) in children under five and OR of 1.23 (95% CI, 1.01-1.50) for children under 11 for developing asthma	https://pmc.ncbi.nlm.nih.gov/articles/PMC10902721/
Pedersen	2024	Birth Cohort Studies of Long-Term Exposure to Ambient Air Pollution in Early Life and Development of Asthma in Children and Adolescents from Denmark	Birth Cohort	1.8 million children had exposure to $PM_{2.5}$ estimated, prenatally to the age of 7, finding that a an 8.7 µg/m³ (1 IQR) increase in $PM_{2.5}$ caused a HR of 1.06 (95% CI 1.04-1.08) for prenatal exposure and 1.08 (95% CI 1.05-1.10) postnatally, for the risk of developing asthma	https://pmc.ncbi.nlm.nih.gov/articles/PMC11525942/pdf/hei-2024-219.pdf
Ni	2024	Long-term exposure to $PM_{2.5}$ has significant adverse effects on childhood and adult asthma: A global meta-analysis and health impact assessment	Meta-analysis	Meta-analysis of 1027 studies finding that a 10 µg/m³ increase in $PM_{2.5}$, causes a 21.4% (95% CI 11.4%–32.3%) increase in childhood and 7.1% (95% CI: 1.6%–12.9%) adult asthma prevalence, incidence, and mortality. They also predict 1/3 of asthma cases in 2019 were associated with $PM_{2.5}$	https://www.sciencedirect.com/science/article/pii/S2590332224004871
Keleb	2025	The odds of developing asthma and wheeze among children and adolescents exposed to particulate matter: a systematic review and meta-analysis	Meta-analysis	Meta-analysis of 47 studies including 417,874 children and adolescents finds the OR between PM10 and asthma at 1.04 (95% CI: 1.03–1.06, $p < 0.001$) and $PM_{2.5}$ at 1.05 (95% CI 1.04–1.07, $p < 0.001$), with high heterogeneity in both categories indicating significant variation in results of different studies	https://bmcpublichealth.biomedcentral.com/articles/10.1186/s12889-025-22382-3
Fan	2015	The impact of $PM_{2.5}$ on asthma emergency department visits: a systematic review and meta-analysis	Meta-analysis	Systematic review and meta-analysis of studies up to 2015, finding ED visits rose 1.5% per 10 µg/m³ increase in $PM_{2.5}$ (95% CI: 1.2–1.7%), with children more susceptible (3.6% increase) than adults (1.7%). The effect was strongest in the warm season (3.7% per 10 µg/m³) compared to the cold season (2.6%)	https://pubmed.ncbi.nlm.nih.gov/26347419
Horne	2024	Association of Short-Term Increases in Ambient Fine Particulate Matter With Hospitalization for Asthma or COPD During Wildfire Season and Other Time Period	Case-crossover	Analysis of wildfire events, showing on same day as a 10 µg/m³ $PM_{2.5}$ increase, asthma hospitalizations rose by 5.7% (OR 1.057, 95% CI: 1.019–1.097) in wildfire season and 2.3% (OR 1.023, 95% CI: 1.010–1.037) during winter inversions.	https://www.chestpulmonary.org/article/S2949-7892(24)00019-9/pdf
Khalili	2018	Early-life exposure to $PM_{2.5}$ and risk of acute asthma clinical encounters among children in Massachusetts: a case-crossover analysis	Case-crossover	This study found no overall association between short-term $PM_{2.5}$ exposure and asthma clinical encounters in children, with odds ratios close to 1.0 across lag days 0–2, though some effect appears in children with low birthweight	https://link.springer.com/article/10.1186/s12940-018-0361-6

Cardiovascular Disease

General Background

Cardiovascular disease (CVD) encompasses disorders of the heart and blood vessels that impair blood flow, cardiac function, or vascular integrity, raising the risk of events like heart attack and stroke. Exposure to $PM_{2.5}$ is associated with elevated cardiovascular morbidity and mortality across diverse populations and settings. It contributes to chronic conditions such as atherosclerosis, hypertension, and arrhythmias, and can precipitate acute events including myocardial infarction and stroke.

Overall Disease Burden

Cardiovascular disease is the leading cause of death in the United States. It accounted for over 940,000 deaths in 2022 — coronary heart disease alone claimed roughly 371,500 lives, and stroke another 165,400 — and nearly half of U.S. adults live with some form of cardiovascular condition. The economic toll is commensurate in its severity. Between 2020 and 2021, CVD imposed an estimated $417 billion in annual costs on the U.S. economy, comprising roughly $233 billion in direct medical expenses (hospital care, treatment, outpatient services, and medications) and $184 billion in indirect costs from lost productivity and premature mortality.

Disease Burden Attributable to Indoor Air Quality

A substantial proportion of American CVD deaths are linked to long-term exposure to fPM$_{2.5}$. Cohort studies consistently show that each 10 µg/m³ increase in annual PM$_{2.5}$ is associated with an approximate 10–20% increase in cardiovascular mortality risk. The Global Burden of Disease project estimates that fine particulate matter contributes to more than 100,000 premature U.S. deaths annually. It further suggests that the majority are due to cardiovascular causes such as heart attack, stroke, and heart failure. Using a basic linear calculation and asuming a 12% reduction in CV mortality associated with a 10 µg/m³ reduction in PM$_{2.5}$ (as reported in a cohort of 2.1 million Canadian adults) the same 1 µg/m³ reduction in office spaces over 40 hours a week could produce a 0.3% reduction in the risk of CV death.

Related Studies

Author	Date	Title	Study type	Description	Link
Hayes	2020	PM$_{2.5}$ air pollution and cause-specific cardiovascular disease mortality	Cohort	In 565,000 older adults (ages 50–71), each 10 µg/m³ rise in chronic PM$_{2.5}$ was cause a 16% increase in ischemic heart disease mortality and a 14% increase in stroke mortality	https://pmc.ncbi.nlm.nih.gov/articles/PMC7124502/
Crouse	2012	Risk of Nonaccidental and Cardiovascular Mortality in Relation to Long-term Exposure to Low Concentrations of Fine Particulate Matter: A Canadian National-Level Cohort Study	Cohort	A cohort of ~2.1 million adults in Canada, where long-term PM$_{2.5}$ exposure was associated with 12–14% higher CVD mortality per 10 µg/m³.and up to 30% for ischemic heart disease	https://pubmed.ncbi.nlm.nih.gov/22313724/
Pope	2014	Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution	Cohort	A nationwide U.S. study tracking 500,000 adults over 16 years. It reported a 10 µg/m³ increase in long-term PM$_{2.5}$ was associated with a 4% all-cause, 6% cardiovascular, and 8% lung cancer mortality risk	https://pmc.ncbi.nlm.nih.gov/articles/PMC4037163/
Miller	2007	Long-term exposure to air pollution and incidence of cardiovascular events in women	Cohort	This study followed ~65,000 postmenopausal U.S. women without prior CVD to examine incidence of first cardiovascular events. It found a 24% increase in overall CV events, including a 35% increase in stroke risk and 76% increase in CV deaths per 10 µg/m³ increase in annual PM$_{2.5}$	https://pubmed.ncbi.nlm.nih.gov/17267905/
Cesaroni	2014	Long term exposure to ambient air pollution and incidence of acute coronary events: prospective cohort study and meta-analysis in 11 European cohorts from the ESCAPE Project	Meta-analysis	An analysis of 11 studies across Europe showed each 5 µg/m³ increase in long-term PM$_{2.5}$ was associated with a 13% increase in risk of acute coronary events	https://pubmed.ncbi.nlm.nih.gov/24452269
Shah	2015	Short term exposure to air pollution and stroke: systematic review and meta-analysis	Meta-analysis	This large meta-analysis of 94 studies across 28 countries found that short-term increases in PM$_{2.5}$ linked a 10 µg/m³ rise in PM$_{2.5}$ was a 1.1% increase in stroke-related events (RR 1.011, 95% CI: 1.011–1.012), with the strongest effects observed on the day of exposure and persisting beyond acute exposure.	https://pubmed.ncbi.nlm.nih.gov/25810496/

Infectious Disease

General Background

In the United States, the largest burden of infectious respiratory disease comes from COVID-19, seasonal influenza, and respiratory syncytial virus, all of which are transmitted through the air. Unlike other IAQ-mediated conditions, infectious diseases spread from person to person, so the effects of interventions are nonlinear and compound through social interactions. For example, preventing infection in one schoolchild can also prevent infections in classmates. As a result, interventions are likely to be most impactful in high-contact settings.

Overall Disease Burden

The health and economic consequences of acute respiratory infections are severe. The CDC estimates that between 2024–2025, there were between 13.4-20 million COVID cases, 370,000–530,000 COVID-related hospitalizations, and 42,000–61,000 COVID-related deaths. COVID can also cause chronic symptoms, usually called long COVID, including fatigue and brain fog. For each year that a person experiences long COVID, the U.S. stands to lose about $5,000-12,000 in productivity losses.

Seasonal flu strains vary from year to year, and so do their health and economic consequences. However, the CDC estimates that flu caused between 9-41 million illnesses, 100,000–710,000 hospitalizations, and 5,000–51,000 deaths in the U.S. each year. In 2018, influenza was predicted to cost a total of $11.2 billion in direct and indirect costs each year.

RSV cases are more difficult to trace and their impact is therefore more challenging to assess., The symptoms are similar to those of the common (coronavirus-based) cold for many people. However, the risks are high, particularly amongst infants and the elderly . In the United States in 2024–2025, there were 3.6–6.5 million outpatient visits, 190,000–350,000 hospitalizations, and 10,000–23,000 deaths. Although most children will be infected with RSV by age two and will not require hospitalization, it is the most common cause of hospitalization in infants.

Disease Burden Attributable to Indoor Air Quality

Infectious respiratory diseases, particularly COVID-19, influenza, and RSV, impose a substantial and recurring burden on the United States, and a growing body of evidence links their transmission to the quality and management of indoor air. Trainees in tightly sealed, poorly ventilated Army barracks experienced significantly higher rates of febrile respiratory illness than those in older, less energy-efficient structures; office workers in buildings with lower outdoor air supply took more short-term sick leave; and in-duct UVGI in office ventilation systems reduced both HVAC microbial contamination and worker-reported respiratory symptoms. Taken together, these studies suggest that indoor air quality shapes the transmission of respiratory infections. At the

same time, quantification of the reduction of respiratory disease via filtration has been challenging, so air-cleaning methods that focus on disinfection (such as germicidal UVC) may be necessary to see a large effect.

Related Studies

Author	Date	Title	Study type	Description	Link
Wells, W.F.	1943	Air Disinfection in Day Schools	Interventional field study (upper-room UVGI in schools)	Multi-year school deployments of upper-room UVGI reported lower measles and other childhood infection attack rates in treated classrooms compared with untreated classrooms.	https://pmc.ncbi.nlm.nih.gov/articles/PMC1527686/
Wells, M.W. (Mildred Weeks)	1945	Ventilation in the Spread of Chickenpox and Measles within School Rooms	Observational/analytic (school epidemiology)	Analysis of school outbreaks and ventilation argued that higher ventilation and/or air disinfection reduced spread of measles and chickenpox in classrooms.	https://jamanetwork.com/journals/jama/article-abstract/275822
Wheeler et al.	1945	Ultra-violet Light Control of Air-borne Infections in a Naval Training Center (Preliminary Report)	Interventional (upper-room UVGI in barracks)	Naval recruit barracks with upper-room UVGI experienced lower respiratory-disease hospitalization rates during UVGI operation periods compared with non-UV periods.	https://pmc.ncbi.nlm.nih.gov/articles/PMC1625411/
Perkins; Bahlke; Silverman	1947	Effect of Ultra-violet Irradiation of Classrooms on Spread of Measles in Large Rural Central Schools (Preliminary Report)	Interventional (upper-room UVGI)	School UVGI program with mixed results for measles reduction across sites, highlighting design and contextual factors.	https://ajph.aphapublications.org/doi/10.2105/AJPH.37.5.529
Miller et al.	1948	Evaluation of Ultraviolet Radiation and Dust Control Measures in Control of Respiratory Disease at a Naval Training Center	Interventional (UVGI ± dust control)	Naval training center study reported fewer respiratory-disease hospitalizations in buildings using UV plus dust control versus comparison conditions.	https://doi.org/10.1093/infdis/82.1.86
Brundage et al.	1988	Building-Associated Risk of Febrile Acute Respiratory Diseases in Army Trainees	Natural experiment (barracks comparison)	Across four training centers over 47 months, trainees in modern airtight barracks had higher febrile ARD rates than those in older leaky barracks (adjusted RR ≈1.5).	https://jamanetwork.com/journals/jama/article-abstract/371466
Milton; Glencross; Walters	2000	Risk of Sick Leave Associated with Outdoor Air Supply Rate, Humidification, and Occupant Complaints	Observational (40 buildings; 3,720 workers)	Lower outdoor air supply was associated with higher short-term sick leave among office workers (RR ~1.5 for lower vs higher ventilation).	https://pubmed.ncbi.nlm.nih.gov/11089326/
Menzies et al.	2003	Effect of UVGI Installed in Office Ventilation Systems on Workers' Health and Well-Being	Double-blind, multiple crossover trial (3 buildings)	In-duct UVGI reduced microbial contamination on HVAC surfaces and was associated with fewer reported work-related respiratory and mucosal symptoms.	https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(03)14897-0/abstract
Shendell et al.	2004	Associations Between Classroom CO_2 Concentrations and Student Attendance in Washington and Idaho	Cross-sectional (434 classrooms)	Higher indoor–outdoor CO_2 (proxy for lower ventilation) was associated with lower average daily attendance; many rooms exceeded 1,000 ppm.	https://energyanalysis.lbl.gov/publications/associations-between-classroom-co2
White et al.	2011	Association Between Barracks Type and Acute Respiratory Infection in a Gender-Integrated Army Basic Combat Training Population	Observational (n=16,258)	Higher ARI risk in 60-person open-bay rooms compared with 8-person rooms; findings suggest room type and occupancy are associated with ARI risk.	https://pubmed.ncbi.nlm.nih.gov/21882781/
Gettings et al.	2021	Mask Use and Ventilation Improvements to Reduce COVID-19 Incidence in Elementary Schools — Georgia, Nov–Dec 2020	Observational (school-level)	Among 169 K–5 schools, ventilation improvements were associated with lower COVID-19 incidence; dilution alone and dilution plus filtration/UVGI had larger reductions relative to no improvement.	https://www.cdc.gov/mmwr/volumes/70/wr/mm7021e1.htm/
Jutkowitz et al.	2023	The Benefits of Nursing Home Air Purification on COVID-19 Outcomes: A Natural Experiment	Interrupted time-series (81 nursing homes; HVAC UV air-purification)	Post-installation trends showed fewer weekly COVID-19 cases per 1,000 residents and a lower probability of any weekly case; no change in mortality detected.	https://pmc.ncbi.nlm.nih.gov/articles/PMC10247880/
Thottiyil S.A.K. et al.	2024	Air Purifiers and Acute Respiratory Infections in Residential Aged Care: A Randomized Clinical Trial	Double-blind, 2-period crossover RCT (HEPA-14 vs sham)	Intention-to-treat showed no significant difference in ARI incidence; among participants completing the full protocol, a lower ARI proportion was observed with HEPA.	https://pmc.ncbi.nlm.nih.gov/articles/PMC11555545/
Shoubridge et al.	2025	Germicidal UV Light and Incidence of Acute Respiratory Infection in Long-Term Care for Older Adults	Cluster, double-crossover RCT (upper-room UVGI in common areas)	Primary analysis found no significant reduction in ARI incidence; secondary analyses over extended follow-up suggested fewer total infections per week with UV.	https://pubmed.ncbi.nlm.nih.gov/40720106/

School Performance

Indoor air quality has measurable effects on student performance and attendance in U.S. schools. Inadequate ventilation, elevated CO_2, $PM_{2.5}$, and indoor pollutants such as mold degrade air quality, impair cognition, and drive up absenteeism. A prospective study of California elementary schools found that increasing classroom ventilation to 7.1 liters per second per person reduced illness-related absenteeism by 3.4%, corresponding to an estimated $33 million increase in attendance-linked funding for a typical district.

Improved IAQ also appears to enhance cognitive performance. Controlled experiments show that doubling ventilation rates increases student task performance by 14%, while modest reductions in classroom temperature yield an additional 4% improvement. Following the 2015 Aliso Canyon gas leak, air filters were installed in Los Angeles schools, resulting in gains of 0.20σ in math scores and 0.18σ in English scores at a cost of roughly $1,020 per classroom per year. Beyond the classroom, reduced sickness and absenteeism also generate broader economic benefits by lowering disruption and caregiving burdens for parents.

Related Studies

Author	Date	Title	Study type	Description	Link
Gilraine	2020	Air Filters, Pollution, and Student Achievement	Natural intervention	Due to a gas leak, air filters were placed in 18 schools. Schools which had filters installed had higher Math (0.20σ) and English scores (0.19σ), or an 8% increase in standardized test scores, at a cost of $1020 per classroom	https://edworkingpapers.com/sites/default/files/Gilraine_AirFilters_1.pdf
Mendell	2013	Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools a prospective study in California elementary schools	Observational	Studied links between illness, absenteeism, and CO2 in 28 schools in California, finding increasing ventilation levels from 4 to 7 L/s/person would create $33 million of benefits at a cost of $4 million	https://pmc.ncbi.nlm.nih.gov/articles/PMC7165692/pdf/INA-23-515.pdf
Bonan	2025	The Effect of Air Purifiers in Schools	RCT	Air filters, installed in 95 classrooms over 5 primary schools in Milan, reduced absence levels by 12.5% at a cost of $12 per day, for a x10 ROI	https://media.rff.org/documents/WP_25-17.pdf
Saverinen-Shaughnessy	2015	Effects of Classroom Ventilation Rate and Temperature on Students' Test Scores	Observational	Study of 140 fifth-grade classrooms in the Southwestern U.S., finding that higher ventilation rates and lower classroom temperatures were significantly associated with better student achievement. Math scores rose by about 11 points (0.5%) per 1 L/s per person increase in ventilation and by 12–13 points per 1°C decrease in temperature within observed ranges, with similar though more variable effects for reading and science.	https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0136165
Wen	2022	Lower test scores from wildfire smoke exposure	Observational	Analysis of standardized test scores from nearly 11,700 U.S. school districts (2009–2016) alongside satellite data on wildfire smoke. An average school-year exposure of ~35 μg/m³ smoke-related $PM_{2.5}$ lowered test scores by ~0.15% of a standard deviation, with stronger effects in younger students. The authors estimate that in 2016 wildfire smoke reduced students' future earnings by $1.7 billion, with about 80% of losses borne by disadvantaged districts	https://www.nature.com/articles/s41893-022-00956-y
Lam	2023	Long-Term Exposure to Fine Particulate Matter and Academic Performance Among Children in North Carolina	Cross-sectional	This study analyzed data for ~2.8 million students in grades 3-8 in North Carolina (2001-2018), using a 2-way fixed-effects model to relate long-term annual $PM_{2.5}$ exposure (prior 12 months) to standardized math and reading test scores. It found that each 1 μg/m³ increase in annual $PM_{2.5}$ was associated with a 0.00976 standard deviation decline in math scores (95% CI: −0.01051 to −0.00899) and a 0.00681 SD decline in reading scores (95% CI: −0.00759 to −0.00602) relative to their grade-year means.	https://jamanetwork.com/journals/jamanetworkopen/fullarticle/2811147

Indoor Air Quality Interventions

Indoor air quality can be improved through four primary approaches: ventilation, filtration, germicidal ultraviolet (GUV) disinfection, and source control. Each targets a different set of pollutants and operates through distinct physical mechanisms, and each carries its own profile of costs, practical constraints, and evidence base. The sections that follow examine these four approaches in turn, weighing the potential benefits of each against the limitations that shape its real-world use. Taken together, they are best understood as complementary rather than competing strategies. No single intervention addresses the full range of indoor air pollutants, and the most effective programs typically combine several in ways suited to the building, occupants, and exposures at hand.

Ventilation

Ventilation replaces indoor air with outdoor air, diluting pollutants such as gases, particulate matter, and pathogens. Mechanical systems, on the other hand, distribute fresh air through either mixing or displacement. Costs vary widely with existing infrastructure. Doubling ventilation rates in a typical office adds roughly $40 per occupant per year in energy use, while HVAC retrofits to support higher airflow can be substantially more expensive and sometimes require full system replacement. Natural ventilation through windows demands little investment but depends on weather and outdoor air quality.

Filtration

Filtration captures particulate matter and pathogens but is ineffective against gaseous pollutants, and because both filtration and ventilation physically move air, they can produce noise and drafts that limit their real-world practicality. Filter performance is typically quantified by the clean air delivery rate (CADR), with larger spaces requiring proportionally more energy to reach recommended levels; the EPA publishes CADR guidelines for various room sizes as a reference.

Portable Air Cleaner Sizing for Particle Removal						
Room area (square feet)	100	200	300	400	500	600
Minimum CADR (cfm)	65	130	195	260	325	390

Various studies have estimated the cost of air filtration across several contexts. One study on HEPA filters in homes gave the cost of two units as $900, with running costs of $500. Another found that doubling the recommended ventilation rate in US offices (from 20 to 40cfm), would cost approximately $40 per occupant per year. A third study estimated the costs of installing and running HEPA filters in a 500m^2 office at $352 annually.

Taken together, these figures suggest a rough upfront cost of under $100 per person in a reasonably large office, with ongoing costs of about $20–50 per occupant. Actual costs vary widely depending on installation scale and existing ventilation systems.

Disinfection and Ultraviolet Light

Germicidal ultraviolet (GUV) systems use UV-C radiation to continuously inactivate pathogens by damaging their DNA and proteins. By acting directly on microorganisms, GUV provides an additional layer of protection in indoor environments where ventilation alone may be insufficient. The approach has been deployed for decades as a supplemental air-disinfection strategy, particularly in healthcare facilities and other high-risk settings, where upper-room GUV systems have been shown to substantially reduce transmission of respiratory infections such as tuberculosis, influenza, and SARS-CoV-2.

Recent advances in far-UVC technology have renewed interest in broadening GUV's applications. Far-UVC light, typically around 222 nm, is largely absorbed by the outermost layers of the skin and eyes and does not penetrate deeply enough to reach living cells, significantly reducing the risk of tissue damage compared with conventional 254 nm UV-C lamps and raising the

possibility of safely deploying continuous disinfection in occupied spaces such as classrooms, offices, and public venues.

Despite its promise, GUV implementation involves several practical considerations. System performance depends on proper maintenance, as dust accumulation and bulb aging can erode effectiveness over time. Poorly designed devices may also produce small amounts of ozone, a respiratory irritant, though this risk can be minimized through appropriate engineering controls. Effectiveness further depends on room geometry, air mixing, and exposure time, making careful system design and placement essential.

Regulatory and economic factors also shape GUV adoption. Occupational safety agencies set exposure limits for UV radiation, but consensus on safe thresholds for continuous far-UVC use in occupied environments is still evolving. Institutions such as schools and workplaces must in turn weigh installation and maintenance costs against expected health and productivity benefits.

Source Control

Source control reduces pollution at its source. It includes measures such as installing kitchen exhaust ventilation, selecting low-emission construction materials, and maintaining humidity levels that prevent mold growth. Source control addresses particulate and gaseous pollutants but does not reduce person-to-person transmission of pathogens. Costs vary widely by intervention. Behavioral changes can be low cost. Kitchen exhaust hoods typically cost $500–5,000. Whole-house humidity control systems typically cost about $2,000–3,800 installed.

Comparison of Methods

Intervention	Particulate Matter	Gaseous Pollutants	Pathogens	Comparative Advantages	Comparative Disadvantages	Maximum ACH (approx)
Source Control	✓	✓	×	Well-designed source control (eg fume hoods) can be extremely effective with low running costs	Only acts in particular locations, requires careful exhausting	N/A
Ventilation	✓	✓	✓	Removes all pollutant types, widely used, can increase subjective comfort	Can be energy intensive (especially with large temperature changes from outdoors), requires significant building infrastructure	5
Filtration	✓	×	✓	Can be highly inexpensive and easy to deploy	Requires regular maintenance, portable units can create noise and thermal discomfort	5
Upper-room UV	×	×	✓	Highly effective against pathogens	Only works against pathogens, complex to install (with significant risk to occupants if installed incorrectly), may require some modification of airflow, may create $PM_{2.5}$ smog	50
Far-UV	×	×	✓	Extremely effective against pathogens	Not widely available, expensive, can create ozone and $PM_{2.5}$ smog	120

Setting	Intervention	Capital Cost	Annual Operating Cost	eACH Achieved	Cost per eACH
Office (100 people)	HEPA Filtration	$3,000-10,000	$300-1,250	3-5	$100-300
Office (100 people)	Upper-room UVC	$33,000-52,000	$14,000	Up to 24	$14
Office (100 people)	Ventilation Upgrade	$40,000+	$4,000	1-2	$135
Office (100 people)	DIY Box Filters	$500-1,500	$200-500	3-5	<$50
Nursing Home (100 residents)	HEPA Filtration	$22,000-50,000	$2,200-4,500	3-5	$100-300
School (1,000 students)	HEPA Filtration	$8,000-16,000	$800-2,000	3-5	$100-300
School (1,000 students)	Upper-room UVC	$150,000-250,000	$15,000-25,000	Up to 24	$14-20

Intervention	Upper-bound of effectiveness (ACH/ eACH)	Installation cost per ~70m² room ($USD)	Relative operational cost	Cost-effectiveness[1] ($/ACH or eACH)
Mechanical ventilation	6ACH[2]	$6000 (modern HVAC system, to provide air quality equivalent to 5-7 ACH)	High, as many HVAC systems must be updated to meet current standards for filtration and flow rate. Increased ventilation may also dramatically increase costs of climate control.	~$135 per ACH
In-duct 254 nm UVC	6 ACH (limited by HVAC efficiency)[3]	$40-150[4]	Medium, as can be retrofitted into systems with inadequate power for sufficient filtration at a given flow rate.	$7-$25 per ACH
Portable air cleaners	12 eACH[5]	$1000-1500 (multiple HEPA purifiers equivalent to 4-6 ACH)[6]	Medium. Draws more energy than central filtration due to lower fan efficiency, but units can be selectively placed.	~$110 per eACH
254 nm UVC as upper room	24-100 eACH[7]	$1500-2500 (8-12 incremental eACH)[8]	Low, and costs are likely to be stable annually since there is no need for climate control.	~$14 per eACH

1 The dollar cost of one equivalent ACH for the first year, including installation/start-up costs. We were unable to find sufficient information to amortize costs over subsequent years; we believe that amortization would make options other than ventilation even more cost-effective.
2 Most HVAC systems in public buildings in the US do not have the duct or blower capacity to be increased to 6 ACH
3 In-duct UVC systems can reach very high levels of air cleanliness, but the eACH is limited by air delivery rate into the target room.
4 Estimated from various commercial quotes ($800, $3000); installed in central HVAC that can already provide 6 ACH, assuming an average of 20 such rooms per such HVAC installation given average commercial building size.
5 This is the preferred ACH level recommended by the CDC for an airborne isolation rooms in hospitals and is achievable via filtration, but cost and noise may be prohibitive beyond this level.
6 Source is the same as above, hypothetically using MERV filters could achieve similar eACH at a tenth of the cost of current commercial models.
7 Upper-room UVC, with good air mixing, has been shown in the real world to achieve 24 eACH and studies suggest it's possible to achieve >100 eACH when paired with adequate ventilation.
8 Source.

Cost of Interventions in Various Settings

In this section, we outline several real-world examples and estimate their efficacy and cost based on existing evidence. For examples, for an office of 100 employees with a 10,000 ft2 open-plan floor with 9-ft ceilings (≈90,000 ft^3), an additional 3-5 ACH via portable HEPA requires ≈4,500–7,500 cfm CADR in total (ACH × volume ÷ 60). This would require ~15–25 units, each providing ~250-350 cfm CDAR. Cost per unit varies across field reports: $200–$400 in a JAMA-affiliated trial context and ~$450 in a hospital/acute-care deployment. This would suggest a cost of $3000–10,000. Running costs for HEPA filters are low, at ~$20-50 per unit per year, implying a running cost of $300–1250 per year.

A nursing home with similar occupancy would likely require more filters, since nursing homes combine larger communal spaces with individual resident rooms that each need their own filtration. For a 100-resident facility with roughly 25,000 square feet of communal space, this would mean about 110 units in total — implying capital costs of $22,000–$50,000 and annual operating costs of $2,200–$4,500. Operating costs are likely to run toward the higher end of this range. Filters often need to operate continuously, and indoor pollution levels in nursing homes are higher than in many other settings.

Schools and barracks, meanwhile, combine higher occupancy in smaller settings. Occupants typically spent less total time in these settings, and are in better health. Previous studies typically place one filter per classroom, so a school with 40 classrooms of 25 students each (1,000 students total) would require roughly 40 units, at $8,000–$16,000 in capital costs and $800–$2,000 per year to operate.

Costs of GUV installations are harder to estimate. A 2003 study estimated the costs of installation of GUV in a 1000 person office to be $52,000, with running costs of $14,000 per annum, equating to $52 per person in capital expenditure, and $14 running costs per annum. The CDC estimates $3.30 per sq-ft of treated area upfront cost, which would imply a cost of ~$33,000 capex for a 10,000 sqft office (theoretical occupancy 100).

Installation of upper-room UVC systems for nursing homes would likely imply higher costs, for the same reasons as filtration; more units would have to be installed for the same number of occupants. Upper-room 254 nm UVC costs approximately $14 per eACH in hospital settings, making it nine times more cost-effective than mechanical ventilation ($135 per ACH). Installation costs are estimated at $52 per person capital expenditure with $14 annual operating costs for a 1,000-person office, or $3.30 per square foot treated area upfront per CDC estimates.

How Interventions Work Together

Ventilation, filtration, and GUV are complementary strategies that together create a layered approach to indoor air cleaning. Ventilation dilutes indoor pollutants by introducing outdoor air. It reduces chemical contaminants, airborne pathogens, and carbon dioxide, supporting both health and cognitive performance. Ventilation alone, however, may be limited when outdoor air is polluted, energy constraints restrict airflow, or occupancy is high.

Filtration adds protection by removing particles from recirculated or incoming air. High-efficiency filters, such as MERV-13 or higher, capture $PM_{2.5}$ and a substantial share of pathogen-containing droplets and aerosols. Continuous filtration lowers background particle levels even when outdoor air quality is poor. It complements ventilation by cleaning air rather than simply diluting it.

Germicidal ultraviolet light provides an additional layer by inactivating airborne pathogens that remain after dilution and filtration. Unlike filters, which rely on particle capture, GUV neutralizes pathogens directly in the air. This makes it especially effective against diseases that spread through fine aerosols that can remain suspended for extended periods.

Representative Use Cases

To illustrate how indoor air quality improvements might translate into concrete health, educational, and economic outcomes, we present two representative cases. Each case draws on existing evidence to estimate the likely scale of benefits and costs in a specific setting, and each is designed to generate real-world data that could inform broader policy. Together, they span two populations with distinct exposure profiles and disease burdens — children in urban classrooms and elderly residents in long-term care — and suggest where IAQ interventions are most and least likely to be cost-effective.

Ohio Nursing Homes

Summary

This case study models a CMS Innovation Center demonstration that would reimburse Ohio nursing homes for installing HEPA air cleaners and germicidal UV (GUV) disinfection, reaching roughly 33,000 elderly residents. GUV appears substantially more cost-effective than HEPA filtration. We recommend a tailored "clean air stack" that prioritizes GUV in common areas, with HEPA as a supplementary measure, paired with a rigorous evaluation using CMS claims data to strengthen the case for broader adoption.

Analysis

Under the proposed demonstration, the CMS Innovation Center would reimburse Ohio[9] nursing homes for indoor air quality improvements, including HEPA filtration in resident rooms and both filtration and germicidal UV disinfection in high-risk common areas. Ohio has more than 960 nursing homes, housing roughly 67,000 residents, the program would reach about 33,000 of them.

To estimate the resulting reduction in chronic disease, we first approximate how much fine particulate matter filtration would remove in a typical facility. Drawing on Montrose et al. (2020), which measured a 24-hour average $PM_{2.5}$ concentration of 3.3 µg/m³ across four U.S. nursing homes, and assuming a 50% filter removal efficiency, we estimate a reduction of 1.65 µg/m³ $PM_{2.5}$.

We then apply risk estimates from studies selected for quality and relevance to Ohio's nursing home populations. For COPD, we use Liu, et al's hazard ratio of 1.17 per 5 µg $PM_{2.5}$ (ie, a long-term increase of 5ug $PM_{2.5}$ leads to a 17% increase in the risk of COPD) was selected. For CVD we use Hayes et al, which reports hazard ratios of 1.16 for ischaemic heart disease mortality, including 1.14 for stroke and 1.16 for ischemic heart disease for a long-term increase of 10 µg/m³. Baseline mortality rates for adults over 75 in Ohio are drawn from the Global Burden of Disease study.

Combining these inputs yields a simple linear epidemiological model that estimates lives saved by applying the 1.65 µg/m³ $PM_{2.5}$ reduction to each condition's hazard ratio and expected deaths across the participating facilities. The results should be read as rough approximations. The model does not account for regional or demographic variation, risk estimates vary substantially across the published literature, and several studies find no measurable benefit from $PM_{2.5}$ reductions of this magnitude.

To estimate the impact on infectious disease, we model the installation of upper-room UV systems. An Australian care home study that found an approximate 12% reduction in cumulative infections, which we apply to respiratory infection mortality. This result was not statistically significant.

9 Ohio was chosen as a state with relatively median health and air quality measures (income, wildfire risk, climate) and a sufficiently large population for useful studies

Disease	Relative Risk	$PM_{2.5}$ (norm)	Risk per 1ug $PM_{2.5}$	$PM_{2.5}$ removed	Relative risk reduction	Death rate per 100,000 per year	Population studied	Expected deaths per year	Reduction in deaths per year
COPD	1.017	5	0.0034	1.65	0.00561	483.99	33500	162.13665	0.01
All CVD	1.12	10	0.012	1.65	0.0198	2,712.89	33500	908.81815	0.18
Ischaemic Heart Disease	1.16	10	0.016	1.65	0.0264	1,355.07	33500	453.94845	0.12
Stroke	1.14	10	0.014	1.65	0.0231	672.43	33500	225.26405	0.05

Disease	Risk reduction	Rate	Population	Expected cases	Reduction
COVID-19	0.12	217.8	33500	72.963	9
LRTIs	0.12	181.32	33500	60.7422	7
All RTIs (+TB)	0.12	400.49	33500	134.16415	16

HEPA Filters Cost Efficacy

To estimate what HEPA filtration would cost and how cost-effective it would be, we model a representative 100-resident facility with private rooms and roughly 25,000 square feet of communal space (at 9-foot ceilings). We assume one portable filter per private room, for 100 units in total. Achieving an additional three air changes per hour in the communal areas — assuming a typical clean air delivery rate of 250 cubic feet per minute per unit — requires another 15 filters, bringing the total to 115.

Reported prices per unit range from $200–$400 in research trials to around $450 in hospital deployments, which translates to capital costs of roughly $23,000–$51,000 for a 100-resident facility, or $230–$510 per resident. Annual operating costs are considerably lower, at $20–$50 per unit, or $2,300–$5,750 per year facility-wide.

Spreading the capital cost over a 10-year useful life and adding operating expenses, and assuming 30 hospitalizations avoided for every death averted, we estimate that HEPA filtration would cost roughly $120,000–$300,000 per hospitalization prevented.

GUV Cost Efficacy

GUV installation costs are harder to estimate, due to their more complex and bespoke requirements. A 2003 study estimated the cost of installing GUV in a 1,000-person office at $52,000 upfront plus $14,000 annually — about $52 in capital and $14 in operating costs per person per year. The CDC's more recent benchmark is $3.30 per square foot of treated area upfront.

Applying the CDC figure to a 100-resident facility with roughly 250 square feet of communal space per resident yields an upfront cost of about $82,500, or $825 per resident. Under the same assumption of 30 hospitalizations avoided per death averted, this works out to approximately $28,600 per hospitalization prevented from installing a simple "clean air stack" that facilities can tailor to their layout and risk profile. This would include portable HEPA air cleaners in resident rooms and common areas, with priority for high-risk spaces such as dining and activity rooms. It also includes UV germicidal irradiation (GUV) in common areas.

New York City Schools

Summary

This case study examines the potential impact of installing HEPA air filters in New York City public schools, where 912,064 students could benefit from improvements to classroom air quality. Existing evidence suggests that filtration would modestly improve both test scores and attendance, at an installation cost of roughly $100–$225 per student. We recommend a citywide trial, and suggest design implementation strategies based on existing examples. NYC's robust educational data infrastructure, meanwhile, offers a valuable chance to generate high-quality real-world evidence on the true impact of air filtration in urban schools.

Analysis

Our estimates draw on a set of real-world studies — summarized in the table below— that measure the effects of $PM_{2.5}$, a key pollutant removed by filtration. These studies vary in design and effect size, so the figures below should be read as indicators of overall magnitude rather than precise predictions. The evidence is strong enough to justify a real-world trial, but not to support firm quantitative conclusions on its own.

Academic Performance

To estimate how filtration might affect school performance, we used a large observational study of more than 2.8 million students in South Carolina, which found that each 1 $\mu g/m^3$ increase in $PM_{2.5}$ was associated with a 0.0098 SD drop in standardized math scores and a 0.0068 SD drop in reading scores. Assuming classroom air filters remove roughly 50% of ambient $PM_{2.5}$ — consistent with real-world performance — New York City may raise math test scores by 0.009755 × 22/2 = 0.107SD, and reading scores by 0.0666SD. The OECD estimates that a full school year produces roughly a 0.20 SD gain in test scores, so these improvements correspond to approximately 2.3 weeks of additional learning in math and 1.6 weeks in reading.

A separate study examined the effect of air filters placed in schools after an industrial gas leak, and found that schools that received air filters saw improvements in maths and English standardized test scores to the order of 0.20 SD.[10] This result is particularly important as it demonstrates direct real-world evidence that these effects are measurable when filters are actually deployed in classrooms.

10 This study has come under particular criticism, which may limit its use

Absenteeism

The evidence on attendance is similarly encouraging but more variable. Bonan et al. found that installing filters in Milan classrooms removed 32% of $PM_{2.5}$ and reduced overall absenteeism by 12.5%. A study by Mendell et al. in California found that increasing the ventilation level per student reduced illness-related absence by 3.4%. Taken together, these studies suggest filtration would meaningfully reduce absences; although it is difficult to predict the magnitude of this decrease without further study. In 2023–2024, New York City students missed a total of 15.3 million school days at an 11.4% absence rate. If Bonan, et al.'s results prove generalizable to the New York City school system, filtration could recover roughly 1.9 million student-days per year, lifting the attendance rate from 89.6% to 90.9%. These results have not been consistently reproducible, which underscores the need to determine whether improving IAQ can reliably deliver meaningful, cost-effective, and sustained gains in student performance and attendance.

Studies on the Effect of Air Filtration in Schools

In previous studies, air filters have been shown to improve both children's cognitive function and their school attendance. However, estimates of effect sizes are diverse and sometimes heterogeneous.

Author	Year	Title	Study type	Outcome	Improvement
Gilraine	2020	Air Filters, Pollution, and Student Achievement	Natural intervention	Test Scores	0.20σ (Maths), 0.19 (English)
Mendell	2013	Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools a prospective study in California elementary schools	Observational	Absenteeism	3.4% reduction (illness absence)
Bonan	2025	The Effect of Air Purifiers in Schools	RCT	Absenteeism	12.5% reduction (overall absence)
Saverinen-Shaughnessy	2015	Effects of Classroom Ventilation Rate and Temperature on Students' Test Scores	Observational	Test Scores	11 points/0.5% (Maths)
Wen	2022	Lower test scores from wildfire smoke exposure	Observational	Test Scores	0.20σ per 35 μg/$PM_{2.5}$ in wildfires
Lam	2023	Long-Term Exposure to Fine Particulate Matter and Academic Performance Among Children in North Carolina	Cross-sectional	Test Scores	0.00976σ (Maths), 0.000681σ (English) per 1 μg/$PM_{2.5}$

Proposed Interventions

We propose installing HEPA air filters in every NYC public school classroom, with the dual aims of improving student outcomes and generating rigorous real-world evidence on the effects of classroom air filtration. Several state and local IAQ initiatives offer useful design precedents. Boston Public Schools (BPS) has installed 4,500 IAQ sensors across classrooms and offices, publishing real-time CO_2, particulate matter, temperature, and humidity data on a public dashboard developed in partnership with Boston University. Rhode Island now requires new school construction and major renovations to meet NE-CHPS indoor air quality standards, including ASHRAE 62.1 compliance and the state has approved more than $5 billion in compliant school construction since 2018. Minnesota requires public schools to maintain health and safety programs aligned with best practices, and its Department of Health provides a full IAQ management plan package with templates, EPA checklists, and annual training. These examples provide suggestions of how IAQ programs can be implemented, but they do not yet provide the robust evidence necessary to support more widespread adoption of IAQ policy.

These programs illustrate how IAQ policy can be implemented at scale, but none has yet generated the rigorous evidence needed to support broader adoption — a gap an NYC rollout is unusually well-positioned to fill. NYC's existing data infrastructure makes evaluation straightforward and inexpensive. School-level attendance and test-score data are already collected annually by the Department of Education. By comparing outcomes across schools with and without filters installed during a phased rollout, policymakers can directly measure filtration's real-world impact without substantial additional investment in oversight.

Other data sources, such as Medicare claims, could help assess broader health effects and potential cost savings to federal healthcare systems. However, collecting this data may be more challenging, and the relatively small number of cases involved may make drawing firm conclusions difficult.

Conclusions

Indoor air quality is an important but underused lever for improving health, productivity, and educational outcomes in the United States. The evidence reviewed in this paper indicates that IAQ interventions can reduce chronic disease burden, improve performance in schools and workplaces, and lower transmission of respiratory infections. These effects vary across settings and depend on baseline air quality, building design, occupancy patterns, and the intervention chosen. Even so, the overall weight of the evidence supports a clear conclusion that improving IAQ in public and institutional buildings is a practical, measurable, and in many cases cost-effective public health strategy.

The strongest evidence for chronic disease concerns fine particulate matter ($PM_{2.5}$), which is linked to elevated risk of COPD, asthma, and cardiovascular disease. Even modest long-term increases in $PM_{2.5}$ exposure are associated with meaningful increases in disease risk, and because indoor environments often harbor persistent $PM_{2.5}$ from both outdoor infiltration and indoor sources, reducing these exposures can reasonably be expected to yield health gains over time. In the United States, where average $PM_{2.5}$ levels are already low, per-person gains may be modest — but given the prevalence and cost of cardiovascular and respiratory disease, even small reductions in risk translate into substantial aggregate benefits at scale.

Interventions targeting infectious aerosols may offer more immediate and visible benefits. The studies reviewed here suggest that ventilation, filtration, and germicidal ultraviolet light can reduce the burden of respiratory infection, particularly in high-contact settings. Evidence from both historical and contemporary studies indicates that improved air sanitation can lower school absenteeism, workplace sick leave, and transmission in congregate environments such as barracks and nursing homes. These effects may be nonlinear, as preventing one infection can reduce onward transmission. Because preventing a single infection can avert onward transmission, these effects are often nonlinear, and the largest returns are likely in dense or high-risk environments such as schools, military housing, and long-term care facilities.

The economics are also favorable, particularly measured against the health and productivity losses these interventions help avoid. Portable HEPA filtration can be deployed at relatively low cost in schools and offices, with lower-cost DIY options extending access further. Upper-room UVGI delivers substantial equivalent clean air at a favorable cost where infection control is the primary goal. Larger ventilation upgrades are more expensive and slower to implement but provide broader co-benefits. These differences underscore the importance of matching interventions to specific goals. In many high-risk settings, filtration or UVGI may offer a more practical and cost-effective approach than full ventilation retrofits.

Uncertainty about real-world effects should not delay action. It actually strengthens the case for programs that generate evidence while delivering immediate benefits. The important policy questions concern how much specific interventions improve outcomes in particular settings, not whether IAQ matters in principle — and these are better answered by embedding evaluation into deployment than by pursuing small isolated trials. Public agencies, school systems, healthcare payers, and long-term care regulators already collect substantial

administrative data. By linking that data to intervention rollouts, and analyzing it with quasi-experimental or randomized designs, can steadily strengthen the evidence base. IAQ policy can thus be both practical and continuously improving.

Benefits will not be uniform across buildings, and some gains in typical U.S. settings will be modest. However, there are contexts where the case for action is already strong. Buildings that house medically vulnerable populations, schools where attendance and learning outcomes are measurable, and high-contact environments where infections spread readily all present particularly promising opportunities. In these settings, interventions such as filtration and germicidal ultraviolet light may offer not only health benefits but, in some cases, net cost savings. Improving standards, declining sensor costs, and increased public awareness of airborne transmission create a timely opportunity to advance IAQ as a serious area of public policy.

Indoor air sanitation is not a substitute for vaccination, medical care, housing policy, or outdoor air pollution control. It is a complement to these efforts and an increasingly actionable one. Thoughtfully implemented, it can reduce disease, improve performance, and generate valuable real-world data. Policymakers should treat indoor air quality not as a peripheral facilities concern, but as a credible and measurable tool for improving public health and social welfare.

1Day Sooner aims to reduce the global burden on infectious disease and avert future pandemics by working to accelerate the development and implementation of vaccines, treatments, and medical interventions. They do so as advocates for people who want to be in high-impact medical studies, including human challenge studies.

www.1daysooner.org