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The effects of ventilation and filtration on indoor $PM_{2.5}$ in office buildings in four countries

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A R T I C L E I N F O

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A B S T R A C T

Fine particulate matter ($PM_{2.5}$) is an airborne pollutant associated with negative acute and chronic human health outcomes. Although the majority of $PM_{2.5}$ research has focused on outdoor exposures, people spend the majority of their time indoors, where $PM_{2.5}$ of outdoor origin can penetrate. In this work, we measured indoor $PM_{2.5}$ continuously for one year in 37 urban commercial offices with mechanical or mixed-mode ventilation in China, India, the United Kingdom, and the United States. We found that indoor $PM_{2.5}$ concentrations were generally higher when and where outdoor $PM_{2.5}$ was elevated. In India and China, mean workday indoor $PM_{2.5}$ levels exceeded the World Health Organization's 24-hour exposure guideline of 25 $\mu g/m^3$ about 17% and 27% of the time, respectively. Our statistical models found evidence that the operation of mechanical ventilation systems could mitigate the intrusion of outdoor $PM_{2.5}$: during standard work hours, a 10 $\mu g/m^3$ increase in outdoor $PM_{2.5}$ was associated with 19.9% increase in the expected concentration of indoor $PM_{2.5}$ ($p < 0.0001$), compared to a larger 23.4% increase during non-work hours ($p < 0.0001$). Finally, our models found that using filters with ratings of MERV 13–14 or MERV 15+ was associated with a 30.9% (95% CI: −55.0%, +6.2%) or 39.4% (95% CI: −62.0%, −3.4%) reduction of indoor $PM_{2.5}$, respectively, compared to filters with lower MERV 7–12 ratings. Our results demonstrate the potential efficacy of mechanical ventilation with efficient filtration as a public health strategy to protect workers from $PM_{2.5}$ exposure, particularly where outdoor levels of $PM_{2.5}$ are elevated.

1. Introduction

Particulate matter with an aerodynamic diameter less than 2.5 μm ($PM_{2.5}$) is an air pollutant that has been shown to have harmful acute and chronic effects on human health. Chronic $PM_{2.5}$ exposure negatively impacts the respiratory [1], cardiovascular [2], and nervous systems [3], and is associated with increased mortality rates [4]. Short-term $PM_{2.5}$ exposure, such as same-day outdoor $PM_{2.5}$, is also associated with hospital admissions for respiratory and cardiovascular diseases [5] and with increased mortality even at concentrations below the World Health Organization's (WHO's) 24-hour exposure guideline of 25 $\mu g/m^3$ [6,7]. $PM_{2.5}$ may even have acute effects on cognitive function; increases in outdoor 12-hour $PM_{2.5}$ over the range from 5 $\mu g/m^3$ to 40 $\mu g/m^3$ have been associated with an increase in errors in skilled task performance [8].

Although much of our knowledge about the health effects of $PM_{2.5}$ has come from epidemiological studies of outdoor $PM_{2.5}$ exposures, exposures to $PM_{2.5}$ (from both indoor and outdoor sources) that occur indoors may have a larger impact on people's health than outdoor exposures because adults spend the majority of their time, in general between 82% and 90%, inside buildings [9–11]. The indoor locations where people spend the most time include homes and, for employed adults, workplaces [9,10]. Employed adults in China, India, the United Kingdom (UK), and the United States (USA) worked, on average, for 25%, 24%, 19%, and 20% of the hours in 2017 [12]. While indoor $PM_{2.5}$ sources, like cooking, may be significant in the home [13] and some indoor sources, like frequently-used printers, may contribute to $PM_{2.5}$ in offices [14], $PM_{2.5}$ of outdoor origin is likely more important in workplaces like office buildings where major indoor sources are less common, particularly in places with high outdoor $PM_{2.5}$ concentrations.

The degree of outdoor $PM_{2.5}$ penetration into a building depends on the building's design and operations. Air filters in building ventilation systems can remove $PM_{2.5}$ from outdoor air before it is distributed to occupied spaces. In the USA, air filters are rated using minimum

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efficiency reporting value (MERV) ratings that range from 1 (lowest efficiency) to 16 (highest efficiency) as defined by ANSI/ASHRAE Standard 52.2–2017 [15]. The MERV rating system is similar to a new global standard from the International Organization for Standardization (ISO), ISO 16980, which replaced an older European Standard called EN 779 in July 2018 [16]. Filters with MERV 8 ratings are considered standard in office buildings where filtration is present, as these filters are recommended by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) for outdoor air being distributed to occupied spaces in areas where the PM_{10} national standard for outdoor air is exceeded [17]. MERV 8 filters are designed to have an average particle removal efficiency of at least 20% for particles between 1.0 and 3.0 μm, while more efficient MERV 13 filters are designed to have an average particle removal efficiency of at least 85% for the same particle size range [15]. In practice, filter performance varies due to differences in how the filters are installed, how often the filters are replaced, how polluted the air being filtered is, and how well the systems are maintained. An experiment in an office building in Philadelphia, Pennsylvania found that the $PM_{2.5}$ removal efficiency of MERV 8 filters ranged from approximately 2% to 39% with a median of 17%, while the $PM_{2.5}$ removal efficiency of MERV 14 filters ranged from approximately 62% to 90% with a median of 72% [18].

In addition to the level of filtration of outdoor air, the route and amount of outdoor air entering a building can influence the degree of outdoor $PM_{2.5}$ penetration into buildings. Higher indoor $PM_{2.5}$ levels can result from higher ventilation air exchange rates that bring more outdoor air indoors instead of recirculating air within a building, particularly when filters with ratings of MERV 8 or lower are used [18, 19]. However, it has been demonstrated that increasing the filter rating from MERV 8 to MERV 14 or 15 can more than compensate for increased indoor $PM_{2.5}$ concentrations that can result from increasing the outdoor air ventilation rate from 1.0 h^{-1} to 5.4 h^{-1} [18], indicating that filtration may be an effective way to control the penetration of outdoor $PM_{2.5}$ in buildings where high air exchange rates are used to protect occupant health, comfort, and productivity [20–22]. Higher indoor $PM_{2.5}$ levels can also result from infiltration of outdoor $PM_{2.5}$ through the building envelope, which may occur when ventilation systems that normally maintain positive pressure in buildings during occupied hours are instead operating at reduced capacity during non-work hours [19]. Limiting infiltration of outdoor air into a building, as well as using filters to protect against the introduction of outdoor $PM_{2.5}$ by high outdoor air ventilation rates, may be able to reduce the degree of indoor exposure to $PM_{2.5}$ of outdoor origin while promoting optimal indoor air quality.

Less is known regarding how ventilation and filtration impact real-world indoor $PM_{2.5}$ exposures across different countries under normal building operating conditions, despite some evidence from experimental work. One study that measured indoor $PM_{2.5}$ levels in operating buildings is exceptional for its size and scale: the United States Environmental Protection Agency's Building Assessment Survey and Evaluation (BASE) study, which was carried out in 1994–1998 [23]. This landmark study investigated indoor environmental parameters, ventilation characteristics, and occupant symptoms in 100 non-problem office buildings in the USA and found that integrated 8- to 10-hour indoor building $PM_{2.5}$ concentrations ranged from 1.3 $\mu g/m^3$ to 24.8 $\mu g/m^3$ (measured in a single location in 70 of the 100 buildings and as the average of three locations in the remaining 30 buildings) [23]. However, the one-time, largely single-location-per-building sampling strategy of the BASE study, and of most of the other studies investigating indoor $PM_{2.5}$, does not account for spatial variability of $PM_{2.5}$ within buildings or for variability over the course of a day, over seasons, or under different ventilation scenarios. Moreover, most studies investigating indoor $PM_{2.5}$ are unable to explore variation between buildings or regions because of small sample sizes. Even the BASE study, which included 100 buildings, did not explore whether ventilation operations and filtration were responsible for the variation in indoor $PM_{2.5}$ levels that was observed among different buildings [23].

To determine how ventilation operating schedule and filtration efficiency influence $PM_{2.5}$ levels in operating and occupied office buildings, we conducted a multi-country, one-year longitudinal study of real-time indoor $PM_{2.5}$ levels at multiple workstations within each of 37 office buildings located in China, India, the UK, and the USA. Compared to prior work, our work is innovative in its geographic scope, long duration, high temporal resolution, and use of statistical models rather than descriptive statistics to evaluate associations between filtration efficiency and indoor $PM_{2.5}$.

2. Materials & methods

2.1. Study design

The Global CogFx Study is a year-long observational study of 43 office buildings in China, India, Mexico, Thailand, the UK, and the USA. The buildings in the Global CogFx Study represent a convenience sample of urban commercial office spaces. In each building, study activities were undertaken by individuals working at a single company and these companies, in many cases, occupied just a portion of their larger buildings (e.g. company leased one floor in large, multi-tenant building). In some cases, multiple office locations of a single company participated in the study. The participating companies included architecture firms, software companies, real estate companies, and engineering firms, as well as eight companies in green buildings in China from a previous study [24]. All participating companies were required to have at least ten employees working in the office building at least three days a week. At each participating company, individual employees were recruited to participate in the study. Each individual participant completed study questionaries and tests on a custom smartphone app, wore a wristband activity tracker, and hosted an environmental sensor package at or near their workstation for their building's one year of participation. The study protocol was reviewed and approved by the Institutional Review Board at the Harvard T.H. Chan School of Public Health.

2.2. Study population

This analysis used data from a subset of the 43 buildings that participated in the Global CogFx Study. For this analysis, we included only the four countries with at least two buildings participating and only the buildings where $PM_{2.5}$ measurements were collected for at least some part of the study period. These criteria resulted in the exclusion of Mexico and Thailand, since each of these countries only had one participating building, and of one building in the USA, because the environmental sensor packages used in this building for the duration of the study did not measure $PM_{2.5}$, leaving a total of 40 buildings in four countries. Of these 40 buildings, one building (in India) was excluded because it was the only building that reported using natural ventilation, which is expected to result in different indoor $PM_{2.5}$ dynamics than mechanical ventilation, and an additional two buildings (in India) were excluded because we were unable to obtain information about their air filters. These exclusions left 37 buildings in the final analysis: eight buildings in China (three in Chengdu, three in Shanghai, and two in Zhuhai), seven buildings in India (three in Bengaluru and one each in Chennai, Gurugram, Hyderabad, and Mumbai), six buildings in the UK (two in Croydon and one each in Birmingham, Cambridge, London, and Sheffield), and sixteen buildings in the USA (two in Los Angeles, two in San Francisco, and one each in Boston, Clearwater, Chicago, Cleveland, Denver, Minneapolis, New York City, Omaha, Overland Park, Phoenix, Seattle, and Washington DC). Each building participated in the study for a full year, with participation in each country occurring over the following time periods: 5/29/2018–8/3/2019 in China, 11/13/2018–11/13/2019 in India, 7/1/2018–7/25/2019 in the UK, and 10/1/2018–3/20/2020 in the USA.

2.3. Building assessment

Information about building design and operational practices was acquired through an online questionnaire or by email correspondence with an individual building contact from the participating company in each building. For this analysis, important questions from the building questionnaire included questions about ventilation type and level of filtration. All building contacts indicated whether their building used natural ventilation, mechanical ventilation, or a combination of the two (i.e. mixed-mode ventilation). They also indicated whether their building ventilation system used filters and, if so, what filter efficiency rating was used. Filter efficiency ratings were reported as MERV ratings; in cases where other rating types were reported, ratings were converted to MERV ratings. Building contacts also answered questions about green certifications, healthy building certifications, building occupancy, building age, and other building operations and design parameters.

2.4. Indoor environmental assessment

Within the office space of each participating company included in this analysis, between one and 12 (median five) low-cost environmental sensor packages were set up on or near workers' desks to measure $PM_{2.5}$, temperature, relative humidity, and carbon dioxide (CO_2) at one-to 10-minute intervals. Five different low-cost sensor packages were used in the 37 buildings in this analysis, including the Harvard Healthy Buildings Sensor (a custom sensor package built for the Global CogFx Study at the Harvard T.H. Chan School of Public Health), the Tsinghua IBEM Sensor (a custom sensor package built at Tsinghua University [24]), the Awair Omni (Awair, Inc., San Francisco, USA), the ChemiSense CS-001 Indoor Air Quality Monitor (ChemiSense Inc., Berkeley, USA), and the Tongdy MSD-16 Sensor (Tongdy Sensing Technology Corporation, Beijing, China). Both of the custom sensor packages, the Harvard Healthy Buildings Sensor and the Tsinghua IBEM Sensor, contained Plantower PMS3003 devices (Beijing Plantower Co., Ltd, Beijing, China) to measure $PM_{2.5}$ concentrations. According to manufacturers' specifications and external evaluations of the five environmental sensor packages, they all use laser-based methods to estimate $PM_{2.5}$ concentrations (see Table 1 for further details of $PM_{2.5}$ sensor specifications). Of the buildings included in this analysis, the buildings in China used the Harvard Healthy Buildings Sensor and/or the Tsinghua IBEM Sensor; the buildings in India used the Harvard Healthy Buildings Sensor or the Awair Omni; the buildings in the UK used the Harvard Healthy Buildings Sensor and the Awair Omni; and the buildings in the USA used the Harvard Healthy Buildings Sensor, the Awair Omni, the ChemiSense CS-001 Indoor Air Quality Monitor, or the Tongdy MSD-16 Sensor.

CO_2 concentrations measured by the environmental sensor packages (see Table S1 in the Supplementary Material for details of the CO_2 sensor specifications) were used to estimate quarterly building air exchange rates by applying the concentration decay test method to data from weekdays between 14:00 and 19:00 local time [27]. These afternoon and evening hours were selected to try to capture CO_2 concentration decays after people left the buildings in the evenings but before the building mechanical systems scaled back or turned off for the evening. If the buildings were more than minimally occupied or the outdoor air ventilation was not constant during these afternoon and evening hours, the estimated air exchange rates may be over- or under-estimates of the true air exchange rates. Briefly, daily air exchange rates were estimated using the regression method for each valid concentration decay curve for all sensor packages in each building. Considerations from ASTM E741-11 [27] and ASTM D6245-18 [28] were used to define valid

Table 1
$PM_{2.5}$ sensor specifications for environmental sensor packages used in buildings from the Global CogFx Study included in this analysis.

Package Name	$PM_{2.5}$ Sensor Name	Type of $PM_{2.5}$ Sensor	Range ($\mu g/m^3$)	Smallest Particle Diameter (μm)	Sensor Output Resolution ($\mu g/m^3$)	Accuracy	Third Party Evaluation
Harvard Healthy Buildings	Plantower PMS3003[a]	Laser light scatter[b]	NR	0.3[b]	NR	0–100 $\mu g/m^3$: ±10 $\mu g/m^3$ 100–500 $\mu g/m^3$: ±10%[c]	NR
Tsinghua IBEM	Plantower PMS3003[d]	Laser light scatter[e]	0–1000[e]	0.3[b]	1[e]	20–500 $\mu g/m^3$: ±10%[e]	Guaranteed by China National Institute of Metrology for $PM_{2.5}$ Standard GSH/J2011-1[e]
Awair Omni	Honeywell HPMA 115S0[f]	Laser light scatter[g]	0–1000[g]	NR	1[g]	0–100 $\mu g/m^3$: ±15 $\mu g/m^3$ 100–1000 $\mu g/m^3$: 15%[g,h]	Interior RESET Air Accredited Grade B monitor[i]
ChemiSense CS-001	Sharp GP2Y-10##[j]	Laser particle counter[k]	0–500[k]	NR	1[k]	0–150 $\mu g/m^3$: ±5 $\mu g/m^3$ or 15% 150–500 $\mu g/m^3$: ±5 $\mu g/m^3$ or 20%[k]	Interior RESET Air Accredited Grade B monitor[i]
Tongdy MSD-16	NR	Laser light scatter[l]	0–1000[m]	NR	0.1[m]	10%[m]	Interior RESET Air Accredited Grade B monitor[i]

NR: Not reported.
[a] Harvard Healthy Buildings sensors were constructed by the authors and their colleagues using Plantower PMS3003 sensors.
[b] PMS3003 Specification Sheet: "Laser dust sensor: PM1.0 p.m.2.5 p.m.10" by GuangZhou LOGOELE Electronic Technology Co., Ltd.
[c] [25].
[d] Tsinghua IBEM sensors are presumed to use Plantower PMS3003 based on observation of deconstructed sensors.
[e] [24].
[f] Awair Omni sensors are presumed to use Honeywell HPMA 115S0 sensors based on observation of deconstructed sensors.
[g] RESET™ Specification Sheet for AWAIR Omni Indoor Air Quality Monitor.
[h] Honeywell HPM Series Particulate Matter Sensors Datasheet. 32322550 Issue F.
[i] RESET Accredited Monitors webpage (https://www.reset.build/monitors).
[j] [26] referred to the $PM_{2.5}$ sensor as the "Sharp Compact Optical Dust Sensor" which was assumed to be one of the Sharp GP2Y-10## models (e.g. Sharp GP2Y-1010, Sharp GP2Y-1012, etc.) based on the descriptions of these products on the SHARP website (https://www.sharpsde.com/products/optoelectronic-components/sensors/air-sensors).
[k] RESET™ Air Accredited Monitor Testing Report for ChemiSense CS-001.
[l] RESET™ Specification Sheet for Tongdy MSD-16 Indoor Air Quality Monitor.
[m] MSD Sensors Specification Sheet: "MSD IAQ Detector – User Manual V.1707" by Tongdy Sensing Technology Corporation.

concentration decay curves; many sensor packages did not have valid concentration decay curves on any given day. Quarterly building air exchange rates were then estimated by taking the 90th percentile of all estimated daily air exchange rates from all sensor packages in each building for each three-month period (December–February, March–May, June–August, and September–November). The 90th percentile was selected to represent the typical quarterly air exchange rate for each building after reviewing the distributions of estimated air exchange rate values and the quality of their associated CO_2 decay curves.

Before the sensors were installed, visual comparisons of real-time data from at least one unit of each type of sensor package and data from colocated recently-calibrated reference instruments were performed. Reference instruments included a TSI DustTrak (TSI Instruments, USA) for $PM_{2.5}$ and a QTrak 7575 (TSI Instruments, USA) for CO_2. Before estimation of air exchange rates, CO_2 values lower than 400 ppm or greater than 5000 ppm were removed. Before data analysis, raw indoor $PM_{2.5}$ measurements were inspected by eye and outlier points and measurements that exceeded 500 $\mu g/m^3$ were removed from the dataset. This data cleaning resulted in the removal of 0.08%, 4.48%, 0.17%, and 0.001% of the raw $PM_{2.5}$ measurements in China, India, the UK, and the USA, respectively.

2.5. Outdoor $PM_{2.5}$ data

Outdoor $PM_{2.5}$ data were obtained from multiple official government sources through the OpenAQ Platform (https://openaq.org). These data were collected using government-approved methods (e.g. Federal Equivalent Methods in the USA); no outdoor $PM_{2.5}$ data were collected by low-cost $PM_{2.5}$ sensors. For each building, outdoor $PM_{2.5}$ was represented by data from the closest government monitor posted on OpenAQ that collected data at a frequency of at least one measurement per hour. For 32 of the 37 buildings in this analysis, there was an outdoor $PM_{2.5}$ monitor within 10 kilometers (km) of the building. The remaining five buildings (three in the UK and two in the USA) were located 13.2 km, 13.2 km, 16.8 km, 19.9 km, and 30.5 km from the closest outdoor $PM_{2.5}$ monitor. In cases where the closest outdoor $PM_{2.5}$ monitor had a period of missing data, data from the next closest monitor within 50 km of the building were used instead.

2.6. Data analysis

All indoor $PM_{2.5}$ measurements from a given sensor were averaged by hour to standardize the interval between data points for indoor $PM_{2.5}$ and to match the frequency of the outdoor $PM_{2.5}$ measurements. For some periods of time at some buildings, outdoor $PM_{2.5}$ data were not available at any of the outdoor $PM_{2.5}$ monitors within 50 km of the building. Additionally, there were some periods when indoor $PM_{2.5}$ sensors failed to collect data. Since the causes of missing indoor and outdoor $PM_{2.5}$ data were likely device malfunctions or internet connectivity issues unrelated to the values of the missing data, it is reasonable to assume that the missing indoor and outdoor data were missing completely at random (MCAR) and that the complete case analysis described here is consequently unbiased. This analysis includes all indoor $PM_{2.5}$ data collected by $PM_{2.5}$ sensors during periods when outdoor $PM_{2.5}$ measurements were also collected by monitors within 50 km of the buildings in which the indoor measurements were made. Overall, 60% of the total study hours for the 37 buildings had both indoor and outdoor $PM_{2.5}$ measurements.

Linear additive mixed models [29] were used to evaluate the impact of buildings' self-reported filter ratings on hourly indoor $PM_{2.5}$ levels. The primary analysis included two models: one model during standard work hours, when ventilation systems were assumed to be operating normally (weekdays between 9:00 and 17:00 local time), and one model during assumed non-work hours, when ventilation systems may have been scaled back or not operating (weekends or weekdays before 7:00 or after 19:00 local time). The modeled outcome was the natural logarithm of hourly indoor $PM_{2.5}$, with zeros substituted by half of the lowest non-zero $PM_{2.5}$ concentration measured by the same sensor. The replacement of zero values with half of the limit of detection was necessary to accommodate the natural logarithm transformation and has been shown to be minimally biased if zero values make up less than 5–10% of the data [30]. Indoor $PM_{2.5}$ was reported to be 0 $\mu g/m^3$ in 13% of the data used in these models, so the substitution with half of the estimated limit of detection will be close to minimally biased. The models included nested random intercepts for the $PM_{2.5}$ sensor unit and for the building to account for non-independence of measurements made by a single $PM_{2.5}$ sensor package and of measurements made within the same building. The models also included a spline on local datetime to account for serial correlation in measurements.

The main covariate in the models was a categorical marker of filter efficiency with categories including MERV 7–12, MERV 13–14, and MERV 15 or greater. In cases where buildings reported multiple filter ratings, the maximum of the reported ratings was used to categorize the building, following the assumption that air being distributed to occupied spaces passed through filters with lower and higher ratings in series. Three buildings (two in China and one in the USA) reported using filters with ratings that fall in the high-efficiency particulate air (HEPA) or ultra low particulate air (ULPA) range. These filters are designed to perform better than filters with the highest MERV rating (MERV 16) and these three buildings were included in the MERV 15+ group.

Additional categorical covariates in the models included variables representing the countries where buildings were located (in the models for standard work hours and non-work hours) and quartiles of estimated quarterly building air exchange rates (in the model for standard work hours only). Continuous covariates in the models included building age and hourly outdoor $PM_{2.5}$ concentrations. Dichotomous variables representing buildings' green building certification status (certified or not certified) and healthy building certification status (certified or not certified) were considered for inclusion in the models, but were ultimately excluded because their inclusion resulted in lower adjusted R^2 values for both models. A model with outdoor $PM_{2.5}$ lagged by 1 hour was also considered, but the model with concurrent indoor and outdoor $PM_{2.5}$ measurements was used as the final model because it had a higher adjusted R^2 than the lagged model.

Statistical significance was evaluated at a level of $\alpha = 0.05$ and suggestive evidence was evaluated at a level of $\alpha = 0.10$. All modeling was done using the R programming language version 3.5.3.

3. Results

3.1. Building characteristics

The sizes, occupancies, ages, ventilation and filtration characteristics, certifications, and types of environmental sensor packages used in the 37 buildings in this analysis are shown in Table 2. Across the 37 buildings, 30 buildings had only mechanical ventilation and seven buildings had mixed-mode ventilation. Among the buildings in this analysis, the popularity of different filter efficiencies varied by country. The most popular filter efficiency category in buildings in this study was MERV 15+ in China, MERV 7–12 in India, MERV 13–14 in the UK, and both MERV 7–12 and MERV 13–14 (tied) in the USA.

3.2. Distributions of indoor $PM_{2.5}$ and CO_2 across four countries and over time

Country differences in indoor and outdoor $PM_{2.5}$ during standard work hours from the 37 buildings in this study are shown in Fig. 1. Indoor $PM_{2.5}$ in the USA and the UK was much lower than in China and India, with overall medians of hourly concentrations measured indoors during standard work hours of 1.0 $\mu g/m^3$ in the UK, 1.7 $\mu g/m^3$ in the USA, 8.0 $\mu g/m^3$ in India, and 18.0 $\mu g/m^3$ in China. These regional differences were mirrored outdoors. Median outdoor $PM_{2.5}$ concentrations

Table 2
Descriptive information for all buildings in this analysis.

	All Countries	China	India	USA	UK
Total Buildings, n	**37**	**8**	**7**	**16**	**6**
Ventilation, n (% of Country Total)					
Mechanical Ventilation	30 (81%)	5 (63%)	5 (71%)	14 (88%)	6 (100%)
Mixed-Mode Ventilation	7 (19%)	3 (38%)	2 (29%)	2 (13%)	0 (0%)
Filter Efficiency Rating, n (% of Country Total)					
MERV 7-12	15 (41%)	3 (38%)	4 (57%)	7 (44%)	1 (17%)
MERV 13-14	14 (38%)	1 (13%)	2 (29%)	7 (44%)	4 (67%)
MERV 15+	8 (22%)	4 (50%)	1 (14%)	2 (13%)	1 (17%)
Healthy Building Certification, n (% of Country Total)					
Yes	10 (27%)	1 (13%)	0 (0%)	9 (56%)	0 (0%)
No	27 (73%)	7 (88%)	7 (100%)	7 (44%)	6 (100%)
Green Certification, n (% of Country Total)					
Yes	25 (68%)	8 (100%)	2 (29%)	11 (69%)	4 (67%)
No	12 (32%)	0 (0%)	5 (71%)	5 (31%)	2 (33%)
Sensor Package Type Used in Study, n (% of Country Total)					
Harvard Healthy Buildings	8 (22%)	1 (13%)	5 (71%)	2 (13%)	0 (0%)
Tsinghua IBEM	6 (16%)	6 (75%)	0 (0%)	0 (0%)	0 (0%)
Awair Omni	5 (14%)	0 (0%)	2 (29%)	3 (19%)	0 (0%)
ChemiSense CS-001	1 (3%)	0 (0%)	0 (0%)	1 (6%)	0 (0%)
Tongdy MSD-16	10 (27%)	0 (0%)	0 (0%)	10 (63%)	0 (0%)
Harvard Healthy Buildings + Tsinghua IBEM	1 (3%)	1 (13%)	0 (0%)	0 (0%)	0 (0%)
Harvard Healthy Buildings + Awair Omni	6 (16%)	0 (0%)	0 (0%)	0 (0%)	6 (100%)
Gross area (1000 m^2), median [range]	5.86 [0.465–1020]	61.2 [2.11–201]	29.7 [1.55–1020]	2.93 [0.465–546]	2.86 [1.53–7.38]
# Occupants during occupied hours, median [range]	400 [42–11,000]	650 [135–4520]	3800 [80–5000]	114 [42–11,000]	460 [288–600]
Building age (years), median [range]	11 [1–120]	5 [2–10]	8 [3–15]	36 [1–120]	23 [3–31]
Median building estimated quarterly air exchange rate (hr^{-1}), median [range]	0.47 [0.15–2.0]	1.0 [0.33–1.8]	0.45 [0.15–0.79]	0.39 [0.19–2.0]	0.54 [0.37–0.97]

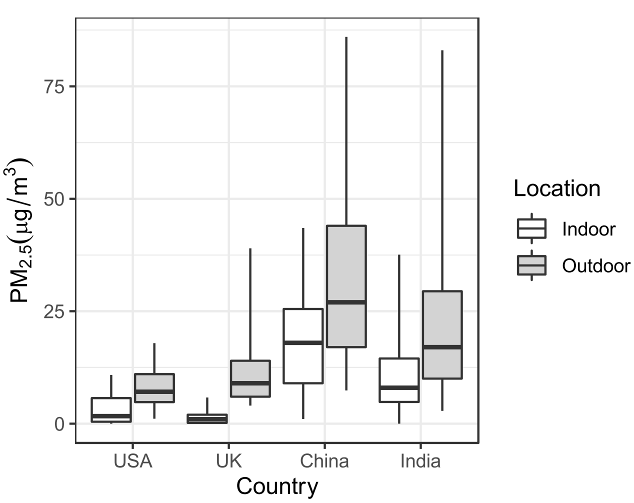

Fig. 1. Boxplots of indoor and outdoor $PM_{2.5}$ concentrations during standard work hours by country. Bottom whisker runs from 5th percentile to 25th percentile and top whisker runs from 75th percentile to 95th percentile. Horizontal lines in box represent 25th, 50th, and 75th percentiles.

during standard work hours were 9.0 $\mu g/m^3$ in the UK, 7.1 $\mu g/m^3$ in the USA, 17.0 $\mu g/m^3$ in India, and 27.0 $\mu g/m^3$ in China.

Median CO_2, indoor $PM_{2.5}$, and outdoor $PM_{2.5}$ concentrations varied by country, time of year, and operating hours at the 37 buildings in this study (Table 3). There was some variation of indoor $PM_{2.5}$ levels by three-month period, with the lowest median concentrations in China and India in June–August and highest median concentrations in China, India, and the UK in December–February. In three of the four three-month periods, the median indoor $PM_{2.5}$ concentrations during standard work hours were lowest in the UK compared to the other three countries. For each three-month period, the median indoor $PM_{2.5}$ concentration during standard work hours in the UK and the USA was less than 3 $\mu g/m^3$. In China and India, three-month median indoor $PM_{2.5}$ concentrations during standard work hours exceeded 9 $\mu g/m^3$ with one exception in India during June–August. In China, for each three-month period, the median indoor $PM_{2.5}$ concentration during standard work hours was between 5.1 and 15.5 times greater than the comparable concentration in the USA. Similarly, in India, for each three-month period, the median indoor $PM_{2.5}$ concentration during standard work hours was between 2.6 and 20.4 times greater than the comparable concentration in the USA. Trends in indoor $PM_{2.5}$ were consistent with trends in outdoor $PM_{2.5}$, although the three-month median indoor $PM_{2.5}$ concentrations for each country were always lower than the three-month median outdoor $PM_{2.5}$ concentrations, both during standard work hours and non-work hours. More detailed summary statistics for indoor and outdoor $PM_{2.5}$ in each country and three-month period can be found Tables S2 and S3 in the Supplementary Material.

Median (Table 3) and 75th percentiles (Table S4 in the Supplementary Material) of hourly device-averaged indoor CO_2 levels during work hours remained lower than 1000 ppm in all countries in all quarters of the year except for December–February in India. These low to moderate CO_2 levels suggest that the buildings in this study were fairly well ventilated and/or had relatively low occupancies. In China, the 95th percentiles of hourly device-averaged indoor CO_2 during work hours were lower than 1000 ppm in all four quarters of the year, suggesting that outdoor air ventilation was relatively effective in these buildings. On the other hand, the 95th percentiles of hourly device-averaged CO_2 during work hours were highest in India in all four quarters of the year (ranging from 1254 ppm to 1806 ppm). These measurements suggest that the buildings in India were not always well ventilated for their occupancies.

3.3. Association between outdoor and indoor $PM_{2.5}$ levels

The results of the linear additive mixed models are shown in Table 4. In separate models for standard work hours and non-work hours, the natural logarithm of indoor $PM_{2.5}$ was positively and significantly associated with outdoor $PM_{2.5}$ ($p < 0.0001$). During standard work hours, a 10 $\mu g/m^3$ increase in outdoor $PM_{2.5}$ was associated with a

Table 3
Summary of hourly measurements of indoor and outdoor $PM_{2.5}$ and indoor CO_2 from buildings in this analysis by country and month, shown separately for standard work hours and non-work hours.

Country	Month	Standard Work Hours or Non-Work Hours	Indoor CO_2, ppm Median (SD)		Indoor $PM_{2.5}$, $\mu g/m^3$ Median (SD)		Outdoor $PM_{2.5}$, $\mu g/m^3$ Median (SD)		# of $PM_{2.5}$ Datapoints
China	Mar–May	Standard work hours	511	(99)	18.3	(15.5)	27.0	(24.7)	11,194
		Non-work hours	423	(59)	17.2	(9.5)	28.0	(24.6)	29,234
	Jun–Aug	Standard work hours	567	(126)	11.8	(15.2)	20.0	(16.0)	10,747
		Non-work hours	421	(65)	9.9	(7.9)	19.0	(15.7)	29,230
	Sep–Nov	Standard work hours	532	(122)	20.0	(14.2)	28.0	(24.5)	10,314
		Non-work hours	432	(75)	18.3	(10.8)	28.0	(24.3)	25,573
	Dec–Feb	Standard work hours	552	(184)	21.7	(16.6)	35.0	(31.0)	10,714
		Non-work hours	431	(82)	20.8	(11.9)	35.0	(30.4)	26,923
India	Mar–May	Standard work hours	630	(441)	17.5	(11.5)	32.2	(30.7)	485
		Non-work hours	473	(270)	23.2	(12.8)	37.0	(36.2)	1055
	Jun–Aug	Standard work hours	753	(316)	6.0	(4.4)	13.0	(24.1)	3012
		Non-work hours	460	(185)	8.8	(7.3)	12.2	(23.7)	8033
	Sep–Nov	Standard work hours	711	(320)	9.2	(10.4)	16.9	(18.0)	2502
		Non-work hours	470	(206)	12.0	(14.5)	17.1	(25.4)	6199
	Dec–Feb	Standard work hours	1058	(444)	28.6	(40.6)	77.3	(57.1)	534
		Non-work hours	560	(221)	45.2	(27.1)	75.0	(53.8)	956
UK	Mar–May	Standard work hours	750	(184)	1.0	(11.3)	10.0	(10.3)	13,282
		Non-work hours	434	(71)	1.5	(4.1)	10.0	(10.0)	36,759
	Jun–Aug	Standard work hours	796	(171)	0.8	(1.6)	7.0	(3.7)	9404
		Non-work hours	433	(99)	1.0	(6.4)	7.0	(3.5)	24,574
	Sep–Nov	Standard work hours	790	(183)	0.0	(2.3)	7.0	(8.8)	1320
		Non-work hours	447	(79)	0.2	(3.1)	7.0	(6.7)	3543
	Dec–Feb	Standard work hours	740	(181)	1.8	(10.7)	14.0	(14.7)	4674
		Non-work hours	456	(91)	3.4	(4.7)	20.0	(13.0)	11,311
USA	Mar–May	Standard work hours	578	(177)	1.2	(3.7)	7.0	(5.0)	21,788
		Non-work hours	444	(125)	1.8	(3.6)	7.5	(6.9)	54,226
	Jun–Aug	Standard work hours	604	(197)	2.3	(3.6)	8.0	(6.3)	22,906
		Non-work hours	458	(137)	2.9	(4.3)	8.3	(6.1)	61,230
	Sep–Nov	Standard work hours	589	(196)	1.7	(4.2)	7.0	(5.6)	15,213
		Non-work hours	443	(135)	2.7	(4.3)	7.0	(5.5)	38,298
	Dec–Feb	Standard work hours	617	(208)	1.4	(4.7)	7.0	(6.1)	17,810
		Non-work hours	441	(145)	1.7	(4.3)	7.2	(6.2)	45,223

19.9% (95% CI: +19.5%, +20.3%) increase in the expected concentration of indoor $PM_{2.5}$, controlling for building age, MERV rating, quarterly air exchange rate, country, and datetime ($p < 0.0001$). For example, for a building where the indoor $PM_{2.5}$ concentration is identical to the median concentration during standard work hours in China (18.0 $\mu g/m^3$), a 10 $\mu g/m^3$ increase in outdoor $PM_{2.5}$ is expected to be associated with a 3.6 $\mu g/m^3$ increase in indoor $PM_{2.5}$ if the observed associations are causal. For a building where the indoor $PM_{2.5}$ concentration is identical to the median concentration during standard work hours in USA (1.7 $\mu g/m^3$), a 10 $\mu g/m^3$ increase in outdoor $PM_{2.5}$ is expected to be associated with a 0.3 $\mu g/m^3$ increase in indoor $PM_{2.5}$.

During non-work hours, a 10 $\mu g/m^3$ increase in outdoor $PM_{2.5}$ was associated with an even higher 23.4% (95% CI: +23.1%, +23.6%) increase in the expected concentration of indoor $PM_{2.5}$, controlling for building age, MERV rating, country, and datetime ($p < 0.0001$). For example, for a building where the indoor $PM_{2.5}$ concentration is identical to the median concentration during non-work hours in China (16.2 $\mu g/m^3$), a 10 $\mu g/m^3$ increase in outdoor $PM_{2.5}$ is expected to be associated with 3.8 $\mu g/m^3$ increase in indoor $PM_{2.5}$ if the observed associations are causal. For a building where the indoor $PM_{2.5}$ concentration is identical to the median concentration during non-work hours in the USA (2.2 $\mu g/m^3$), a 10 $\mu g/m^3$ increase in outdoor $PM_{2.5}$ is expected to be associated with 0.5 $\mu g/m^3$ increase in indoor $PM_{2.5}$.

3.4. Association between filtration and indoor $PM_{2.5}$ levels

Indoor and outdoor $PM_{2.5}$ concentrations during standard work hours by the MERV rating of the filter in the building where the measurements were collected are shown in Fig. 2. The results of the linear additive mixed models (Table 4) show suggestive and statistically significant evidence that office buildings' filter ratings were associated with concentrations of indoor $PM_{2.5}$. When filters with higher MERV ratings were used, indoor $PM_{2.5}$ tended to be lower. During standard work hours, the expected concentration of indoor $PM_{2.5}$ was approximately 39.4% (95% CI: −62.0%, −3.4%) lower in buildings with MERV 15+ filters than in buildings with MERV 7–12 filters, controlling for outdoor $PM_{2.5}$, building age, building air exchange rate, country, and datetime ($p = 0.04$). During standard work hours, the expected concentration of indoor $PM_{2.5}$ was approximately 30.9% (95% CI: −55.0%, +6.2%) lower in buildings with MERV 13–14 filters than in buildings with MERV 7–12 filters, controlling for outdoor $PM_{2.5}$, building age, building air exchange rate, country, and datetime ($p = 0.09$). For example, if the indoor $PM_{2.5}$ concentration in a building with a MERV 7–12 filter was equal to the median concentration during standard work hours in China (18.0 $\mu g/m^3$), a co-located identical building that had a MERV 13–14 filter would be expected to have an indoor $PM_{2.5}$ concentration during standard work hours of only 12.4 $\mu g/m^3$.

During non-work hours, indoor $PM_{2.5}$ was not significantly associated with building filtration and standard errors for the effect estimates of the association between filtration and indoor $PM_{2.5}$ were larger during non-work hours than during standard work hours. These results are likely due to more variation in ventilation operations during non-work hours than during standard work hours, perhaps due to buildings scaling back their ventilation operations to different degrees or perhaps due to our definition of non-work hours inadvertently including some work hours when buildings were occupied.

3.5. Association between air exchange rate and indoor $PM_{2.5}$ levels

The results of the linear additive mixed model for standard work hours (Table 4) show that office buildings' air exchange rates were significantly associated with indoor $PM_{2.5}$ concentrations, with buildings where quarterly air exchange rates exceeded the 25th percentile (0.31 h^{-1}) having lower indoor $PM_{2.5}$ than buildings where quarterly air

Table 4
Results, shown as percent changes in indoor $PM_{2.5}$, from the model predicting the natural logarithm of indoor $PM_{2.5}$ using data from buildings with mechanical or mixed-mode ventilation and filtration, with random intercepts for building and for device. Models also included a spline on datetime.

	Standard Work Hours % change (95% CI)	*p-value*	Non-Work Hours % change (95% CI)	*p-value*
Outdoor $PM_{2.5}$ (+10 $\mu g/m^3$)	+19.9% (+19.5%, +20.3%)	<0.0001	+23.4% (+23.1%, +23.6%)	<0.0001
Building age (+1 year)	+1.3% (+0.5%, +2.1%)	0.002	+1.2% (−0.1%, +2.5%)	0.07
Level of Filtration (Reference = MERV 7–12)				
MERV 13-14	−30.9% (−55.0%, +6.2%)	0.09	+20.6% (−43.6%, +158%)	0.63
MERV 15+	−39.4% (−62.0%, −3.4%)	0.04	−37.4% (−74.1%, +51.4%)	0.30
AER (Reference = Quartile 1)				
Quartile 2	−30.0% (−31.6%, −28.3%)	<0.0001		
Quartile 3	−29.3% (−31.2%, −27.4%)	<0.0001		
Quartile 4	−13.6% (−16.1%, −11.2%)	<0.0001		
Country (Reference = USA)				
UK	+4.9% (−36.1%, +72.2%)	0.85	−6.3% (−65.3%, +153%)	0.90
China	+735% (+364%, +1403%)	<0.0001	+791% (+216%, +2416%)	<0.0001
India	+653% (+313%, +1274%)	<0.0001	+657% (+170%, +2024%)	0.0001

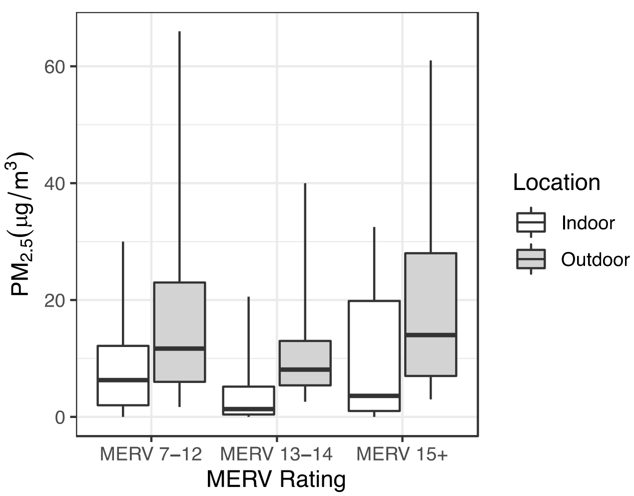

Fig. 2. Boxplots of indoor and outdoor $PM_{2.5}$ concentrations during standard work hours by building MERV rating. Bottom whisker runs from 5th percentile to 25th percentile and top whisker runs from 75th percentile to 95th percentile. Horizontal lines in box represent 25th, 50th, and 75th percentiles.

exchange rates were lower than the 25th percentile. Compared to buildings with quarterly air exchange rates in the first quartile (<0.31 h^{-1}), the expected concentration of indoor $PM_{2.5}$ during standard work hours was approximately 30.0% (95% CI: −31.6%, −28.3%) lower in buildings with quarterly air exchange rates in the second quartile (0.31 h^{-1} – 0.47 h^{-1}), 29.3% (95% CI: −31.2%, −27.4%) lower in buildings in the third quartile (0.47 h^{-1} – 0.84 h^{-1}), and 13.6% (95% CI: −16.1%, −11.2%) lower in buildings in the fourth quartile (>0.84 h^{-1}), controlling for outdoor $PM_{2.5}$, building age, MERV rating, country, and datetime ($p < 0.0001$).

3.6. Model variances

In the model using data from standard work hours, the variances of the random intercepts for building and for $PM_{2.5}$ sensor and of the residuals were 3.94×10^{-5}, 1.52, and 0.874, respectively. These variances indicate that the variables included in the model explained essentially all of the variability in the natural logarithm of indoor $PM_{2.5}$ concentrations between buildings in the study. By contrast, there was much more unexplained variation between sensors within a building; 63% of the residual variability in the modeled natural logarithm of indoor $PM_{2.5}$ concentrations unexplained by the model covariates was explained by differences between sensors within buildings. During non-work hours, the variances of the random intercepts for building and for sensor and of the residuals were 0.770, 0.672, and 0.993, respectively. The notable increase in variance at the building level during non-work hours compared to standard work hours suggests that differences in indoor $PM_{2.5}$ concentrations between buildings are only well explained by the building characteristics in the model when building systems are in use.

4. Discussion

The results of this analysis suggest that indoor $PM_{2.5}$ concentrations are generally lower than outdoor $PM_{2.5}$ concentrations in buildings with mechanical ventilation and filtration. Nonetheless, in countries with high outdoor $PM_{2.5}$ levels, indoor $PM_{2.5}$ concentrations sometimes exceeded health-based exposure guidelines. For example, in India and China, 17% and 27%, respectively, of daily mean (during standard work hours only) indoor $PM_{2.5}$ concentrations in these data exceeded the WHO average 24-hour exposure guideline of 25 $\mu g/m^3$ [31]. The results of this analysis demonstrate that buildings with high filter efficiencies had statistically significantly lower indoor $PM_{2.5}$ than buildings with standard filter efficiencies across the four countries studied. This result suggests that filters can reduce indoor $PM_{2.5}$ exposure in regions with high and low outdoor $PM_{2.5}$ exposures, both of which are important because there is no known threshold below which $PM_{2.5}$ exposure is thought to be safe [31] and since harmful effects of $PM_{2.5}$ have been seen for short- and long-term exposures to relatively low and commonly-encountered $PM_{2.5}$ concentrations [4,6,32]. These findings suggest that office buildings should consider operating their ventilation systems with filters with the highest MERV rating that can function in their system to provide the strongest health benefit for their occupants. The expected health impact of enhanced filtration includes improved health outcomes associated with acute and chronic $PM_{2.5}$ exposures including cardiovascular and respiratory health.

4.1. Impact of mechanical system operation, filtration, and air exchange rate on indoor $PM_{2.5}$ concentrations

The results of the linear additive mixed models indicate that indoor $PM_{2.5}$ increases more quickly as outdoor $PM_{2.5}$ increases during non-work hours compared with standard work hours. This analysis also found that buildings that used filters with ratings of at least MERV 13 had lower indoor $PM_{2.5}$ concentrations than buildings that used filters with ratings of MERV 7–12 during standard work hours, but not during non-work hours. These results suggest that filters are effective to reduce indoor $PM_{2.5}$ in occupied buildings during operating hours. These results support a prior finding that indoor $PM_{2.5}$ was significantly lower during work hours compared to non-work hours in three of six buildings studied in China, though it is not clear what level of filtration was present in these buildings [33].

This analysis found that quarterly air exchange rates in the second, third, and fourth quartiles were associated with reductions in average indoor $PM_{2.5}$ concentrations compared to quarterly air exchange rates in the first quartile. While this finding seems to contradict prior work that found higher ratios of indoor $PM_{2.5}$ to outdoor $PM_{2.5}$ (I/O ratios) as ventilation rates increased from 1.0 h^{-1} to 2.4 h^{-1} to 5.4 h^{-1} in experiments with MERV 8, MERV 14, and MERV 15 filters, the results in our analysis were not necessarily comparable with these prior results because all four quartiles in our analysis included air exchange rates lower than the lowest rate of 1.0 h^{-1} examined previously [18]. Our air exchange rate estimates may be underestimates of the true air exchange rates in the participating buildings if they were influenced by employees still in the building or if they were influenced by evening changes in ventilation system operations. In our results, the most notable finding was that $PM_{2.5}$ tended to be higher when quarterly air exchange rates were in the first quartile (<0.31 h^{-1}) compared to when quarterly air exchange rates were higher; it is possible that these periods with very low air exchange rates represent periods when outdoor air ventilation was so low that indoor $PM_{2.5}$ could accumulate due to indoor sources of $PM_{2.5}$ that were never diluted due to the lack of input of filtered outdoor air. In any case, our results agree with prior work that found that adjusting filters from MERV 8 to MERV 14 or 15 had a bigger impact on reducing indoor $PM_{2.5}$ than adjusting the outdoor air ventilation rate did [18]. In this analysis, MERV 13–14 filters and MERV 15+ filters reduced indoor $PM_{2.5}$ by 30.9% and 39.4%, respectively, compared to MERV 7–12 filters, while the effects of quarterly air exchange rate (the difference between the first and other quartiles) ranged from −13.6% to −30.0%.

4.2. Comparison of indoor $PM_{2.5}$ concentrations and the relationship between indoor and outdoor $PM_{2.5}$ with other studies

In the Global CogFx Study and in prior studies of $PM_{2.5}$ in office buildings in the USA, Europe, and Asia, outdoor $PM_{2.5}$ concentrations generally exceeded indoor $PM_{2.5}$ concentrations [23,33–36]. The indoor $PM_{2.5}$ values measured in USA, UK, and Chinese buildings in this analysis were also somewhat lower than prior measurements in USA, European, and Chinese office buildings. In the BASE study (in 1994–1998) in the USA, approximately 75% of one-workday integrated indoor $PM_{2.5}$ concentrations during business hours were less than 10 $\mu g/m^3$ [23]. By comparison, approximately 93% of hourly indoor $PM_{2.5}$ measurements during standard work hours were less than 10 $\mu g/m^3$ in data from USA buildings in this analysis. Similarly, a recent study of 37 small and medium commercial buildings, including 9 offices, in California found that the median one-day integrated indoor $PM_{2.5}$ concentration in offices during business hours was 6.4 $\mu g/m^3$ [36] which exceeds the median indoor $PM_{2.5}$ concentration of 1.7 $\mu g/m^3$ in USA office buildings in our analysis of data from the Global CogFx Study. These differences may be due to differences between the buildings in the studies' convenience samples. For example, compared to buildings in this analysis which all had filter efficiencies of MERV 7 or higher, the California offices had low filter efficiencies (i.e. MERV 4 or lower) [36]. These differences could also be due to the 43% reduction in the national average outdoor $PM_{2.5}$ over the two decades that have elapsed between the BASE study (in 1994–1998) and the Global CogFx Study (in 2018–2020) [37] because outdoor $PM_{2.5}$ can be an important source of indoor $PM_{2.5}$ [19,34,38].

In a study conducted on 13 floors of six buildings in Chengdu, China during autumn 2016, building floor average indoor $PM_{2.5}$ levels over the full monitoring period ranged from 35 $\mu g/m^3$ to 97 $\mu g/m^3$ [33]. By contrast, the mean of all hourly indoor measurements during September–November in the three Chengdu buildings in our study was only 16.8 $\mu g/m^3$. Interestingly, the mean I/O ratios in the 2016 measurements ranged from 0.38 to 0.97 [33]; this range includes the mean I/O ratio for all the hourly measurements in September–November in the three Chengdu buildings in our study of 0.41. Though the absolute indoor $PM_{2.5}$ concentrations in our study were lower than those in the 2016 study, the overlap of our I/O ratio with the 2016 study's range of I/O ratios suggests that the differences may be due to elevated outdoor $PM_{2.5}$ concentrations during the 2016 study compared to our study. The differences could also be due to differences between the buildings in the studies' convenience samples, as the Chinese buildings in our study all had green certifications and tended to have high filtration efficiencies.

Prior research investigating relationships between indoor and outdoor $PM_{2.5}$ has found indoor $PM_{2.5}$ concentrations to be moderately correlated with outdoor $PM_{2.5}$ concentrations. For example, the 20-building European OFFICAIR study found a correlation of 0.74 between integrated 100-hour measurements of indoor and outdoor $PM_{2.5}$ concentrations in two seasons [35]. Given the influence that building ventilation practices are expected to have on the relationship between indoor and outdoor $PM_{2.5}$, this high degree of correlation suggests that the buildings in the OFFICAIR study may have had air filters with relatively low filter efficiencies, that infiltration occurred overnight (while $PM_{2.5}$ measurements continued overnight), or that open windows allowed unfiltered outdoor air to enter (OFFICAIR windows were generally closed, but open in some buildings for part of the study). In the USA-based BASE study, the correlation between integrated 8-hour measurements of indoor and outdoor $PM_{2.5}$ concentrations in 100 buildings was only 0.44 [23]. The authors of the BASE study suggested that this correlation was not higher due to the decoupling of indoor and outdoor $PM_{2.5}$ concentrations by filtration. The Global CogFx Study data corroborate this finding of the BASE study. In this study, the Spearman correlation between building daily average concentrations of indoor and outdoor $PM_{2.5}$ measured during standard work hours was 0.09 in USA buildings, 0.41 in UK buildings, 0.40 in China buildings, and 0.67 in India buildings. Although the larger ranges of indoor and outdoor $PM_{2.5}$ in China and India compared to the USA and the UK likely contribute to the higher correlations in buildings in those countries, these low to moderate correlations support the authors of the BASE study's suggestion that the operation of ventilation systems decouples indoor and outdoor $PM_{2.5}$ concentrations to a degree.

4.3. Comparison of the impact of filtration with other studies

Only a limited number of prior studies have examined the impact of MERV rating on concentrations of indoor pollutants in situ, and even fewer of these studies have done so in multiple buildings. In an experiment that tested three filter efficiencies in a single building in Philadelphia, Pennsylvania, $PM_{2.5}$ I/O ratios were lower when MERV 14 and MERV 15 filters were used compared to MERV 8 filters at all three air exchange rates tested [18]. In 40 measurements in 37 commercial buildings in California, including offices, retail establishments, restaurants, and gas station convenience stores, the ratio of measured indoor black carbon (a component of $PM_{2.5}$) to outdoor black carbon was lower in the 12 buildings with MERV 6–8 filters than in the 23 buildings with filter ratings of MERV 4 or lower, though this difference was not significant [36]. Importantly, this California analysis also did not control for any building characteristics that could be relevant. Consequently, their result may not necessarily indicate that higher MERV ratings result in less indoor black carbon; for example, if one building type was more likely to have low-efficiency filters and more likely to have higher ratios of indoor to outdoor black carbon perhaps due to re-suspension of settled black carbon by occupant movement, it is possible that there would appear to be a relationship between filter efficiency and black carbon when none existed. Our analysis addressed this issue and found that filter efficiency was associated with reduced indoor $PM_{2.5}$ after controlling for outdoor $PM_{2.5}$, building characteristics, and datetime.

4.4. Public health impact of improved filtration

Reducing indoor $PM_{2.5}$ levels through filtration may reduce the risks of adverse outcomes of $PM_{2.5}$ exposure for office workers. Although the relationship between indoor $PM_{2.5}$ concentrations and various health outcomes is relatively understudied, we can draw on research that links outdoor $PM_{2.5}$ with health outcomes. For example, the recently-published Global Exposure Mortality Model (GEMM) used data from 41 cohort studies in 16 countries to develop age-specific hazard ratios for long-term outdoor $PM_{2.5}$ exposures and various causes of death [4]. Under the assumptions that the relationship between outdoor $PM_{2.5}$ and mortality from the GEMM represents the relationship between in-office $PM_{2.5}$ and mortality, upgrading a filter from MERV 7–12 to MERV 15+ in a building where indoor $PM_{2.5}$ is 18.0 $\mu g/m^3$ (the median indoor concentration during standard work hours in Chinese buildings in this study) would be expected to reduce the hazard ratio for mortality from non-communicable diseases and lower respiratory infections among 25- to 29-year-olds from approximately 1.21 to 1.14 if our observed associations are causal. Similarly, upgrading a filter from MERV 7–12 to MERV 13–14 in a building where indoor $PM_{2.5}$ is 18.0 $\mu g/m^3$ would be expected to reduce the hazard ratio for mortality from non-communicable diseases and lower respiratory infections among 25- to 29-year-olds from approximately 1.21 to 1.15. In reality, these reductions in the hazard ratio may be underestimates if $PM_{2.5}$-relatated mortality is more strongly related with indoor $PM_{2.5}$ than it is with outdoor $PM_{2.5}$; on the other hand, they may be overestimates because workers will only be helped by the in-office $PM_{2.5}$ reduction during the approximately 20%–25% of their time they spend at their offices. In addition to reducing the likelihood of health problems caused by chronic exposure to $PM_{2.5}$, improving office filtration could also reduce the harmful health effects due to acute exposures to $PM_{2.5}$. Subclinical effects of acute $PM_{2.5}$ exposure, such as changes in cardiac function [39] and clinical effects of acute $PM_{2.5}$ exposure, such as respiratory or cardiovascular hospitalization (Dominici et al., 2006), would be expected to be improved with higher levels of filtration. While effects of chronic exposures may take years to appear, acute exposures on the order of minutes, hours, or a day can occur during a single workday, so the benefits of indoor $PM_{2.5}$ mitigation on these outcomes are more certain to be realized.

A filter rating of at least MERV 8 is recommended by ASHRAE for outdoor air being distributed to occupied spaces in areas where the PM_{10} national standard for outdoor air is exceeded [17]. A filter rating of at least MERV 13 for outdoor air being distributed to occupied spaces is included in the optional United States Green Building Council's LEED Enhanced Indoor Air Quality Strategies credit [40] and is a prerequisite in the Air Filtration category for achieving the WELL Building Standard's healthy building certification [41]. The MERV 13 threshold used by the LEED and WELL rating systems is supported by our result that buildings with filters rated MERV 13–14 had 30.9% (95% CI: –55.0%, +6.2%) lower indoor $PM_{2.5}$ than buildings with filters rated MERV 7–12, controlling for outdoor $PM_{2.5}$, building characteristics, and datetime. Since there is no known safe threshold of exposure to $PM_{2.5}$ [31], the additional reductions in $PM_{2.5}$ achieved by using filters with ratings of at least MERV 13 would promote the health of office workers in places with high and low concentrations of outdoor $PM_{2.5}$.

4.5. Effect of potential measurement error of indoor $PM_{2.5}$ concentrations

Recent advancements in low-cost sensor technology have opened up new opportunities for monitoring indoor environmental quality. Due to its global and distributed scale and one-year duration, the Global CogFx Study was only feasible with the use of low-cost laser-based $PM_{2.5}$ sensors. Prior work on various types of low-cost $PM_{2.5}$ sensors indicates that there is often a high degree of consistency in measurements made by multiple sensors of the same type when they are collocated, while sensors of different types may exhibit more variation [42–45]. In some circumstances, these sensors are less accurate than research-grade instruments and prior characterization of sensors similar to those in the Global CogFx Study found that sensor measurements can differ from research-grade measurements by up to a factor of two [45,46]. It has also been shown that the characteristics of the $PM_{2.5}$ being measured, such as the size distribution, impact the degree of error in the measurement. For example, it is common for some low-cost sensors to underreport $PM_{2.5}$ concentrations when measuring $PM_{2.5}$ that is mostly comprised of particles with diameters of less than approximately 0.3 μm. One study of six types of low-cost $PM_{2.5}$ sensors found that they did not respond to particle sources with diameters smaller than 0.25 μm [45]. The specifications for the sensors used in this study (Table 1) indicate that errors of up to 10–15 $\mu g/m^3$ could be present in the measured indoor $PM_{2.5}$ concentrations in this analysis. However, in our analysis, measurement error due to differences between the multiple sensor types or due to underreporting of certain particle sizes can only bias our result showing lower indoor $PM_{2.5}$ concentrations in buildings with more efficient filters if the degree of error differs across the three filtration categories (i.e. if differential measurement error in indoor $PM_{2.5}$ with respect to MERV ratings is present). We will briefly consider whether this was the case for the two potential sources of bias mentioned.

Differential measurement error of indoor $PM_{2.5}$ with respect to filtration categories could occur if specific sensor types with different degrees of bias were used in buildings in each filtration category (i.e. if sensor type and MERV rating were not independent). For our data, a chi-squared test of whether sensor types used in buildings were independent from MERV rating categories of the buildings (MERV 7–12, MERV 13–14, or MERV 15+) failed to reject the null hypothesis that sensor type and filtration level were independent ($\chi^2 = 10.8$, $p = 0.21$). This lack of significant association between filtration and study sensor type was expected, as the research team did not know the buildings' filtration levels when choosing which sensor to deploy. Since sensor type and filtration level appear to be independent, the measurement error in indoor $PM_{2.5}$ measurements due to different sensor types is expected to be nondifferential with respect to filtration level and is not expected to result in any systematic bias in our model results, though it may result in larger standard errors.

Differential measurement error of indoor $PM_{2.5}$ with respect to filtration category could also occur if the degree of undercounting of particles of certain sizes, say smaller than approximately 0.30 μm, differed between buildings with different filter efficiencies. While 0.30 μm is the minimum particle diameter that is considered when assigning a MERV rating to a filter, office buildings with more efficient filters are expected to have lower concentrations of particles of all diameters including those less than 0.30 μm [47,48]. Consequently, though some low-cost $PM_{2.5}$ sensors may underreport $PM_{2.5}$ because they underreport concentrations of certain particle sizes (e.g. smaller than approximately 0.30 μm), it is expected that the ratio of measured $PM_{2.5}$ to true $PM_{2.5}$ due to this undercounting is similar for all filtration categories. In other words, the percent error in $PM_{2.5}$ measurement due to undercounting certain particle sizes does not depend on the level of filtration in buildings. As a result, we do not expect that this error in $PM_{2.5}$ measurements will result in a biased estimate of the impact of filtration on indoor $PM_{2.5}$.

In summary, although measurement error may be present in the indoor $PM_{2.5}$ measurements used in this analysis, it is not expected to be differential with respect to the main covariate of interest. Therefore, our model results are not expected to be biased, though they may suffer from inflated standard errors.

4.6. Strengths & limitations

Due to the scale of this study, study team members did not visit all of the buildings that participated in the study. Consequently, this study is limited by incomplete knowledge of all relevant variables that could impact indoor $PM_{2.5}$ concentrations, such as proximity of building air inlets to sources of pollution, use of portable air cleaners or open windows, configuration of ventilation systems including filter locations, total recirculated and outdoor airflows, locations and frequency of use of indoor $PM_{2.5}$ sources, and deposition and resuspension rates of indoor $PM_{2.5}$. Similarly, we did not measure outdoor air ventilation in each building which could have resulted in more accurate estimates of quarterly air exchange rates than the CO_2-based estimates that were used in this study. On the other hand, by using continuous CO_2 measurements to estimate air exchange rates, we were able to build estimates for each three-month quarter of the year to account for variation across the year. Finally, this analysis made the assumption that standard work hours in each office were contained within the 9:00–17:00 window on weekdays and that ventilation systems typically operated normally during these hours; if this assumption is wrong, our estimates of the impact of filtration during work hours may be biased toward no effect.

Nonetheless, this study has significant advantages over previous analyses of $PM_{2.5}$ measurements in office buildings. First, this study measured $PM_{2.5}$ in many buildings in widely varying cultural and geographical contexts making the results of this work more generalizable than prior work examining fewer than 10 buildings generally located in the same city or region [19,49–54]. Second, this study measured $PM_{2.5}$ in multiple locations in each building, ensuring that the measurements accurately represented the spectrum of exposures within each office; most prior studies have not accounted for within-building variation because they only measured $PM_{2.5}$ in a single indoor location or they aggregated $PM_{2.5}$ measurements collected at a handful of indoor locations [23,49,52,55]. Third, this study measured $PM_{2.5}$ continuously over a full year to understand how office workers' exposures varied between standard work hours and non-work hours and across the year; many prior studies did not address variability in exposure over time because they only made spot or integrated measurements of $PM_{2.5}$ during normal business hours [23,49].

5. Conclusions

This study suggests that office building operations can protect against exposure to air pollution indoors. In all four countries in this study, indoor $PM_{2.5}$ was generally lower than outdoor $PM_{2.5}$; nonetheless, indoor $PM_{2.5}$ still exceeded WHO health-based exposure guidelines in some instances in countries with elevated outdoor $PM_{2.5}$. Even when indoor $PM_{2.5}$ is below exposure guidelines, it is still desirable to reduce concentrations in office buildings as much as possible because the duration of office workers' exposure to pollutants in their workplaces is substantial and because there is no known safe threshold for $PM_{2.5}$ exposure. Building operations can impact how much $PM_{2.5}$ of outdoor origin comes indoors and how long $PM_{2.5}$ of indoor origin remains present. The results of this study suggest that filters, in particular, are an intervention that can reduce $PM_{2.5}$ indoors, as buildings in this study with MERV 13 or higher filters had lower indoor $PM_{2.5}$ than buildings with MERV 7–12 filters during standard work hours, controlling for relevant variables. This effect was strongest for the filters with the highest ratings, MERV 15+. As long- and short-term $PM_{2.5}$ exposures have various harmful impacts on people's health and wellbeing, buildings should consider upgrading filters beyond what is considered standard to protect the health of their occupants.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.107975.

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