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Long-term application of low-cost sensors for monitoring indoor air quality and particle dynamics in a commercial building

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ABSTRACT

Human exposure to indoor particles has been associated with increased rates of morbidity and mortality. To develop efficient particle control measures in indoor environments, there has been an increasing demand for the use of low-cost particle sensors towards indoor air quality applications. However, few studies have examined the potential application of low-cost particle sensors for monitoring indoor air quality and particle dynamics under a long-term deployment in commercial buildings. Given this background, we conducted a case study of six-month field investigation on the use of low-cost sensors for evaluating particle emission, concentration, and removal in an office building. Our results illustrate the necessity of improving control strategies for fine particles <1 μm in commercial buildings (e.g., utilizing high efficiency particle filters). Deploying low-cost particle sensors within an air handling unit and occupied spaces could be a quick and simple approach for monitoring particle filtration effectiveness of a mechanical ventilation system. Furthermore, this study suggests that coupling low-cost particle sensors with CO_2 measurements can offer informative data for analyzing particle emissions associated with occupant activities. Our results reveal that particle resuspension due to occupants can be an important emission source for particles >5 μm in office environments. The study findings could help future research and applications of low-cost sensors in monitoring indoor air quality in commercial buildings.

1. Introduction

Human exposure to indoor particulate matter has been associated with health outcomes such as asthma, lung cancer, and cardiovascular diseases [1–5]. The global crisis of coronavirus disease 2019 (COVID-19) has further demonstrated the necessity of enhancing existing particle mitigation strategies in buildings (e.g., demand-controlled ventilation and effective filtration) [6–9]. To develop effective and energy-efficient particle control measures, there has been an increasing demand for the use of low-cost particle sensors for indoor air quality applications [10]. Compared to traditional particle measurement instruments, low-cost sensors are relatively inexpensive (a few 10's or 100's of US dollar), compact, and portable, allowing a real-time and high-resolution particle monitoring in indoor spaces [11,12]. Moreover, low-cost sensors are relatively easy to install, use, and maintain compared to lab-grade monitors, thereby offering the opportunity to promote public awareness and engagement towards indoor air quality issues [11,13].

Given these advantages, several studies examined and/or discussed the utilization of low-cost particle sensors for indoor air quality applications such as particle distribution measurements with high spatiotemporal resolutions, emission source identification, real-time personal exposure monitoring, Internet of Things, etc. [10,14–20] Table 1 summarizes previous field studies on indoor applications of low-cost particle sensors [21–34]. However, compared to investigations in residential buildings, fewer studies existed on the

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Table 1
Previous field investigations of low-cost particle sensor applications in indoor environments.

Reference	Study domain	Location	Ventilation	Time span	Device
Jones et al. [21]	Office	China, India, the UK, and the USA	Mechanical	12 months	Plantower PMS3003
Coulby et al. [22]	Office	Newcastle Upon Tyne, UK	Natural	1 month	Plantower PMSA003i
Palmisani et al. [23]	Hospital ward	Bari, Italy & Barcelona, Spain	Mechanical	17 months	Speck DSM 501
Tryner et al. [24]	Residence	Colorado, USA	Natural	7 days	Plantower PMS5003 & Sensirion SPS30
Shen et al. [25]	Residence	Beijing, China	Natural	10 days	Plantower PMS3003
Zamora et al. [26]	Residence	Maryland, USA	N/A	12 months	AirVisual Pro, Speck, & AirThinx
Hegde et al. [27]	Residence	Utah, USA	Natural	2 months	Dylos DC1100 Pro & Plantower PMS3003
Kaliszewski et al. [28]	Residence	Warsaw, Poland	Mechanical	10 days	AlphaSense OPC-N3 & Plantower PMS5003
Levy Zamora et al. [29]	Residence	Maryland, USA	N/A	<1 day	Plantower PMSA003
Moreno-Rangel et al. [30]	Residence	Glasgow, UK	N/A	4 days	Foobot FBT0002100
Patel et al. [31]	Residence	Raipur, India	Natural	6 days	Sharp GP2Y1010AU0F
Zikova et al. [32]	Residence	New York, USA	N/A	3 days	Speck
Semple et al. [33]	Residence	N/A	N/A	1 day	Dylos DC1700
Olivares et al. [34]	Residence	Auckland, New Zealand	Natural	7 days	Sharp GP2Y1010AU0F

potential use of low-cost particles sensors in assessing indoor air quality in commercial buildings over a long-term deployment (e.g., more than three months). Moreover, limited information is available about the utilization of low-cost particle sensors in evaluating particle removal performance of mechanical ventilation systems at a full building scale. Given this background, we conducted a field case study to explore the application of low-cost particles sensors in monitoring indoor air quality and particle dynamics in an office building equipped with mechanical ventilation over six months. Our study results could provide useful dataset to the existing literature and benefit future smart building applications based on low-cost air quality monitoring.

2. Methods

2.1. Field experiment set-up

We conducted a field case study of low-cost particle sensor application at an office building (Building 661, The Navy Yard) located in Philadelphia, Pennsylvania, USA, over six months (July 2018–January 2019). This two-story building (see Fig. 1a) has a total floor area of 3500 m^2 and was ventilated by a centralized variable air volume mechanical system. Fig. 2a displays a picture of the air handling unit that served this building. Fig. 2c depicts a schematic of the air handling unit. The percentage of outdoor air was automatically adjusted based on the measured indoor CO_2 concentration with a setpoint at 700 ppm. When indoor CO_2 level was below the setpoint, 20% outdoor air and 80% return air were introduced to mixed air chamber, otherwise 100% outdoor air was supplied. Note that outdoor air chamber and return air chamber were equipped with MERV 8 particle filters. To examine the potential application of low-cost particle sensors for monitoring particle removal performance of the mechanical ventilation system, we placed two low-cost sensor units within the outdoor air chamber and supply air chamber of the air handling unit, respectively (see Fig. 2b and c). The measurement data were collected by a laptop computer placed in the mechanical room, and then were uploaded to a cloud server automatically. In addition, we deployed another low-cost sensor unit at a work desk in a typical office (floor area = 70 m^2, see Fig. 1b) on the first floor of the building. This office was occupied by two people performing sitting office work for most of the time during work hours (8 a.m.-5 pm) on weekdays.

2.2. Sensor characteristics

The low-cost particle sensors used in this study were IC Sentinel (Oberon Inc., State College, Pennsylvania, USA), which were equipped with optical-based particle counters that measured particle number concentrations using 10 mW laser diodes (with a light source wavelength as 650 nm) at a sampling flow rate of 0.045 m^3/h. The sensor measured four particle size ranges: 0.5–1 μm, 1–5 μm, 5–10 μm, and >10 μm at a 2 min time resolution. The measurements of particles with different sizes can provide useful information for identifying particle sources, evaluating particle dynamics, and predicting health effects due to particle exposure, since particle size is a key factor affecting particle emission, transport, dynamics behaviors, fates, and health outcomes [35]. In addition, IC

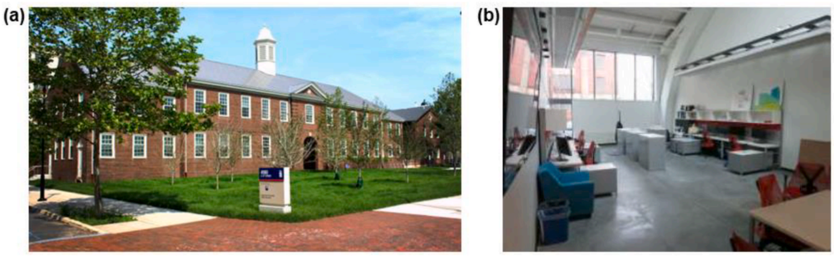

Fig. 1. Images of studied (a) building and (b) office room.

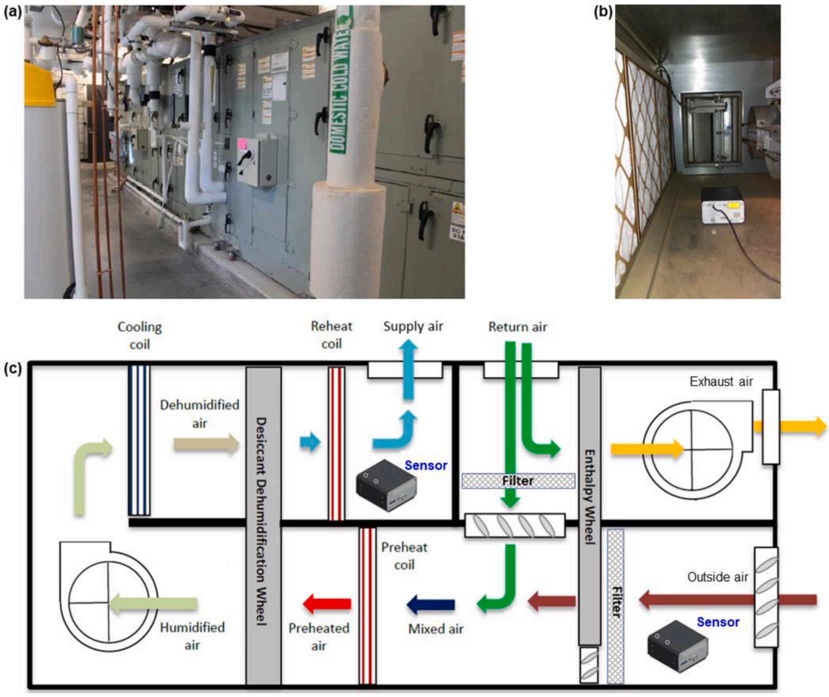

Fig. 2. (a) Image of air handling unit serving the studied office; (b) image of low-cost sensor deployed in the outdoor air chamber; and (c) schematic of the air handling unit and sensor locations.

Sentinel measured environmental parameters including CO_2 concentration, temperature, relative humidity, sound level, and light intensity at a 15 s time resolution.

The particle data quality of IC Sentinel was evaluated under laboratory conditions before the field deployment. A detailed description of the sensor assessment process can be found in Salimifard et al. [36] To give a brief summary, Salimifard et al. [36] compared the particle measurement accuracy of IC Sentinel against other three widely used low-cost particle sensors as well as a lab-grade reference sensor in a controlled environment chamber. They reported that IC Sentinel could provide measurements relatively close to the reference sensor compared to other tested low-cost sensors. Furthermore, to evaluate the on-site performance of IC Sentinel, we compared the field measurements of outdoor PM_{10} from IC Sentinel against EPA ambient air quality data [37]. As shown in Fig. S1, the low-cost sensor can provide reasonable particle measurements within the error bars of EPA data.

3. Results and discussion

Fig. 3 shows the time series of particle number concentrations at outdoor air, supply air, and indoor air at the office building over six months. The figure compares the time series of different particle sizes: 0.5–1 μm, 1–5 μm, and >5 μm. For both outdoor and indoor environments, particles <5 μm dominated the number concentrations (about three orders of magnitudes larger than particles >5 μm), consistent with previous observations in urban enviroments [38–40]. For particles in the size range of 0.5–1 μm, seasonal variations in outdoor, supply, and indoor concentrations can be observed: the particle concentrations during cooling season (July and August) and heating season (November and December) were higher than those during shoulder season (September and October). However, the seasonal variations were less notable for larger particles (1–5 μm and >5 μm). Fig. 4 presents outdoor particle concentrations during different seasons for various particle size ranges. For 0.5–1 μm particles (Fig. 4a), the mean outdoor concentration during cooling season (6,000,000 particles/m^3) and heating season (5,500,000 particles/m^3) were 62.2% and 48.6% higher than that during shoulder season (3,700,000 particles/m^3). For larger particles, the differences in mean outdoor concentrations among different seasons were less than 18% for 1–5 μm particles (Fig. 4b) and were less than 12% for particles >5 μm (Fig. 4c). These results suggest that seasonal variation in ambient particle concentrations could be more significant for smaller particles in the urban area. This phenomenon is likely attributed to particle emissions from fossil fuel combustions to produce electricity for cooling as well as to provide on-site heating, which have greater impact on number concentrations for fine particles (<2.5 μm) [41–43].

Fig. 5 displays the boxplots of particle concentrations at outdoor air, supply air, and indoor air for three particle size ranges: 0.5–1 μm, 1–5 μm, and >5 μm. For all particle sizes, there were notable reductions from outdoor concentrations to supply concentrations. The mean concentration reductions were 75.6%, 90.1%, and 98.6% for particles in the size ranges of 0.5–1 μm, 1–5 μm, and >5 μm, respectively. These reductions were mainly attributed to the MERV 8 particle filters placed in the air handling unit as well as particle deposition effect [39,44–46]. Since the MERV 8 filter is more effective for particles >3 μm [44], and the deposition effect is more pronounced for larger particles, the concentration reduction from outdoor air to supply air was greater for coarser particles (1–5 μm and >5 μm) than for fine particles of 0.5–1 μm. This result suggests that more efficient par-

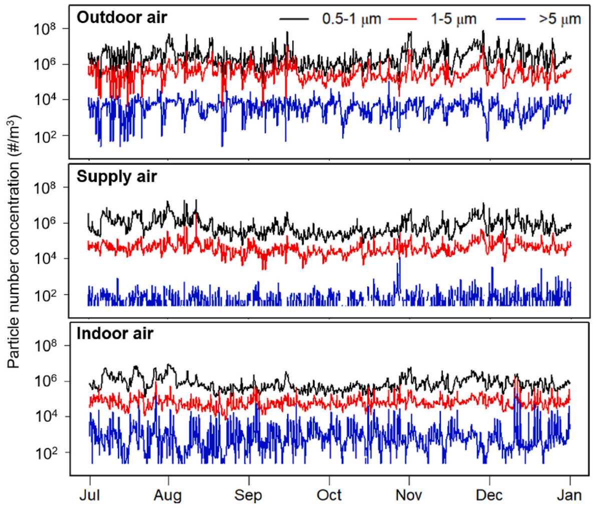

Fig. 3. Time-varying particle number concentrations of outdoor air, supply air and indoor air over six months for three particle size ranges: 0.5–1 μm, 1–5 μm and > 5 μm.

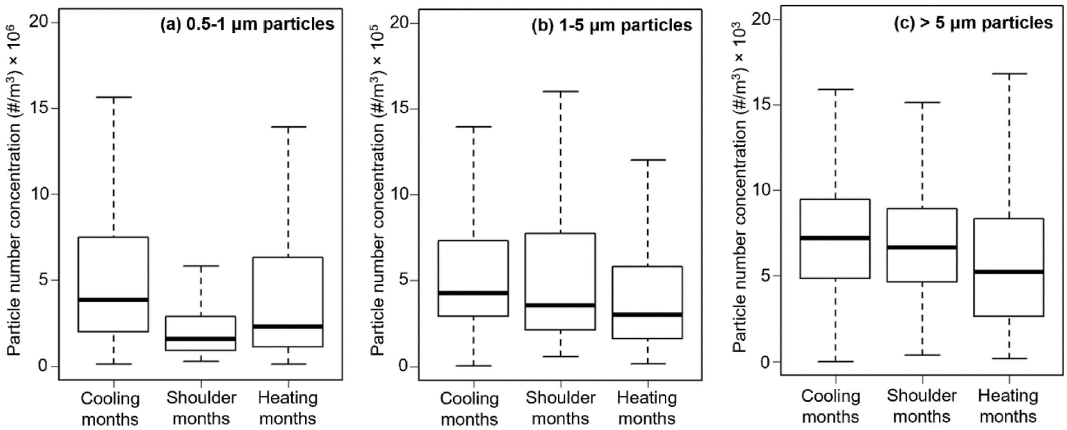

Fig. 4. Outdoor particle number concentrations during cooling months (July and August), shoulder months (September and October), and heating months (November and December) for three particle size ranges: (a) 0.5–1 μm, (b) 1–5 μm, and (c) > 5 μm.

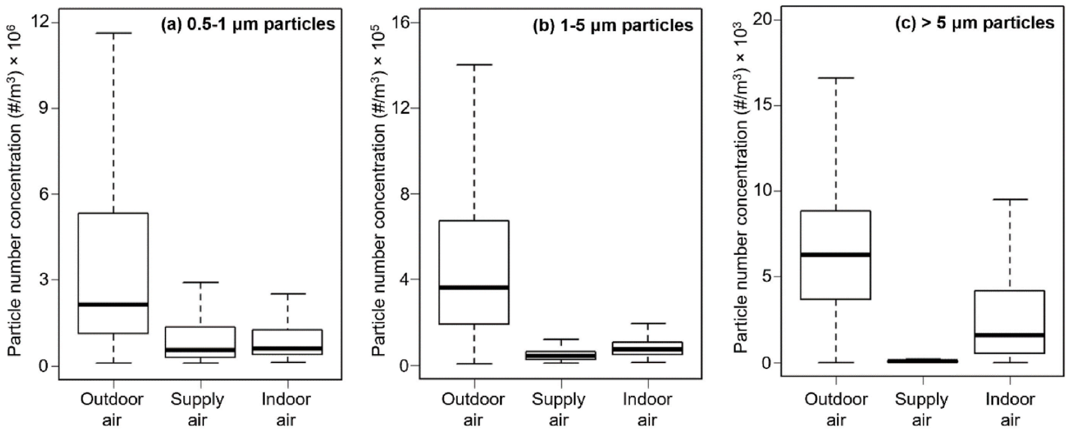

Fig. 5. Particle number concentrations at outdoor air, supply air and indoor air for three particle size ranges: (a) 0.5–1 μm, (b) 1–5 μm, and (c) > 5 μm.

ticle filtration for particles <1 μm (e.g., MERV 13 filters) could be installed in mechanical ventilation systems to further reduce adverse health outcomes associated with fine particles such as asthma, lung cancer, and airborne disease transmission [3,47].

Fig. 5 also shows that for particles >5 μm, despite low particle concentrations at supply air, there were relatively high indoor particle concentrations in the office (see Fig. 5c), implying possible indoor emission sources of coarse particles in the office space. However, for particles of 0.5–1 μm (Fig. 5a) and 1–5 μm (Fig. 5b), the concentrations at indoor air were comparable to those at supply air, indicating that the indoor emission sources in the studied office were more relevant to particles >5 μm compared to fine particles.

To further characterize the potential indoor particle sources in the room, Fig. 6 depicts the time series of indoor-outdoor particle number concentration ratio (I/O ratio) for various particle sizes. For particles in the size ranges of 0.5–1 μm and 1–5 μm, the I/O ratio was below 0.5 at most of the time, with an average as 0.40 (standard deviation = 0.53) and 0.37 (standard deviation = 0.86), respectively. This result is in alignment with previous measurements in office environments [48,49]. For particles >5 μm, there were more drastic increases of I/O ratio than 0.5–1 μm and 1–5 μm particles (see Fig. 6), resulting in an average as 1.06 with a standard deviation as high as 7.15. These results further indicate the presence of important indoor emission sources for coarse particles in the office space.

To examine the potential role of occupant activities as indoor particle sources, we compared time-varying indoor particle concentration and indoor CO_2 concentration (as an indicator of occupancy level) from the IC Sentinel measurements, as shown in Fig. 7. For

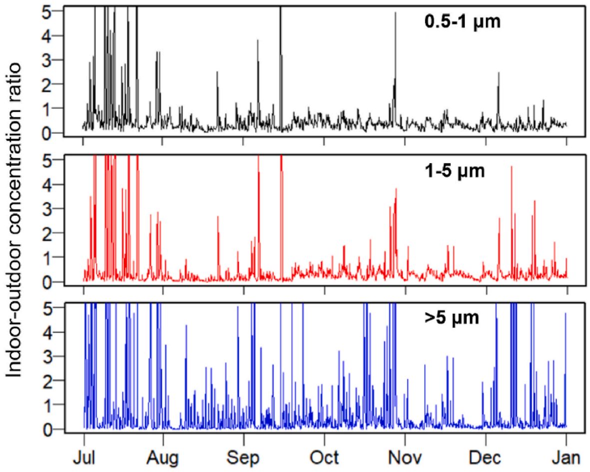

Fig. 6. Time series of indoor-outdoor concentration ratio for three particle size ranges: 0.5–1 μm, 1–5 μm, and >5 μm.

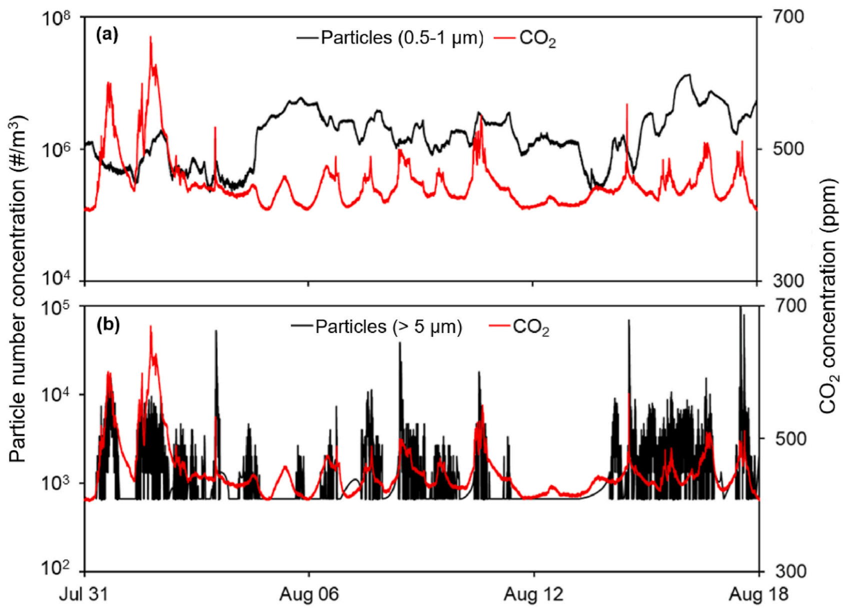

Fig. 7. Time series of indoor concentrations of particles (0.5–1 μm and >5 μm) and CO_2.

particles >5 μm (Fig. 7b), the time series of indoor particle concentration and CO_2 concentration exhibit a clear correlation, with a Spearman correlation coefficient as 0.66 (p-value <0.001). However, for particles in the size range of 0.5–1 μm (Fig. 7a), there was no discernible correlation between particle and CO_2 concentrations (Spearman coefficient $= -0.13$). These results suggest that occupants can be important emission sources in an office environment, particularly for coarse particles (>5 μm); whereas fine particles (0.5–1 μm) were less sensitive to the occupancy. This trend is likely caused by particle resuspension from indoor surfaces induced by occupant activities (such as walking), which is more pronounced for larger particles [48].

In general, our study provides insights into applying low-cost particle sensors for assessing indoor particle dynamics under long-term deployment in commercial buildings. Previous studies have investigated applications of low-cost particle sensors in residential buildings [24–32]. For instance, Hegde et al. [27] deployed low-cost particle sensors in two households in Salt Lake City during summer and winter. They observed that different particle sources triggered different sensor responses. By analyzing the measured data, they found that frying food and spraying aerosol products generated the largest elevation in indoor particle concentrations. Kaliszewski et al. [28] utilized low-cost particle sensors in an apartment in Warsaw for 10 days. They reported that frying and toast-making were major particle sources and particle concentrations were considerably lower in the room with lower occupancy. Shen et al. [25] measured $PM_{2.5}$ concentrations using low-cost sensors in an apartment in Beijing for 10 days. They evaluated the spatiotemporal variation of indoor $PM_{2.5}$ and reported that the primary sources were outdoor infiltration and cooking. These studies showed the potential of using low-cost sensors to analyze particle sources and concentrations in home environments. Fewer studies have tested the long-term application of low-cost particle sensors in commercial buildings [21,23]. Jones et al. [21] measured indoor $PM_{2.5}$ using low-cost sensors in 37 urban commercial offices worldwide for one year. They found that offices using filters at ratings > MERV 13 had up to 40% lower indoor $PM_{2.5}$ concentrations than those with filters at ratings of MERV 7–12. Our study suggests that MERV 8 filters can perform well in removing particles >5 μm in an office building, while are less effective for 0.5–1 μm particles. Furthermore, our study proposes that deploying compact and portable low-cost particle sensors within an air handling unit could be a quick and simple approach to monitor particle filtration effectiveness of mechanical ventilation systems, which can potentially be useful for smart building applications such as demand-controlled mechanical systems [50–52]. Another study of Palmisani et al. [23] monitored $PM_{2.5}$ levels in two oncology units in Bari and Barcelona for 17 months and 5 months, respectively. They reported elevated $PM_{2.5}$ concentrations in daytime hours associated with high occupancy in the wards for scheduled treatments, indicating human activities (e.g., human emissions, walking-induced resuspension, cleaning) as predominant $PM_{2.5}$ sources. Our study also reveals that occupants are important indoor particle sources in office environments. By analyzing the correlations between indoor concentrations of CO_2 and particles at different sizes, we found that occupant-related resuspension can be a key emission source for particles >5 μm in offices. This result suggests that coupling low-cost particle sensor and CO_2 sensor in a single device can help identify and analyze particle emissions associated with occupant activities. Overall, our study results provide information for future research and applications of low-cost sensors in monitoring particle emissions, concentrations, and removal mechanisms in commercial buildings.

A few limitations of this study should be noted. First, the low-cost sensor used in this study was not able to detect particles smaller than 0.5 μm. Future research is warranted to examine the long-term application of low-cost sensor to monitor ultrafine particles (UFP) as the indoor UFP concentrations are closely associated with human activities [53,54]. Besides, although this field case study provides information on the application of low-cost sensors for evaluating mechanical ventilation system performance, it was carried out in an office building in Philadelphia. Future studies could be performed to understand the longitudinal and cross-sectional variabilities in low-cost sensor performance considering different types of populations and buildings [21].

4. Conclusions

This study provides new information on long-term application of low-cost particle sensors for evaluating indoor air quality and particle emissions and removals in commercial buildings by conducting a six-month field case study in an office building in Philadelphia. Based on the measurement data, we found that placing low-cost sensors within air handling units could provide quick assessments of filtration effectiveness of mechanical ventilation systems. Installing high efficiency filtration (e.g., MERV 13 filters) is essential to remove indoor fine particles (<1 μm) in office buildings. Furthermore, the combination of low-cost particle sensor and CO_2 sensor within a single device can readily detect particle emissions associated with occupant activities. Our results show that occupant-induced resuspension can be an important emission source for particles >5 μm in office environments.

CRediT authorship contribution statement

Gen Pei: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **James D. Freihaut:** Conceptualization, Methodology, Resources, Writing – review & editing. **Donghyun Rim:** Conceptualization, Investigation, Methodology, Resources, Supervision, Project administration, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2023.107774.

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