Indoor Air Pollution of Outdoor Origin: Mitigation Using Portable Air Cleaners in Singapore Office Building

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ABSTRACT

Landscape fires in Indonesia and traffic pollution have been receiving increasing attention as sources of particulate matter (PM) in Singapore. Although mitigation measures to reduce PM levels using portable air cleaners (PACs) have been used in residential buildings, its application for office buildings is unknown. Using PAC, we demonstrated their potential for indoor particles removal in an office building and presented a method to evaluate their performance and estimate number of units to be deployed. Modelled and in-situ measured PAC effectiveness using up to twelve units was evaluated in three office sizes (30, 80 and 1490 m³). Measured effectiveness using indoor concentrations and indoor/outdoor ratios was obtained in a randomised intervention experimental design involving 3 weeks per location. Indoor particle concentration reductions in the three offices were dependent on particle size and confounded by variations in indoor emissions and outdoor levels resulting in low correlation and higher RMSE between modelled and measured effectiveness. PAC effectiveness computed using I/O ratios for removing UFP, PM2.5 and PM10 ranged 24–43%, 23–53% and 7–37% respectively. PAC has a higher in-situ effectiveness in small compared to larger spaces and the effectiveness is logarithmically dependent on the number of units deployed. We validated the use of our model to determine PAC effectiveness in the offices using up to eleven PACs (RMSE between modelled and measured data ranging from 3.9 to 6.6%). Lastly, we developed a design method to size the number of PAC needed for office buildings. The results from this study can be used for standards organization, policy makers and researchers interested in particle exposure reductions in large spaces.

Keywords: Air pollution, Indoor particles, Portable air cleaners, Office buildings

1 INTRODUCTION

Southeast Asian countries, such as Singapore, are periodically exposed to large-scale emissions of airborne particulate matter (PM) from landscape fires in Indonesia (Nichol, 1998; Chen et al., 2016). Caused by uncontrolled biomass and peat burning in Indonesia, these transboundary pollution episodes have reduced outdoor air quality and are associated with increases in outpatient hospital visits, respiratory infection, asthma, and rhinitis (Cheong et al., 2019). Additionally, most buildings are in big cities surrounded by traffic pollution where its exposure is linked to similar mortality and morbidity outcomes (Gall et al., 2015). Considering that people spend most of their time in buildings (Klepeis et al., 2001; Gall et al., 2015), outdoor PM exposures likely occur indoors (Baxter et al., 2013). This means that indoor exposure to PM from landscape fires or traffic pollution is an important contributor to the adverse health effects caused by outdoor particles (Klepeis et al., 2001; Gall et al., 2015; Baxter et al., 2013). In Singapore, one fifth of the time spent
indoors occurs primarily in office buildings (Gall et al., 2015). Outdoor PM enter the indoor environments of buildings at different levels typically by adventitiously infiltrating through cracks and gaps in the building envelope as well as via ventilation (Wallace, 1996; Riley et al., 2002; Chen and Zhao, 2011). Current research on mitigation strategies have mainly revolved around the use of high efficiency filters in HVAC systems (Fisk et al., 2000; Zuraimi and Tham, 2009) and building pressurization (Bhattacharya et al., 2021). Although high efficiency HVAC filters can effectively remove PM of various sizes downstream of the mechanical ventilation system, their effectiveness in reducing indoor concentrations vary significantly (Fisk et al., 2000; Riley et al., 2002; Zuraimi and Tham, 2009). Buildings will need to have an airtight envelope or be over pressurized to benefit fully from high efficiency filtration (Fisk et al., 2000). This suggests that a certain fraction of outdoor PM may infiltrate indoors bypassing filters in HVAC systems of leaky buildings. Even for airtight buildings that employ high efficient filters, indoor concentration may remain elevated if there are sources of particles indoors ( Turk et al., 1989; Zuraimi and Tham, 2009). Lastly, high efficiency media filters in commercial systems are traditionally associated with higher pressure drop and may lead to energy penalties (Siegel, 2016; Sultan et al., 2022). Taken together, these drawbacks indicate the potential need to have effective localised air cleaning within the office.

Portable air cleaners (PACs) have been deployed mainly for residential building applications (Shaughnessy et al., 1994; Henderson et al., 2005; Shaughnessy and Sextro, 2006; Macintosh et al., 2008; Novoselac and Siegel, 2009; Sublett, 2011; Sultan et al., 2011; Siegel, 2016; AHAM, 2020). Field studies have shown that HEPA-based PACs can achieve large reductions of PM in residences (Tables S1 and S2) and may lead to clinical health benefits (Sublett, 2011). Many of these studies were conducted using only a single unit in a residential room (Table S1; Sublett, 2011) but there has been no study conducted in large open plan office spaces (Table S1; Stauffer et al., 2020; Wheeler et al., 2021; Lindsley et al., 2021). Although chamber results can predict their performance in offices (Waring et al., 2008; Sultan et al., 2011), prediction accuracy is unknown due to the absence of quantitative validation of modelled values with experimental data from a real office building. For example, in-situ short-circuiting of airflows and air bypass can potentially reduce overall particle removal effectiveness (Novoselac and Siegel, 2009; Macintosh et al., 2008).

Despite its potential, it is unclear if PACs can provide effective air cleaning of PM pollution in office buildings. Office buildings have dissimilar characteristics (size, function, occupant activities emissions, ventilation and particle deposition rates) compared to other tested environments (Fisk et al., 2000; Riley et al., 2002; Zuraimi and Tham, 2009; Chen et al., 2016). To extent current PAC residential application to office building requires research, validation and evidence-based guidance. Due to these knowledge gap, we evaluate PM removal performance of a commercially available PAC using several units in three office rooms of various sizes in a Singapore building. This study will demonstrate how intrinsic performance of a PAC unit can be used to design the number of units to be deployed in office buildings to mitigate indoor exposure of outdoor PM pollution.

2 METHODS

2.1 Test Office and Equipment

Measurements were performed in the eleventh-floor office space of a sixteen-story energy efficient building in Singapore. The studied space is a mix of one large open plan office, two meeting and six small individual rooms and one printing room—all with low-pile carpeting, acoustic ceiling tiles, normal office furniture and non-operable glazed windows. Three office spaces of various sizes were used as test locations: 1) large open plan office; 2) meeting room; and 3) small room. The large open plan office has a total volume 1490 m³ which constitutes the bulk of the total space area. It has one-metre-tall partitions with 52 workstations. There are no grids in the large office that could affect the air distribution. The tested small room has a desk, a chair and 2 small shelves and has a dimension of 2.5 m by 4.4 m by 2.7 m (volume: 30 m³). The tested meeting room has a dimension of 3.5 m by 8.5 m by 2.7 m (volume: 80 m³). Apart from printing, other sources of particles such as smoking, cooking, candle burning, air fresheners or cleaning agents were absent. The eight-year-old building is about 30 metres from a major eight lane highway.
The air-conditioning system is a single pass, no recirculation (also known as Dedicated Outdoor Air System (DOAS)), active chilled beam system relying on chilled water distribution to various terminal points to maintain indoor temperature and relative humidity. Outdoor air is treated in the roof-top (located at thirteenth floor) pre-air handling unit (PAHU) that has media bag filters at MERV 13 rated performance. Exhaust air from the office was drawn through grilles in the suspended acoustic ceiling and exhausted out at the rooftop away from the outdoor air intake. Throughout the study, the outdoor air amount into the office was fixed. To confirm this, we measured CO2 as a tracer gas (Roulet and Foradini, 2002) using Onset data loggers (HOBO MX1102). Pure CO2 was released into the tested office environments at the end of the day to reach peak level of about twice the background CO2 concentrations.

A pair of NanoScan SMPS (TSI model 3910) was used to simultaneously monitor particles between 10 nm to 421.7 nm in the indoor and outdoor air. Additionally, a pair of Optical Particle Sizer OPS (TSI model 3330) was used to monitor particles between 0.3 µm to 10 µm. Sampling time resolution was 1 min with a flow rate 1 L min⁻¹. Prior to the experiments, individual pairs of NanoScan and OPS monitoring data were tested side-by-side in a well-mixed laboratory to assess similarities in the measurements. The results revealed good agreement with R² values for various sizes ranging from 0.96 to 0.99 and 0.85 to 0.99 for the NanoScan and OPS respectively. In addition to size-resolved particle number concentration data from the NanoScan and OPS, we calculated three aggregated particle indices; 1) UFP (no cm⁻³); 2) PM2.5 (µg m⁻³); and 3) PM10 (µg m⁻³). Since the OPS and Nanoscan can only measure particle number concentrations, we assume airborne particles density to be 1.6 g cm⁻³ (midpoint density between 1.5 and 1.7 g cm⁻³ for ambient particles) and spherical to calculate the mass based on the fractions of the main substances to assess PM levels (Hinds, 1999; Tuch et al., 1999; Wallace et al., 2011). For the indoor monitoring, one set of NanoScan and OPS is placed in the middle of the office at a height of between 1.1 to 1.5 m above the ground. For the outdoor monitoring, another set is placed near the PAHU fresh air intake at the 13th story.

The PAC used in this study are twelve HEPA-based units that are cylindrically designed to draw surrounding air (0.2 m diameter and 0.7 m height). The filtered air is then distributed using a fan that can be set at multiple airflow speeds. All the experiments were conducted with the PACs running at maximum fan speed. The PAC has a rated CADR of 70 m³ h⁻¹ and operating power of 40 W. The use of low CADR PACs may reduce the likelihood of short-circuiting when multiple units are deployed.

The air temperature and relative humidity were also measured using the Onset data loggers (HOBO MX1102). The office sound level during the experiment was measured for a day using a Extech sound level meter (407732) placed in the middle of the office. The sound level meter is capable of measuring 30 to 130 dB with an accuracy of ± 1.5 dB. For each scenario, minute-level sound level data was obtained between 09:00 and 17:30 hrs.

2.2 PAC Effectiveness: Modelled, Measured and Validation

Laboratory-testing of intrinsic PAC performance was performed in a small room (30 m³) using the pull-down test method (AHAM, 2020) to calculate the mean and standard deviation of total and size-resolved CADR (m³ h⁻¹) (See S2). The modelled effectiveness, εm, is calculated using the CADR to provide the expected PAC performance in the location where it will be deployed according to the following equation (Siegel, 2016):

\[
ε_m = 1 - \left( \frac{a + k}{a + k + \frac{CADR}{V} N} \right)
\]

where a is the ventilation rate (h⁻¹), k is the particle deposition rate (h⁻¹) and N is the number of PAC deployed (unitless). In this study, the combined particle deposition and ventilation rates (a + k) were obtained using 1-min room particle data, calculating their decay rates from indoor peak concentrations (Thatcher and Layton, 1995, see S1). Rearranging Eq. (1) we can derive the relationship to predict N using V, CADR and building information:
\[ N = \frac{(a + k)V}{CADR \left( \frac{1}{\epsilon_{m}} - 1 \right)} \]  

(2)

The in-situ testing was performed from September 13, 2019 to October 9, 2020. Three baseline monitoring (B1–B3) and four different interventions (I1–I4) scenarios were scheduled to evaluate the impact of switching on and off the operation of the PAC and its use under different indoor conditions (Table 1). Fig. S1(a) illustrates the layout of PACs in the three office test scenarios. When multiple units were deployed, we located them away from the walls and equidistant from each other as much as office furniture layout permits and ensured that PACs do not blow air directly from one person to another. The order of the scenarios for monitoring was randomly assigned. Each scenario is a weeklong which excluded holidays and weekends. Each test condition was repeated twice giving a total of three sets of baseline and intervention scenarios. Within the three sets, two were obtained under occupied and the remaining one under non-occupied periods. The non-occupied periods were conducted during COVID-19 lockdown period where the building air-conditioning operated as per normal but under zero occupancy. The number office workers during the occupied period was 43 but the exact numbers vary within a day. These scenarios allowed us to study the impact of office volume, indoor emissions and number of units use on in-situ PAC performance.

To calculate measured effectiveness, we compared indoor concentration data as well as I/O ratios under baseline and intervention scenarios in the three offices using Eqs. (3) and (4).

\[ \epsilon_I = 1 - \frac{I_{PAC}}{I_{no PAC}} \]  

(3)

\[ \epsilon_I = 1 - \frac{(I/O)_{PAC}}{(I/O)_{no PAC}} \]  

(4)

where, \( I \) = indoor PM concentration, (I/O) is the indoor/outdoor concentration ratio and the subscripts PAC and no PAC refer to the presence or absence of PAC respectively.

We averaged the particle concentration and I/O ratio data for 4.25 hours to minimise the effects of indoor-outdoor time lags (see S1). We included data during office hours when the air-conditioning system is running (between 0900 to 1730 hrs). In total, thirty data set for each of the three weeklong intervention or baseline scenarios were obtained. We assumed that three weeks of scenario monitoring is sufficient to yield effectiveness values that are unbiased. Since baseline and intervention scenarios were assigned in random orders, potential systemic bias from differences in outdoor concentrations and indoors emissions should not influence the overall results. We calculated the uncertainty as the standard deviation of the calculated effectiveness over the three weeklong monitoring periods under a certain intervention scenario over the three weeklong monitoring periods under baseline scenario.

<table>
<thead>
<tr>
<th>No</th>
<th>ID</th>
<th>Scenario</th>
<th>Test Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B30</td>
<td>Baseline</td>
<td>Small room</td>
<td>PAC off</td>
</tr>
<tr>
<td>2</td>
<td>B80</td>
<td>Baseline</td>
<td>Meeting room</td>
<td>PAC off</td>
</tr>
<tr>
<td>3</td>
<td>B1490</td>
<td>Baseline</td>
<td>Large office</td>
<td>PAC off</td>
</tr>
<tr>
<td>5</td>
<td>I30</td>
<td>Intervention</td>
<td>Small room</td>
<td>1 PAC on</td>
</tr>
<tr>
<td>6</td>
<td>I80</td>
<td>Intervention</td>
<td>Meeting room</td>
<td>1 PAC on</td>
</tr>
<tr>
<td>7</td>
<td>I1490-1</td>
<td>Intervention</td>
<td>Large office</td>
<td>1 PAC on</td>
</tr>
<tr>
<td>8</td>
<td>I1490-12</td>
<td>Intervention</td>
<td>Large office</td>
<td>12 PAC on</td>
</tr>
</tbody>
</table>
To validate our model effectiveness, we compared the modelled with measured effectiveness under controlled conditions. For the measured effectiveness, we performed six additional experiments of two days each under non-occupied conditions in the three tested indoor environments using different numbers of PAC units. Additional experiments using three PAC units were conducted in the small and meeting rooms. Four additional experiments involving six, seven, nine and eleven PAC units were used in the large office. Using Eq. (1), we modelled the removal effectiveness, \( \varepsilon_m \) for UFP, PM\(_{2.5}\) and PM\(_{10}\) as a function of PAC units for the three indoor environments and compared it with measured effectiveness. The measured effectiveness and its standard deviation were measured for each of the six experiments.

2.3 Data Analysis

Data analyses were performed using the statistical software package, SPSS Version 25. Kolmogorov-Smirnov test was performed to test for normality of data distributions. Student’s t-test was performed to examine whether the mean concentrations and I/O ratios were different across groups. Correlation between two variables was performed by computing the Pearson’s correlation coefficient. Performance of modelled effectiveness was measured in terms of the RMSE (root mean squared error) by comparing it to measured effectiveness. A significance level of \( p < 0.05 \) was used for all statistical tests.

3 RESULTS

3.1 Background Office Environment Measurements

We noted that the daily variation in particle number and mass concentrations (UFP, PM\(_{2.5}\) and PM\(_{10}\)) often displayed similar trends under baseline conditions with and without occupancies. Figs. S2(a) and S2(b) show their typical daily concentration variation measured for every minute indoors and outdoors. Usually, the indoor concentrations levels decrease in midmorning after early morning peaks and then peak again in late afternoon/early evening following the outdoor levels. This was very clear for UFP and PM\(_{2.5}\) under non-occupied periods (Fig. S2(b)) indicating the dominant contribution of outdoor traffic combustion sources on fine and ultrafine particles in the indoor environment (Riley et al., 2002). Under occupied periods however, we noticed distinct indoor peaks in PM\(_{10}\), some of which exceeded outdoor levels, coinciding with presence of occupants in the office. Noticeably, PM\(_{10}\) levels appeared to increase after the occupants returned to the office following their lunchtime break, increasing a little before mid-afternoon. It appeared that occupants and their activities generated large particles via mechanical forces (Wallace, 1996; Thatcher and Layton, 1995). The trend between the presence of occupants and UFP or PM\(_{2.5}\) was not as evident. Indoor and outdoor PM concentrations were correlated in all the locations (Table S4).

3.2 CADR and Modelled Effectiveness

The PAC has a mean (± standard deviation) CADR of 58 ± 25, 50 ± 15 and 80 ± 5 m\(^3\) h\(^{-1}\) for UFP, PM\(_{2.5}\) and PM\(_{10}\) respectively. Using the CADR values, we obtained modelled effectiveness in the three test locations (Fig. 1; size-resolved removal effectiveness is given in Fig. S3(b)). The relationship between effectiveness and PAC numbers is logarithmic (\( R^2 = 0.99 \)). Fig. 1(A) illustrates the number of PAC needed to achieve different removal effectiveness of UFP in the three locations. Comparing UFPs with larger particles (Fig. 1(B)), the latter are more likely to be removed by deposition and hence their removal effectiveness via PAC is smaller (Hinds, 1999; Riley et al., 2002; Shaughnessy and Sextro, 2006). It is noted that for a particular number of deployed PAC, particle modelled effectiveness removal in the small room is higher than either the meeting room or large office. In the small room, a single unit of PAC removes 40 to 51% of particles. The effectiveness decreased to 20–30% for the meeting room and which further decreased to 4% for the large office. This demonstrates the effects of office room size on PAC particle removal effectiveness (see Table 3 below). Also, for the PAC to be more effective in the large office, up to 50 PAC are required to achieve the same level of removal effectiveness in the small room. It should be noted however, that the number of deployed PAC units in a particular room may have a limit. For example, it is impracticable to accommodate large PAC numbers in the small room due to space constraints.
Fig. 1. Modelled effectiveness for removing (A) UFP in the three test locations and (B) UFP, PM$_{2.5}$ and PM$_{10}$ in the large office using different numbers of PAC.

Also, discharge airflows from multiple PACs in a small volume of space may lead to short-circuiting (MacIntosh et al., 2008). The relationships among effectiveness, room volume and number of PAC are further discussed below.

3.3 Baseline and Intervention Scenarios

The sound level measured in the small room was higher with the PAC on but there was no statistical difference in the large office with a single PAC. Increasing the number of PAC in the large office from 1 to 12 increased the sound levels significantly (Table 2). The measured ventilation rates were statistically similar under baseline and intervention scenarios ($p > 0.5$) confirming that the outdoor air amount of the office was fixed. This means that ventilation rate would not be a confounder during analysis of PAC performance. Table 2 also provides the average indoor and outdoor concentrations of UFP (no cm$^{-3}$), PM$_{2.5}$ ($\mu$g m$^{-3}$) and PM$_{10}$ ($\mu$g m$^{-3}$) under baseline and intervention scenarios for the test locations. The particle concentration data were naturally distributed (Kolmogorov-Smirnov test). Across all test locations, average indoor concentration levels were statistically similar ($p > 0.5$) confirming that the outdoor air amount of the office was fixed. This means that ventilation rate would not be a confounder during analysis of PAC performance. Using student’s t-test, statistically significant lower indoor concentrations were noted for PM$_{2.5}$ in the small room and large office, and PM$_{10}$ for the large office. UFP differences between the scenarios were not statistically significant presumably due to the higher outdoor baseline UFP concentrations. Outdoor intervention concentrations of PM$_{2.5}$ and PM$_{10}$ were significantly lower in the large office which could positively bias PAC performance. Average particle concentrations were below the WHO guidelines for PM$_{2.5}$ and PM$_{10}$.

Figs. 2(A–C) provide the indoor to outdoor concentration (I/O) ratios. We noticed that the baseline I/O values range between 0.3 to 0.4 in our single pass system despite its use of MERV13 filters at the outdoor intake. These values are higher than typical office buildings with recirculated air systems (I/O: 0.05–0.12) (Zuraimi and Tham, 2009) where air passes through the AHU filter more frequently, per unit time. This could be a concern given that DOAS systems are advertised sustainable and used in many projects. Under the intervention scenarios, the I/O ratios for UFP, PM$_{2.5}$ and PM$_{10}$ were reduced to 0.2 to 0.3. The general trend in I/O ratio reductions for UFP and PM$_{2.5}$ using a single PAC shows a decrease as we moved from the small room to the meeting room to the large office. This is different from the UFP and PM$_{2.5}$ concentrations reduction which do not demonstrate a clear decreasing trend moving from the small room to the large office (Table 2). For the large office, increasing the number of PAC lowered further the I/O ratios to a certain extent. Although I/O reductions were significant for UFP and PM$_{2.5}$, corresponding reductions for PM$_{10}$ were non-significant (Fig. 2(C)) due the higher deposition rates and presence of indoor sources. Figs. 2(D–F) provide I/O ratios dichotomised into unoccupied and occupied periods. Under the latter, the I/O ratios are generally higher and have broader standard deviations suggesting strong
Table 2. Summary statistics of sound level, indoor and outdoor measurements of UFP, PM$_{2.5}$ and PM$_{10}$ and ventilation rates (ACH) under baseline and intervention scenarios.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Scenario</th>
<th>Mean Sound Level (dB)</th>
<th>Mean UFP (no cm$^{-3}$)</th>
<th>Mean PM$_{2.5}$ (mg m$^{-3}$)</th>
<th>Mean PM$_{10}$ (mg m$^{-3}$)</th>
<th>ACH (h$^{-1}$)</th>
<th>Mean SD</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor</td>
<td>B30</td>
<td>32.4 0.00*</td>
<td>1.9 2.0</td>
<td>1.9 2.0</td>
<td>1973 0.03</td>
<td>973 0.03</td>
<td>3.7 0.38</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>I30</td>
<td>48.8 1.9</td>
<td>2.0 2.0</td>
<td>2.0 2.0</td>
<td>1973 0.03</td>
<td>973 0.03</td>
<td>3.7 0.38</td>
<td>0.00</td>
</tr>
<tr>
<td>Outdoor</td>
<td>B30</td>
<td>49.2 0.00*</td>
<td>2.0 2.0</td>
<td>2.0 2.0</td>
<td>1973 0.03</td>
<td>973 0.03</td>
<td>3.7 0.38</td>
<td>0.00</td>
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<tr>
<td></td>
<td>I30</td>
<td>45.2 1.9</td>
<td>2.0 2.0</td>
<td>2.0 2.0</td>
<td>1973 0.03</td>
<td>973 0.03</td>
<td>3.7 0.38</td>
<td>0.00</td>
</tr>
</tbody>
</table>

*Statistically significant difference.
Fig. 2. (A–C) Indoor-outdoor ratios for UFP, PM$_{2.5}$ and PM$_{10}$ under baseline and intervention scenarios and (D–F) unoccupied and occupied periods under intervention scenario. Percentages are I/O reductions compared to the baseline. Stars indicate statistically significant differences between variables.

emissions from indoor sources. This is especially pronounced in the meeting room where there are varying occupant numbers and sporadic use occurrence. Except for the small room location, the differences are statistically significant especially for PM$_{10}$ indicating strong contributions from indoor sources.

For size-resolved particles, the I/O ratios demonstrate similar curve shapes across all rooms, in particular under unoccupied periods (Figs. 3(A–C)). The I/O ratios for particles below 20.5 nm are typically about 0.2–0.3 increasing up to 0.4–0.5 for particles around 64.9 nm before decreasing to 0.1–0.2, demonstrating similar curve profiles for UFP reported elsewhere (Zhu et al., 2022). We note an I/O peak of around 0.6–0.7 at 346 nm, before going down to 0.1 at 1442 nm and
Fig. 3. Size resolved particles indoor-outdoor ratios under baseline and intervention scenarios in the small room, meeting room, large office with 1 PAC and large office with 12 PAC under (A) unoccupied and (B) occupied periods.
finally an upward trend for larger particles beyond. For occupied periods however, the valley at around 100–346 nm is replaced with a peak demonstrating contributions from emissions associated with occupants for particles at these size ranges. When the PAC was turned on, the I/O ratios curve shapes did not alter from the baseline scenarios. But I/O ratios were reduced more pronouncedly for particles between 11.5 to 1140 nm. I/O ratio reduction of particles associated with occupants (100–346 nm) up to 57% could be achieved by PAC use. There is no difference for the large office because minimal filtering is accrued from the use of only one PAC. Interestingly, I/O ratios for particles > 1876 nm in the large office with 12 PAC appear to be significantly higher under the intervention compared to baseline scenarios, even under unoccupied periods. However, Students’ t-test revealed there were no statistical difference between the two experiments.

### 3.4 PAC Effectiveness

Fig. 4 illustrates the PAC modelled and measured effectiveness using both indoor concentration and I/O ratios for different particle indices and locations. Measured effectiveness using indoor concentrations range from −0.13 to 0.32 (SD: 0.44–0.83), 0.18–0.52 (SD: 0.45–0.86) and 0.11–0.43 (SD: 0.43–1.20) for UFP, PM$_{2.5}$ and PM$_{10}$ respectively. The negative effectiveness for UFP in large office reflects the lower indoor concentrations under the baseline condition. This scenario is likely influenced by the fact that the use of only one PAC is not be sufficient to cause a discernible removal of UFP levels indoors. Corresponding measured effectiveness using I/O ratios range from 0.24 to 0.43 (SD: 0.16–0.71), 0.23–0.53 (SD: 0.07–0.34) and 0.07–0.37 (SD: 0.07–0.44) for UFP, PM$_{2.5}$ and PM$_{10}$ respectively. Indeed, the standard deviations of effectiveness were lower using I/O ratios. The differences between modelled and measured effectiveness using indoor concentration varied from a modest difference range between 0.0 to 0.2 for UFP to wide difference ranges between −0.5 to 0.1 or −0.4 to 0.2 for PM$_{2.5}$ and PM$_{10}$ respectively. Good correlation (0.93) between modelled and measured effectiveness using indoor concentration was found for UFP while poor correlations (−0.01 and −0.47) were noted for PM$_{2.5}$ and PM$_{10}$ respectively. The root mean square error (RMSE) for UFP, PM$_{2.5}$ and PM$_{10}$ were 0.15, 0.25 and 0.23 respectively. The poor correlations and higher RMSE values for PM$_{2.5}$ and PM$_{10}$ appear to be due to indoor source emissions variations under baseline/intervention scenarios and to a smaller extent, outdoor concentration differences. Correlations between modelled effectiveness with measured effectiveness using I/O ratios were much better (UFP: 0.92; PM$_{2.5}$: 0.96; and PM$_{10}$: 0.95) with smaller differences varying between −0.2 to 0.1, −0.2 to 0.0 and −0.1 to 0.0 for UFP, PM$_{2.5}$ and PM$_{10}$ respectively.

![Fig. 4. Measured (using indoor concentration and I/O ratio) and modelled PAC effectiveness for UFP, PM$_{2.5}$ and PM$_{10}$ removal in the test offices. The error bars have not been included for the purpose of visual clarity.](image-url)
**Fig. 5.** Relationship between removal modelled effectiveness and measured I/O reduction for UFP, PM$_{2.5}$ and PM$_{10}$ with number of PAC units for the small room (30 m$^3$), meeting room (80 m$^3$) and large office (1490 m$^3$). The error bars are one standard deviation of measured I/O reduction.

Corresponding RMSE values for UFP, PM$_{2.5}$ and PM$_{10}$ were 0.12, 0.15 and 0.05 respectively. Indeed, while indoor and outdoor emissions can increase and decrease respective I/O ratios under baseline or intervention scenarios, the I/O reduction in Eq. (4) cancels out their effects (Henderson et al., 2005; Zuraimi and Tham, 2009). For these reasons, we recommend the use of I/O ratios for computing measured effectiveness.

Fig. 5 illustrates the validation of the modelled effectiveness. We used measured I/O ratios for comparison because it is less influenced by the confounding effects of indoor emissions and outdoor concentration variations as shown above. The measured effectiveness values are within one standard deviation of the modelled effectiveness for UFP and PM$_{2.5}$ suggesting reasonable agreement. For PM$_{10}$, the fit is much lower with the measured effectiveness standard deviations involving 7 and 6 PACs experiments being marginally outside of the modelled effectiveness. RMSEs between modelled and measured effectiveness for UFP, PM$_{2.5}$ and PM$_{10}$ were 6.3, 3.9 and 6.6% respectively.

**4 DISCUSSION**

This study demonstrated airborne particle removal via PACs in three office environments of different sizes. Significantly, our study is the first to show PAC effectiveness in a large office space using large number of units. In previous published studies, they were conducted using at most 5 units in residential buildings or small office rooms not bigger than 340 m$^3$ (Table S1). Indeed, these studies are not demonstrative of the full measure of PAC use and its application for office buildings where there could be larger rooms needing greater unit numbers. Also, we validated the model used to describe PAC performance in office space by showing reasonably good agreement between measured and modelled PAC effectiveness. Thus, we can use the measured model parameters to assess the influence of each particle removal mechanism on effectiveness and provide the basis for designing the number of PAC units in office buildings.
Table 3. Scenarios for particle monitoring in the study under occupied and non-occupied periods.

<table>
<thead>
<tr>
<th>UFP Removal Process</th>
<th>Small Room</th>
<th>Meeting Room</th>
<th>Large Office</th>
<th>Large Office (12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation + Deposition ( (a + k) )</td>
<td>h(^{-1})</td>
<td>1.9</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>m(^3) h(^{-1})</td>
<td>55.7</td>
<td>118.8</td>
<td>2487.4</td>
<td>2487.4</td>
</tr>
<tr>
<td>PAC (CADR)</td>
<td>h(^{-1})</td>
<td>1.9</td>
<td>0.7</td>
<td>0.0</td>
</tr>
<tr>
<td>m(^3) h(^{-1})</td>
<td>58</td>
<td>58</td>
<td>58</td>
<td>696</td>
</tr>
<tr>
<td>Removal Process Ratio ( \frac{PAC}{ventilation + deposition} )</td>
<td>unitless</td>
<td>1.1</td>
<td>0.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>

We found that for a given number of PACs deployed, modelled particle removal effectiveness decreases as office room size increases (Fig. 1). The relative changes in the effectiveness-PAC unit curves as room volumes changed reflect the effects of competing PAC particle removal rates with ventilation and deposition. Consider the UFP removal rates via ventilation, deposition and air cleaning given in Table 3. Although the ventilation and deposition particle removal rates (in h\(^{-1}\)) for the 3 rooms are relatively close, the equivalent volumetric removal rate (in m\(^3\) h\(^{-1}\)) gets bigger as the size of the office becomes larger. The corresponding removal process ratio (PAC/ventilation + deposition) gets smaller demonstrating a greater number of PAC units needed to compete with ventilation and deposition in larger spaces. Our calculations revealed that to achieve 80% effectiveness, approximately four test units are needed for the small room but at least 185 units are required for the large office. Using the results from this study, we developed the CBE PAC calculator to allow building managers, researchers and designers to quickly estimate PAC numbers given the room size, ventilation rate and the PAC’s CADR. The CBE PAC calculator is freely accessible via the following public URL: https://cbe-berkeley.shinyapps.io/airpurifier/.

The Singapore government ministries (BCA-MOH-NEA, 2021) recommended that the total CADR (i.e., \( N \cdot CADR \)) of the PACs to be deployed in an office space without ventilation system should be at least five times the room volume in m\(^3\). This “volume factor” is based on the AHAM standard using residential \( (a + k) \) value of 1.2 h\(^{-1}\) to obtain \( \varepsilon = 80\% \) (AHAM, 2020). Rearranging Eq. (2), we have the following:

\[
N \cdot CADR = \frac{\varepsilon_m}{1 - \varepsilon_m} (a + k)V
\]  

We anticipate that using the above recommendation may lead to an underestimation of PACs needed for office buildings. Our study showed \( (a + k) \) values ranging from 1.5 to 1.9 h\(^{-1}\) (Table 3) with the resulting volume factors to achieve \( \varepsilon = 80\% \) ranging between 6 and 7.6. To provide a scientific basis for accurate volume factors for office building, we compiled office building ventilation, infiltration and particle deposition rates from the literature (Tables S4–S6). For buildings without fresh air provision (e.g., split air conditioner, fan coil units) we relied on reported office building infiltration rates (Table S5). Using the compiled \( (a + k) \) values, we next utilised Monte Carlo method to calculate a large number of \( (a + k) \) values and ventilation and deposition rates inputs for office buildings (S5). Simulations were run for UFP, PM\(_{2.5}\) and PM\(_{10}\) using 10,000 trials per simulation. The results revealed mean (standard deviation) simulated \( (a + k) \) values for UFP, PM\(_{2.5}\) and PM\(_{10}\) of 2.8 (1.0), 2.9 (0.9), 4.6 (4.0) h\(^{-1}\) respectively. For office buildings relying on infiltration rates, mean (standard deviation) simulated \( (a + k) \) values for UFP, PM\(_{2.5}\) and PM\(_{10}\) were 1.8 (0.7), 1.8 (0.6), 3.5 (3.9) h\(^{-1}\) respectively. We recommend that for office buildings that requires supplementary air cleaning, the minimum effectiveness should be 50% while for enclosed air-conditioned office buildings without mechanical ventilation provision effectiveness should be 80%. Using these values, the respective volume factors for these two office building types should be at least 2.8 and 7.2 times the room volume in m\(^3\).

We need to put into context the seemingly high number of PAC units needed to achieve good particle removal effectiveness in the large office of our study. Here, we compare the results from our tested units with other PACs published elsewhere (Table S1; Offermann et al., 1985; Shaughnessy et al., 1994; Waring et al., 2008; Sultan et al., 2011) to illustrate the performance variance using
other brands in the market. Fig. 6 shows that for a particular office volume, a wide range of unit numbers can be deployed depending on PAC brands. \( N \) ranges between 25 to 185 units for the large office and 1 to 10 units for the meeting room. The large variation is not surprising as there is broad range of CADR values for HEPA based PAC (Table S1). Our test unit requires the greatest number of units given its lowest CADR and appears to be the least effective.

We found that indoor emissions and outdoor concentration variations under baseline and intervention scenarios can result in discordance between measured PAC effectiveness using indoor concentrations and modelled PAC effectiveness using its CADR performance. Elsewhere, Zhang et al. (2020) reported in-duct residential filter effectiveness ranging from –97% to 77% and noted that lower effectiveness is due to indoor sources presence, in-situ filter efficiency and HVAC system runtime. A lower HVAC system runtime would mean having less opportunities for particles to be filtered and having more outdoor particles infiltrating indoors. MacIntosh et al. (2008) reported variations in filtration effectiveness which may have come from cooking indoors. Fisk et al. (2000) modelled particle effectiveness of several higher efficiency filters relative to MERV 8 filters and noted that the modelled effectiveness was lower due the strong influence of air infiltration rate presumably bringing in larger amounts of outdoor particles. Thus, under situations where there are variations in outdoor levels and indoor emissions, PAC performance will be confounded. To overcome this, measured PAC effectiveness using I/O ratios is recommended for the purpose of assessing in-situ PAC particle removal performance. Although our study was performed using a single pass system, computing PAC effectiveness using I/O ratios may still be applicable for recirculation system. This is because both recirculation and AHU filters parameters will not change under baseline and intervention scenarios. More research is advocated to look into the impact of recirculation and centralized filtration on effectiveness using I/O ratios.

One of the limitations of our study was that the results did not consider long term PAC performance. In a laboratory study, a 42% decrease in CADR for particles greater than 300 nm was reported after approximately six months of simulated use (Zuraimi et al., 2017). This decrease in performance is due to the reduction of the PAC air flow rate by the trapped particles on the old PAC filters. Another study showed a drop of 25% in CADR after a month continuous use in a residential bedroom (Shaughnessy et al., 1994). To maintain PAC effectiveness, the loaded PAC filters should be replaced with new ones once their service lifespan have expired. Another limitation

Fig. 6. Relationship between number of units versus volume of office space to achieve 80% UFP removal effectiveness for tested PAC (this study) and other HEPA-based PACs (published elsewhere). The y-axis is on logarithmic scale. Note that environmental tobacco smoke CADRs obtained from Shaughnessy et al. (1994) and Offerman et al. (1985) were used as an approximate comparison.
relates to how good mixing could have enhanced effectiveness via reduction of short-circuiting of filtered air (re-entrainment of outlet air from PAC into its inlet air) when compared to the baseline scenario without PAC. Macintosh et al. (2008) documented that using 5 PAC in a house resulted in much lower measured CADR of 1080 m³ h⁻¹ than expected CADR of 1860 m³ h⁻¹, explaining that the PAC were not able to draw air effectively from locations outside of their immediate area. Also, despite higher measured I/O ratios under occupied periods, we were not able to discern if there were systematic differences from occupants or source activities that may bias our results. However, the likelihood of a bias to the overall result should be low because of the random order of test our scenarios. Lastly, we conducted this study in an office with a single pass HVAC system to highlight the sole impact of PAC performance. In many office buildings, a large fraction of the indoor air is recirculated back to the air handling unit (AHU) where it can be further filtered (Fisk et al., 2000; Zuraimi and Tham, 2009).

In keeping with the above, we have not conducted a full cost-benefit analysis (CBA) comparing use of PACs with centralised high efficiency filters as this is beyond the scope of the paper. However, available data indicates a slightly lower performance and higher operating costs using PACs. Macintosh et al. (2008) had reported whole house particle removal rates comparing high efficiency induct electronic filters with five HEPA-based PACs (CADR: 360 m³ h⁻¹). The authors documented marginally lower particle decay rates (5.5 vs. 4.1 h⁻¹) and removal effectiveness (98.2% vs. 97.5%) using the PACs. Sultan et al. (2022) conducted a whole building energy simulation comparing energy consumption: EUI increased from a baseline of 142 to 143.4 kWh m⁻² a⁻¹ when MERV 6 filters were replaced with MERV 14 filters while 8 hr workday running of energy efficient HEPA-based PACs resulted in an EUI increase up to 151 kWh m⁻² a⁻¹. For maintenance of centralised filtration cost, Fisk et al. (2000) reported monthly costs between US$3.80 and US$10.40 and labor costs ranging US$3.90 to US$11.10. Using the base cost of replacement of HEPA and prefilters provided by Batterman et al. (2002), corresponding monthly maintenance cost for efficient HEPA-based PACs ranges from US$91 to US$275. Future studies should evaluate full cost benefit impact of PAC maintenance, changing of the loaded HEPA filters in the office setting, airflow effects on PAC effectiveness and combined AHU filtration and PAC effects in the office environment.

5 CONCLUSIONS

This study has demonstrated the performance of PACs in an office building to mitigate indoor exposure of outdoor PM pollution. Using three office environments and a randomised intervention design, we demonstrated particle reductions associated with the use of a low CADR PAC and compared with modelled effectiveness. The particle reductions we noted are modest (4–51%) and are dependent on the room and particle sizes. We noted that both indoor emissions and outdoor sources can confound the performance of PAC in the offices. Using I/O ratios reduced this confounding effect; therefore, we recommend using this method to assess in-situ PAC performance. We validated the model linking the number of PAC to be deployed with respect to volume of the office space and effectiveness. We also presented a method to estimate the number of needed PAC deployment for office buildings that requires supplemental air cleaning or those without ventilation provision systems. This design information derived from this study will be useful for standards organization and building owners intent on reducing particle exposures in office environments.

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**SUPPLEMENTARY MATERIAL**

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.220204

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