Assessing the effectiveness of portable HEPA air cleaners for reducing particulate matter exposure in King County, Washington homeless shelters: Implications for community congregate settings

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DOI: https://doi.org/10.1016/j.scitotenv.2023.164402

Keywords:
Congregate living setting, homeless shelter, particulate matter (PM), portable air cleaner (PAC), indoor/outdoor ratio (I/O), COVID-19

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Abstract

Over four thousand portable air cleaners (PACs) with high-efficiency particulate air (HEPA) filters were distributed by Public Health - Seattle & King County to homeless shelters during the COVID-19 pandemic. This study aimed to evaluate the real-world effectiveness of these HEPA PACs in reducing indoor particles and understand the factors that affect their use in homeless shelters. Four rooms across three homeless shelters with varying geographic locations and operating conditions were enrolled in this study. At each shelter, multiple PACs were deployed based on the room volume and PAC's clean air delivery rate rating. The energy consumption of these PACs was measured using energy data loggers at 1-min intervals to allow tracking of their use and fan speed for three two-week sampling rounds, separated by single-week gaps, between February and April 2022. Total optical particle number concentration (OPNC) was measured at 2-min intervals at multiple indoor locations and an outdoor ambient location. The empirical indoor and outdoor total OPNC were compared for each site. Additionally, linear mixed-effects regression models (LMERs) were used to assess the relationship between PAC use time and indoor/outdoor total OPNC ratios (I/O_{OPNC}). Based on the LMER models, a ten percent increase in the hourly, daily, and total time PACs were used significantly reduced I/O_{OPNC} by 0.034 [95% CI: 0.028, 0.040; $p< 0.001$], 0.051 [95% CI: 0.020, 0.078; $p< 0.001$], and 0.252 [95% CI: 0.150, 0.328; $p< 0.001$], respectively, indicating that keeping PACs on resulted in significantly lower I/O_{OPNC}. The survey suggested that keeping PACs on and running was the main challenge when operating them in shelters. These findings suggested that HEPA PACs were an effective short-term strategy to reduce indoor particle levels in community congregate living settings during non-wildfire seasons and the need for formulating practical guidance for using them in such an environment.

1. Introduction

Individuals experiencing homelessness account for a significant proportion of the US population, estimated at approximately 568,000 people each night in 2019, with the majority (63%) of homeless persons housed in shelters (Henry et al., 2020). Research has documented infectious disease outbreaks in homeless shelters, including airborne droplet transmission of *M. tuberculosis* in shelters operated in multiple U.S cities (Coffey et al., 2009; Martin et al., 2013, 2014). Findings from these previous studies included inspections of air handling and air flows and resulted in recommendations for the use of improved filtration, improved fresh air supplies, maintenance of existing ventilation units, and the need for written respiratory protection plans and separation of suspected infected individuals from the general population. With the COVID-19 pandemic, there has been renewed concern over the potential for airborne transmission of infectious droplets and particles in homeless shelters. Homeless people are more vulnerable to severe COVID-19 due to a higher burden of comorbidities, with estimates that they may be two to three times as likely to die of the disease than the general population (Culhane et al., 2020; Perri et al., 2020). These concerns have been partially supported by case reports of SARS-CoV-2 transmission in homeless shelters in different US metropolitan areas, including in King County, Washington (Baggett et al., 2020; Imbert et al., 2021; Mosites et al., 2020; Tobolowsky et al., 2020).

In King County, Washington, the single night count of individuals experiencing homelessness was estimated to be 13,368 in 2022, with 43% of the population sheltered (King County Regional Homelessness Authority, 2022). A case report from King County documented outbreaks in April 2020 at three homeless shelters, with 10.5% test positivity among the 181 residents and higher numbers of positives in the ensuing weeks afterward, including infections in both shelter occupants and staff members (Tobolowsky et al., 2020). In shelter settings, where masks and vaccinations are not consistently adopted, reducing airborne particles may be one of the most effective interventions that can be deployed in congregate shelter settings to reduce SARS-CoV-2 transmission (Agarwal et al., 2021; Piscitelli et al., 2022).

Controlling infectious airborne droplets and particles in congregate living settings or homeless shelters is further complicated by the summer wildfire smoke season, which results in conflicting guidance on ventilation for indoor air. Generally, increasing ventilation and outdoor air exchange, and improving filtration may be considered for infection control. But, for managing wildfire smoke, it is recommended that outdoor air exchange be minimized to reduce the infiltration of outdoor smoke into the indoor environment. Managing the potential overlapping risks of SARS-CoV-2 transmission and wildfire smoke-related respiratory health effects may be especially challenging as there may be increased demand for and occupancy of homeless shelters (thus greater density of people) during wildfire smoke episodes (Seattle Human Services, 2021). Although generally less severe, a similar situation can occur in the winter during wood burning, which settles in the central low-lying areas of Seattle and King County, sometimes leading to poor air quality during winter inversion events. This could be a problem for congregate and emergency shelters that are set up during extreme weather events.

Portable air cleaners (PACs) equipped with a high-efficiency particulate air (HEPA) filter have been shown to be effective in reducing particle concentrations in several studies conducted in residential settings, and for wildfire smoke specifically. Multiple agencies, including the Centers for Disease Control (CDC) and the Environmental Protection Agency (EPA), have recommended using HEPA PACs to supplement HVAC systems to reduce indoor particle levels (Centers for Disease Control and Prevention, 2021). Barn et al. summarized some studies, many of which were based on randomized controlled study designs (Barn et al., 2016; U.S. Environmental Protection Agency, 2022), that support this recommendation. Henderson et al. documented up to 63-88% lowered $PM_{2.5}$ concentrations with HEPA PACs (Henderson et al., 2005), while crossover studies by Barn et al. and Allen et al. found lower infiltration of smoke when PACs were used compared to when they were not (Allen et al., 2011; Barn et al., 2007). A recent study of HEPA PACs used during the September 2020 Washington State wildfire episode indicated $PM_{2.5}$ reduction effectiveness ranged from 48-78% across seven homes (Xiang et al., 2021), while other studies have investigated the use of PACs in reducing indoor particle concentration in large open spaces such as workplaces (Sultan et al.,

2022) and schools (Carmona et al., 2022). Despite the evidence supporting home HEPA PAC use for reducing particle exposure, there are challenges for PAC performance in multi-zone indoor environments. There remains considerable uncertainty in the performance of HEPA PACs in multi-zone congregate housing settings such as homeless shelters, where there may be competing decisions related to ventilation due to the need to manage both SARS-CoV-2 transmission and wildfire smoke. To date, there have been no studies presenting data on the real-world effectiveness of HEPA PACs for reducing particle exposures in larger multi-zone homeless shelters. Further, no empirical studies have quantified the usage of HEPA PACs in homeless shelters and attempted to correlate performance with site, building, or management decisions. Most studies of PACs are based on optimal usage without considering real-world scenarios, such as user behaviors, compliance, and building characteristics (Barn, 2014).

Since 2020, over 4,000 HEPA portable air cleaners were deployed at homeless shelters in King County, Washington, by Public Health – Seattle & King County (PHSKC) to help control the COVID-19 pandemic and protect the homeless population from acquiring infection. Considering the significant demand, shelters were prioritized for distribution using an equity tool that considered location, population served, and shelter resources. Multiple units were given to shelters for use in the common and sleeping areas. In this study, we aimed to evaluate the real-world effectiveness of these PACs in reducing indoor particles in these community congregate living settings. The objectives of this research were to understand the (1) usage pattern and (2) factors that affect the use of the HEPA PACs deployed at the shelters, and (3) the effectiveness of these PACs in reducing indoor particle levels, relative to the outdoor particle concentrations at each site.

2. Methods

2.1 Site selection and collection of site characteristics

Four rooms across three different homeless shelters (denoted as sites 1, 2a, 2b, and 3 hereafter) in King County, Washington with varying geographic locations and building/operating conditions were selected to participate in this study. These three sites were among the sites that were pre-selected by the county for HEPA PACs deployment. For each selected site, information on building openings (including doors and windows), operating schedules, HVAC system, floor plan, room size, and the primary indoor and outdoor particle sources were collected via field survey. Additional site characteristics, including the residential history of clients, were collected via a post-hoc survey. The survey was anonymous and administered to the site operators and clients aged 18 or older at the end of the study via email and paper. The survey also collected information about residents' perceptions of air quality and pollution sources, and attitudes toward HEPA PACs. The study protocol and recruitment and consent procedures were approved by the University of Washington Human Subjects Division and the Washington State Institutional Review Board and qualified for exemption status.

2.2 Deployment of HEPA PACs and usage monitoring

Multiple portable HEPA PACs (C535 3-stage True HEPA Air Purifier and XQ dual 4-stage True HEPA Air Purifier; Winix America) with brand new sets of filters were deployed in the sleeping dorm or main activity area of each shelter based on the room volume and the clean air delivery rate (CADR) rating of the PACs using the ANSI/AHAM (American National Standards Institute/Association of Home Appliance manufacturers) AC-1 method (recommended PAC working room size (with an 8 ft ceiling height) in square feet = 1.55 × CADR rating in cubic feet per minute) (Association of Home Appliance Manufacturers, 2013). The locations of the PACs were recorded and tracked during the study. The C535 PACs contain three stages of filters, including a pre-filter, an activated carbon filter, and a HEPA filter. The XQ PACs contain two sets of 3-stage filters (a pre-filter, an activated carbon filter, and a HEPA filter) on the front and rear sides of the body. Both models of PAC contain a bipolar ionizer (which can be disabled) and provide five fan speed level settings, including sleep mode, fan speed 1 to 3, Turbo, and an "Auto-mode" feature (i.e., the fan speed level will be adjusted according to the feedback of the built-in air quality sensor). According to the manufacturer, the CADR ratings for dust and smoke of the C535 PAC are 243 m^3/h and 232 m^3/h, respectively, whereas the CADR ratings for dust and smoke of the XQ PAC are 360 m^3/h and 419 m^3/h. The detailed specifications of these two PACs and the measured energy consumption under different fan speed levels were summarized in Table A.1. Both PAC models were certified by the California Air Resources Board (CARB) to meet the ANSI/UL 867 (Underwriters Laboratories) standard (i.e., produce an ozone emission concentration of less than 0.050 parts per million) (California Air Resources Board, 2023). Before the second and third sampling round, the pre-filter of each PAC was vacuumed with a handheld vacuum cleaner to remove the dust built-up. The bipolar ionizer of each PAC was turned off before each sampling round.

The PACs were deployed and monitored for three two-week sampling rounds at each site, separated by single-week gaps, between February and April 2022. Each of the PACs deployed at each site was assigned a unique ID and plugged into a power data logger (HOBO® Plug Load Logger Model UX120-018; Onset Computer Corp.), which measured time-stamped energy usage at 1-minute intervals for the entire study period to allow tracking of their usage and fan speed. The logged data were downloaded by study staff for each data collection period. During the round 1 and round 2 deployments, the PACs were purposely set to operate on Auto-mode. During the round 3 deployment, the PACs were set to operate on fan speed level 3. However, the clients or shelter staff were allowed to change the fan speed setting however they wished during each deployment. At the beginning of each deployment, if a PAC was found unplugged or turned off, it was plugged back in and turned on according to the fan speeds noted above by the research staff.

2.3 Indoor and outdoor particle concentration monitoring

At each site, multiple indoor locations in the selected sleeping dorm or main activity area with PAC were monitored throughout the three sampling rounds using real-time air quality monitors (PurpleAir PA-II-SD; PurpleAir) placed and secured at the height of 1-2 m above the floor and at least 1 m away from any PAC or HVAC inlet/outlet. The PurpleAir PA-II-SD monitor contains two duplicate optical particle counters (OPC) (Plantower PMS 5003; Beijing Plantower Co. Ltd.), pressure, temperature, and humidity sensor (BME280; Bosch SensorTec). The OPC uses the laser scattering principle to measure the number of particles suspended in the air. The photodiode of the OPC is positioned perpendicular to the excitation beam and measures the ensemble scattering of particles in the optical volume. The measured scattering light intensity is converted to a voltage signal to estimate the number concentration of particles with an optical diameter ranging from 0.3 to 10 microns in six size bins (>0.3, >0.5, >1.0, >2.5, >5.0, and >10.0 µm) and mass concentrations for PM_1, $PM_{2.5}$, and PM_{10} (See Fig A.6 for the correlations between particle count measurements for the different size bins in our study). In this study, the number concentration reported in size bin >0.3 µm was defined as the total optical particle concentration (OPNC). OPNC was used because previous studies have observed lower limit of detection issues associated with the $PM_{2.5}$ algorithm of the PurpleAir monitor, in which low concentrations are reported as a value of zero, while the OPNC measurements are less susceptible to this limit of detection issue and will still be able to resolve particle count concentrations when the PurpleAir reports zero mass concentration (Wallace, 2022; Wallace et al., 2020). Because this is an issue with low concentrations, the use of OPNC may be more appropriate for indoor air studies involving HEPA PACs (See Table A.3 for more information on the frequency of zero $PM_{2.5}$ measurements observed in our study).

The OPNC data were timestamped and saved to the internal Secure Digital (SD) memory card at 2-minute intervals. Prior to their use in the study, these monitors were individually calibrated in a chamber experiment with woodsmoke particles against a real-time optical particle sizer (TSI optical particle sizer model 3330, TSI Inc.). The calibration shows R^2 ranging from 0.97 to 0.99 for these monitors, and the root mean squared error (RMSE) of these calibrated monitors was less than 900 #/cm^3 within the measurement range of 0 – 20000 #/cm^3 (Table A.2 and Fig A.7). The optical particle sizer was factory-calibrated prior to this study. In addition to the multiple indoor sampling locations at each site, a single PurpleAir PA-II-SD was placed outside at each shelter that monitored the outdoor ambient particle concentrations throughout the study periods. The outdoor locations were selected based on the representativeness of the general ambient air situation at each shelter, access to an electrical outlet, and were secured to minimize the potential for theft.

2.4 Statistical analysis

For the analysis, the 2-minute particle monitoring data were first aggregated hourly. The empirical indoor and outdoor total OPNC data were then compared within sites. Based on the Shapiro-Wilk tests, the indoor and outdoor total OPNC data were not normally distributed. Thus, the Wilcoxon signed-rank tests (for paired comparison) were conducted to compare the indoor and outdoor total OPNC levels of each site and for each individual sampling round.

Next, three PAC usage metrics were computed for each site: (1) the percent time the PACs were on different fan speed levels, including sleep mode, fan speed level 1 to level 3, and Turbo; (2) the percent time the PACs were on; and (3) the total energy consumption of all PACs. Linear mixed effects regression (LMER), which incorporated random intercepts for sites to account for between-site correlations, as well as within-site correlations of repeated measurements, was used to examine the relationship between the indoor/outdoor total particle number concentration ratio (I/O_{OPNC}) and different PAC usage metrics (Eq. (1) – (3)):

$$I/O_{OPNC_{it}} = \beta_0 + \beta_1 T_{PAC-sleep_{it}} + \beta_2 T_{PAC-fan\,1it} + \beta_3 T_{PAC-fan\,2_{it}} + \beta_4 T_{PAC-fan\,3_{it}} + \beta_5 T_{PAC-turbo_{it}} + W_i + \varepsilon_{it} \quad (1)$$

$$I/O_{OPNC_{it}} = \beta_0 + \beta_1 T_{PAC-on_{it}} + W_i + \varepsilon_{it} \quad (2)$$

$$I/O_{OPNC_{it}} = \beta_0 + \beta_1 P_{it} + W_i + \varepsilon_{it} \quad (3)$$

where $I/O_{OPNC_{it}}$ is the indoor/outdoor total optical particle number concentration ratio of site i at time (hour) t; β_0 – β_5 are the coefficients of the LMER models; $T_{PAC-sleep\,mode_{it}}$, $T_{PAC-fan\,1_{it}}$, $T_{PAC-fan\,2_{it}}$, $T_{PAC-fan\,3_{it}}$, $T_{PAC-turbo_{it}}$ in Eq (1) are the percent time that the PACs were on sleep mode, fan speed 1, 2, 3, and Turbo of site i at time t, respectively, %; $T_{PAC-on_{it}}$ in Eq (2) is the percent time that the PACs were on of site i at time t, %; P_{it} in Eq (3) is the total energy consumption of all PACs of site i at time t, Watts; W_i is the random effect factor, and ε_{it} is the residual. The LMER models were also assessed on daily and round levels. The outliers of $I/O_{OPNC_{it}}$ (i.e., measurements that were 1.5 interquartile range below the first quartile or above the third quartile) were removed for the modeling. For all statistical tests, $p \leq 0.05$ indicated statistical significance in this study. All calculations and figures were made using “nlme”, “data.table”, and “ggplot2” packages in R Version 4.1.1 embedded in Rstudio Version 2021.09.0.

3. Results

3.1 Site characteristics

Table 1 summarizes the characteristics of the enrolled sites based on the field and post-hoc surveys. All three sites were located on the 1st floor. Site 1 and site 3 were mechanically ventilated 24 hours per day with built-in HVAC systems, whereas site 2 (including two separate rooms 2a and 2b) was naturally ventilated without HVAC systems. Due to the study seasons (winter and spring), site 1 and site 3 used central heating systems to provide warmth to the rooms. Site 2 (including two separate rooms 2a and 2b) used wall radiators for heating. While windows were not available in the monitored area at site 1 and site 3, doors leading to the outdoor area were present and could have been opened during the study periods by shelter clients or staff. Site 1 is in the busy metro center and about 120 meters away from the major highway in the area. This site served approximately 20 clients from 9 am to 8 pm on weekdays, and 10 am to 2 pm on Saturdays. Site 2 (including two separate rooms 2a and 2b) is about 320 meters away from a major highway, whereas site 3 is only 60 meters away from the closest highway. Site 2 (including two separate rooms 2a and 2b) and site 3 offered overnight services, were open 24 hours per day, seven days per week, and served approximately 50 and 100 clients per day, respectively. Onsite cooking took place only at sites 1 and 3, although already cooked meals were provided at sites 2a and 2b.

Table 1. General characteristics of the study sites.

Site ID	Monitored area	Room volume (m^3)	Year first built	Ventilation type	Window opening	Cooking onsite
Site 1	Main activity area	996	1922	Mechanical	NA[a]	Y
Site 2a[b]	Sleeping dorm #1	921	1903	Natural	Possible	N
Site 2b[b]	Sleeping dorm #2	1021	1903	Natural	Possible	N
Site 3	Sleeping dorm	238	1975	Mechanical	NA[a]	Y

[a] No windows present in the monitored area.
[b] Site 2 had two areas monitored.

3.2 Measured PAC energy consumption and usage

Fig. 1 illustrates the measured % time of PACs operating under different fan speed levels at each site. The PACs deployed at site 1, site 2a, and site 2b were found operating under the Turbo fan speed during round 1 most of the time (~45%). This could be because the shelter clients or staff adjusted the PAC fan speed settings manually to Turbo rather than keeping them running in Auto mode during the study. This assumption is supported by the time series of the individual PAC energy consumption shown in Fig. A.1-A.4. Fig. A.1 shows the time series of the 13 PACs deployed at site 1. During sampling round 1, the energy consumption of multiple PACs (e.g., PAC-003, PAC-004, and PAC-006) remained at ~ 60 watts most of the time. This watt level corresponds to the energy consumption of the PAC running at Turbo fan speed (Table A.1). Because the PACs were set to Auto-mode by the study staff at the beginning of sampling round 1, it is unlikely that the PACs remained at the Turbo fan speed for such extended periods of time due to the decreasing particle concentration in the environment (Fig. 2 and Fig. 3). The PAC operating fan speed would stay at Turbo for such extended hours only if it were manually adjusted. Similar PAC energy consumption can be observed for round 1 sampling at site 2a (Fig. A.2), site 2b (Fig. A.3), and site 3 (Fig. A.4). Diurnal patterns of PAC usage were also observed. Fig A.5. shows the heatmap of the normalized hourly total PAC energy consumption at each site. Lower hourly total PAC energy consumption can be seen during the nighttime compared to the daytime, especially during round 2 sampling at Site 2a, and round 1 and round 2 sampling at Site 3. This again highlighted users' preferences for adjusting the PAC operating fan speed. The total minutes of the PAC energy consumption monitored at each site are summarized in Table A.4. The incompleteness of site 1 and site 3 data was due to the power data loggers being unplugged from the PACs during the monitoring.

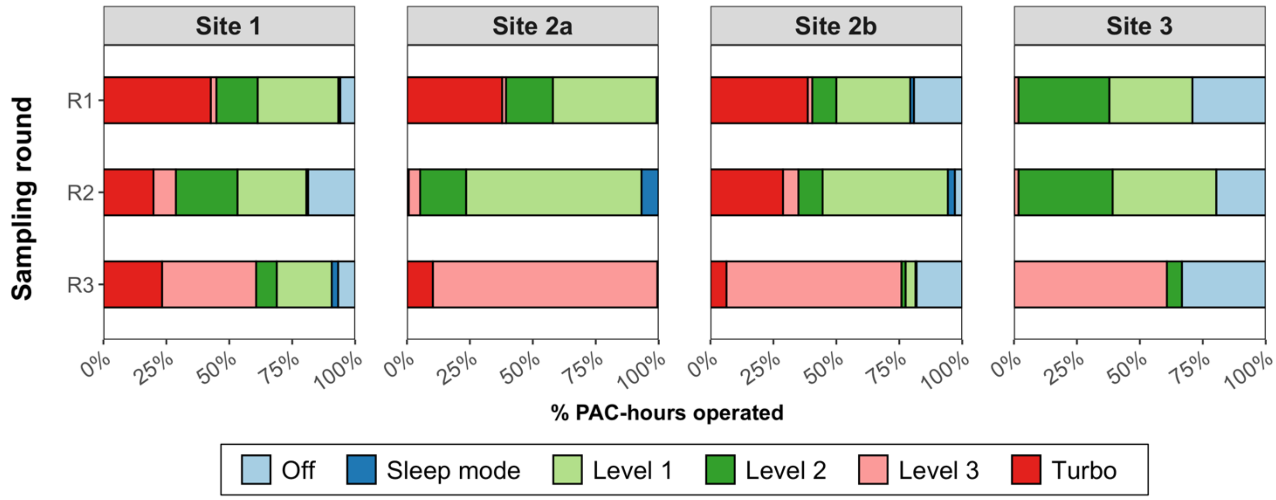

Fig. 1. The measured % time of PACs operated under different fan speed levels.
R1: round 1; R2: round 2; R3: round3. The PACs were initially set to operate on Auto-mode during round 1 and round 2, and fan speed level 3 during round 3.

3.3 Empirical particle concentrations

Table 2 shows the hourly mean indoor and outdoor total particle concentrations, and temperature and humidity at four sites. Overall, the mean indoor total OPNC concentrations at each site were relatively low during all sampling rounds (< 200 #/cm^3). In contrast, the outdoor total OPNC concentrations were significantly higher than the indoor levels across all three sites and sampling rounds ($p < 0.001$). Pooling all sampling rounds together within each site, the median (interquartile range, IQR) reduction of hourly indoor total OPNC level was 78% (49%), 84% (25%), 65% (58%), and 80% (30%) compared to outdoor levels at site 1, site 2a, site 2b, and site 3, respectively. At site 1, multiple peaks were observed in the outdoor total OPNC levels, with a maximum concentration of 20298 #/cm^3 during round 2 sampling (Table 2 & Fig. 2). Despite the indoor OPNC levels being lower than outdoors most of the time, the hourly indoor levels observed at each site sometimes were comparable to or higher than the outdoor levels (Fig. 2, site 2b), indicating the presence of strong indoor particle sources. The heatmap in Fig. 3 shows the temporal variation in total indoor and outdoor OPNC levels. For site 1, over 90% of the indoor total OPNC observations were missing during round 1 sampling because the indoor monitors were unplugged by people at the site.

Table 2. Summary of the hourly averaged indoor and outdoor total particle concentration at three sites.

Site	Round	Indoor total OPNC (#/cm³) [a]					Outdoor total OPNC (#/cm³)					p-value [c]
		Min	Median (IQR)	Mean (SD)	Max	N	Min	Median (IQR)	Mean (SD)	Max	N [b]	
Site 1	R1	0.50	94.43 (114.23)	133.22 (124.36)	750.89	659	91.26	609.39 (684.99)	891.08 (1011.65)	8882.23	327	< 2.2e-16
	R2	6.63	101.28 (115.73)	156.38 (169.90)	1420.44	657	35.16	319.15 (344.75)	780.26 (1982.68)	20298.03	312	< 2.2e-16
	R3	0.70	82.76 (95.01)	89.85 (76.73)	251.60	49	117.55	452.71 (321.34)	639.17 (827.45)	9850.99	276	1.82e-12
Site 2a	R1	0.51	53.22 (64.10)	64.51 (52.35)	346.7	610	31.61	286.26 (274.20)	346.28 (237.02)	1537.67	329	< 2.2e-16
	R2	0.11	61.02 (58.78)	78.18 (80.97)	639.93	652	13.19	427.94 (349.83)	452.46 (270.22)	1983.50	330	< 2.2e-16
	R3	0.27	53.67 (57.67)	70.41 (82.45)	636.80	619	8.05	289.38 (339.51)	357.79 (243.59)	1259.93	330	< 2.2e-16
Site 2b	R1	3.60	101.57 (99.47)	163.91 (264.25)	2768.55	637	31.61	286.26 (274.20)	346.28 (237.02)	1537.67	329	< 2.2e-16
	R2	4.82	102.39 (92.41)	131.16 (109.34)	999.80	659	13.19	427.94 (349.83)	452.46 (270.22)	1983.50	330	< 2.2e-16
	R3	0.42	122.88 (143.37)	161.51 (134.86)	980.24	660	8.05	289.38 (339.51)	357.79 (243.59)	1259.93	330	< 2.2e-16
Site 3	R1	14.40	77.15 (71.87)	99.82 (72.38)	431.55	330	21.40	376.63 (291.69)	433.78 (275.73)	1574.26	329	< 2.2e-16
	R2	6.60	44.89 (31.92)	49.44 (33.16)	337.44	330	44.11	286.86 (278.43)	318.00 (194.83)	1165.74	330	< 2.2e-16
	R3	8.87	64.19 (54.19)	85.12 (86.86)	1098.08	330	43.49	275.72 (208.92)	283.39 (159.06)	1148.29	330	< 2.2e-16

[a] For sites with multiple indoor monitors (site 1, site 2a, and site 2b), the average concentrations across all indoor monitors were presented.
[b] Number of data points.
[c] Comparison between the indoor and outdoor total OPNC based on the Wilcoxon signed-rank tests (for paired comparison).

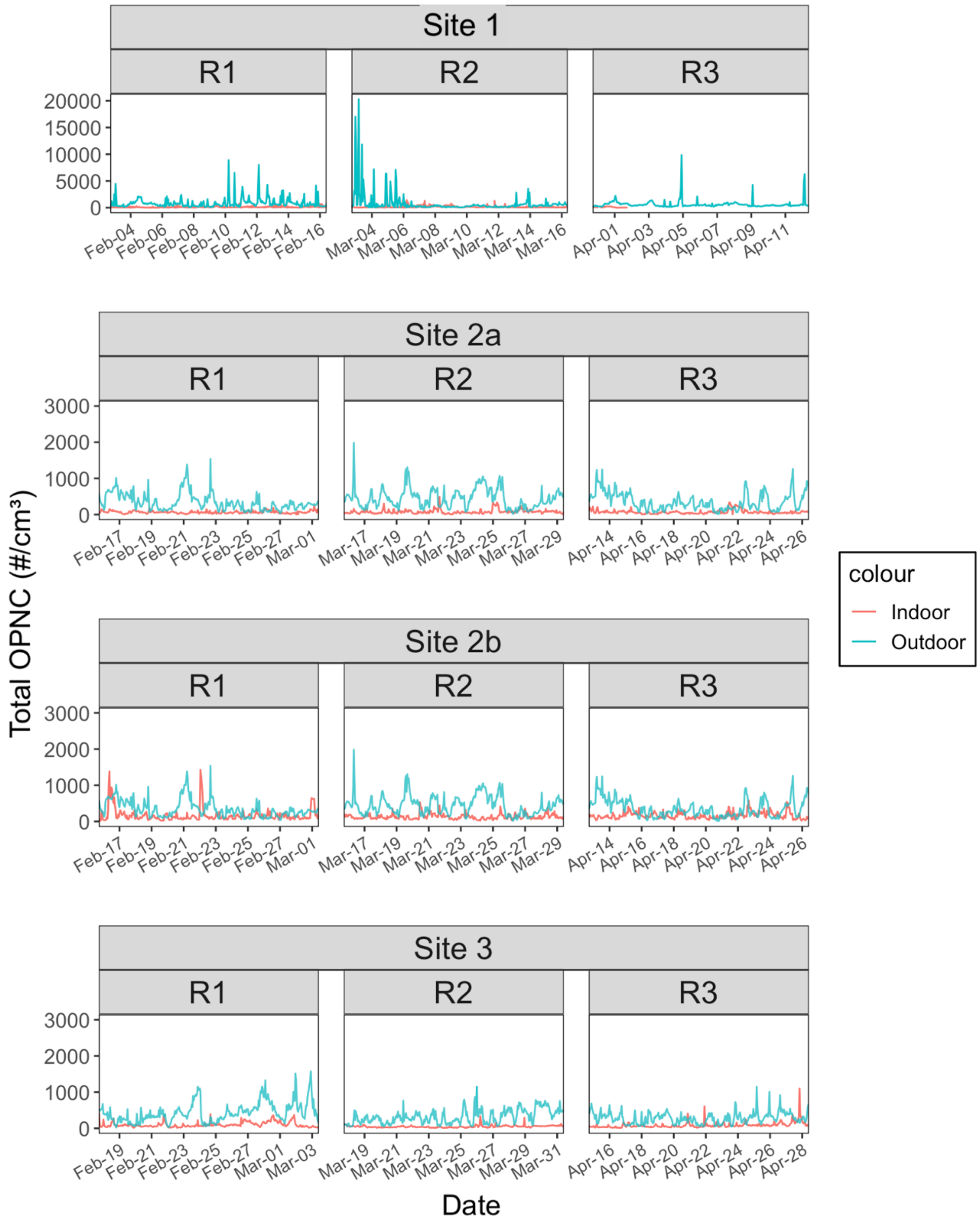

Fig. 2. Time series of the indoor and outdoor total OPNC at three sites. For sites with multiple indoor monitors (site 1, site 2a, and site 2b), the average concentrations were plotted. The y-axis of site 1 was plotted on a different scale.

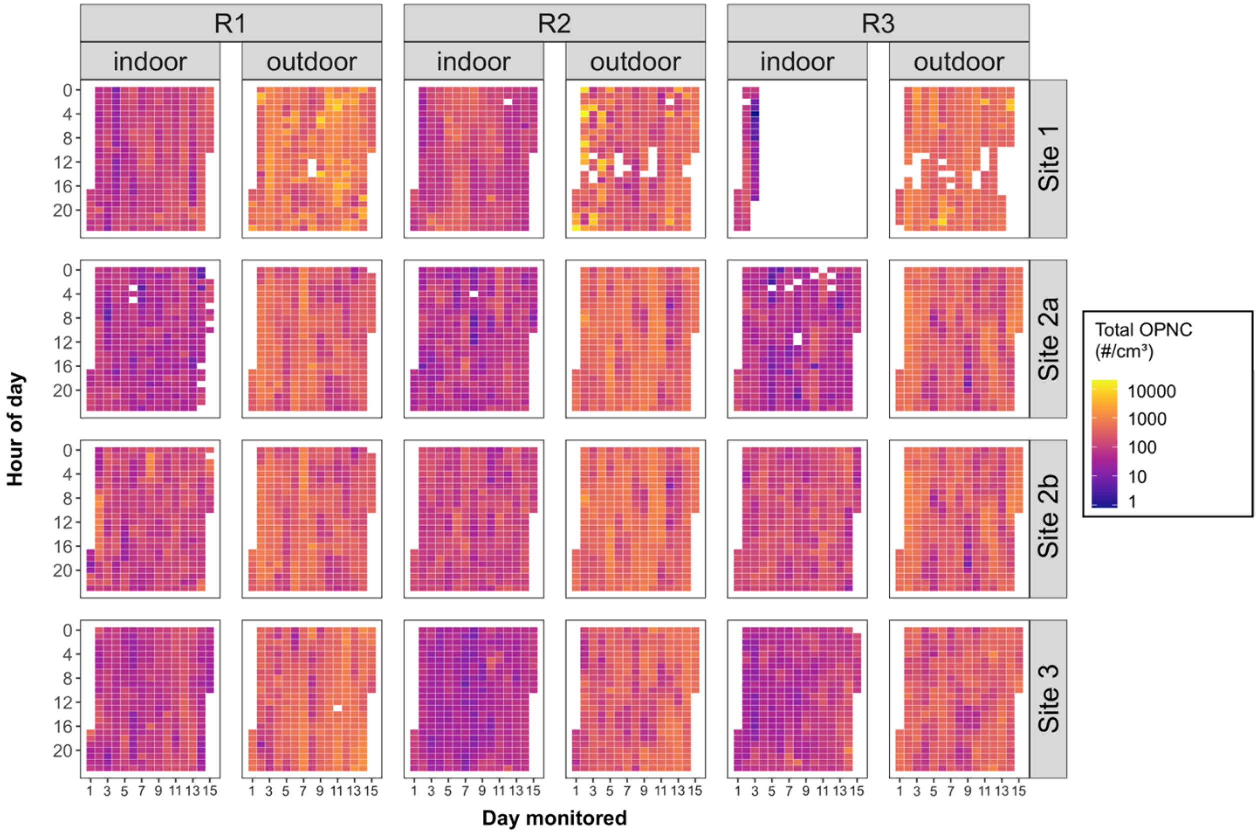

Fig. 3. Heatmap of the indoor and outdoor total OPNC at each site. For sites with multiple indoor monitors (site 1, site 2a, and site 2b), the average concentrations were plotted.

Fig. 4 and Table 3 show the hourly indoor/outdoor total OPNC ratios (I/O_{OPNC}) under different sampling rounds at each site. For all sites, the median hourly I/O_{OPNC} during all sampling rounds was lower than 1, indicating that the indoor total OPNC levels were lower than the outdoor ones for 50% of the study period. However, the maximum I/O_{OPNC} at each site was larger than 1 (the data for round 3 of site 1 was excluded from the discussion due to incompleteness), suggesting the presence of indoor particle sources at each site.

Table 3. Summary of the hourly averaged indoor/outdoor total particle concentration ratio (I/O_{OPNC}) at three sites.

Site	Round	I/O_{OPNC}				N [a]
		Min	Median (IQR)	Mean (SD)	Max	
Site 1	R1	<0.01	0.15 (0.30)	0.29 (0.43)	4.93	653
	R2	<0.01	0.37 (0.72)	0.79 (1.43)	19.45	623
	R3	<0.01	0.19 (0.26)	0.18 (0.15)	0.55	40
Site 2a	R1	<0.01	0.18 (0.31)	0.31 (0.42)	4.05	610
	R2	<0.01	0.14 (0.24)	0.28 (0.43)	8.10	652
	R3	<0.01	0.16 (0.23)	0.39 (1.11)	18.82	619
Site 2b	R1	0.01	0.37 (0.58)	0.71 (1.27)	16.50	635
	R2	0.01	0.28 (0.41)	0.49 (0.73)	8.10	659
	R3	0.01	0.42 (0.79)	0.84 (1.34)	18.98	660
Site 3	R1	0.01	0.23 (0.32)	0.33 (0.31)	2.42	329
	R2	0.02	0.15 (0.17)	0.23 (0.23)	1.49	330
	R3	0.02	0.27 (0.38)	0.46 (0.73)	8.52	330

[a] The number of complete hours with both indoor and outdoor measurements.

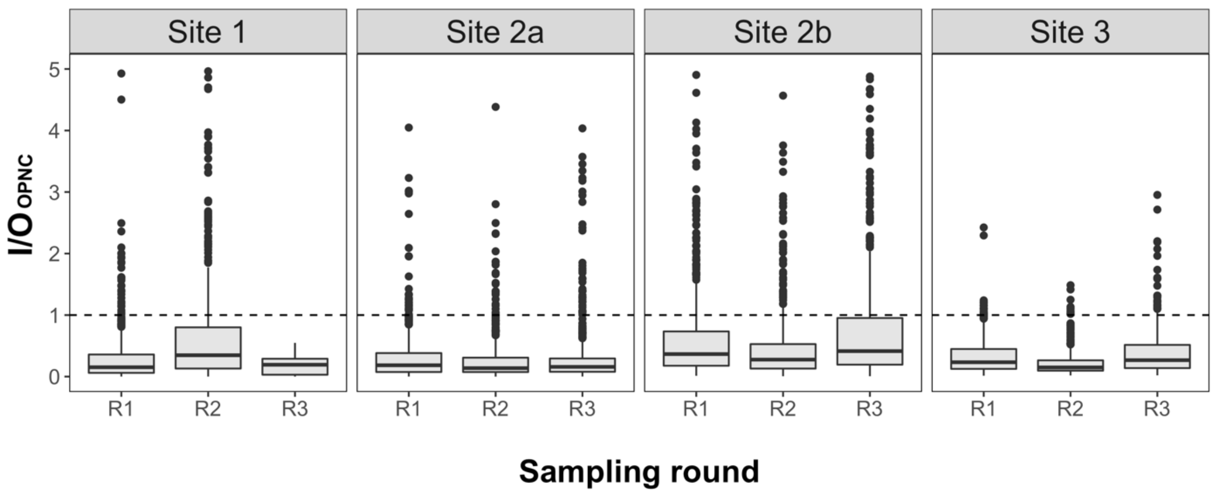

Fig. 4. Boxplot of the hourly averaged indoor/outdoor particle number concentration ratio (I/O_{OPNC}). Data points larger than 5 (0.8 % of the total observations across all sites and all sampling rounds) were excluded from plotting (max values are provided in Table 3).

3.4 Relationship between PAC usage metrics and indoor/outdoor total OPNC ratio (I/O_{OPNC})

Table 4 presents the results of the LMER models. Models 1-3 assessed the relationship between the I/O_{OPNC} and the "percent time the PACs were on different fan speed levels," "percent time the PACs were on," and "hourly total energy consumption of all PACs" metrics, respectively, on different time averaging scales. The coefficient estimates show the effect of per 10% change in PAC usage time on I/O_{OPNC} for model 1 and model 2, and the effect of per one-watt change in PAC energy consumption on I/O_{OPNC} in model 3. In model 1, the coefficient estimates for the hourly time PACs were on sleep mode (β_1), fan speed level 1 (β_2), level 2 (β_3), level 3 (β_4), and Turbo (β_5) were negative, indicating that regardless of the fan speed level, using PACs result in lower I/O_{OPNC}. However, the reductions in these coefficient estimates were non-linear, indicating that running the PACs at higher fan speed did not result in lower I/O_{OPNC} than at lower fan speed.

In model 2, regardless of the time averaging scale, the regression coefficients were negative for the percent time PACs were on (β_1), indicating that keeping PACs on resulted in significantly lower I/O_{OPNC}. Ten percent increase in the hourly, daily, and total time PACs were used significantly reduced I/O_{OPNC} by 0.034 [95% CI: 0.028, 0.040; $p < 0.001$], 0.051 [95% CI: 0.020, 0.078; $p < 0.001$], 0.252 [95% CI: 0.150, 0.328; $p < 0.001$], respectively. Fig. 5 shows the predicted hourly I/O_{OPNC} under 50% to 100% of PACs operating time, based on model 2 with an hourly averaging scale. Overall, hourly PAC operating time ranging from 50% to 100% results in I/O_{OPNC} smaller than 1, and with the increasing amount of hourly PAC operating time, the I/O_{OPNC} becomes lower. Similarly, in model 3 with different time averaging scales, the regression coefficients of the total energy consumption of all PACs (β_1) were insignificant and the values were close to zero or negative, meaning that higher total energy consumption of PACs did not significantly lower I/O_{OPNC}.

Table 4. Summary of the results for the linear mixed-effects regression (LMER) models. The estimate shows the effect of per 10% change in PAC usage time for model 1 and model 2, and the effect of per one-watt change in PAC energy consumption for model 3, respectively, on I/O$_{OPNC}$.

Model	Averaging Scale	Coefficient	Estimate	Standard error	95% CI [a]
Model 1	Hourly	β_0	0.597	0.036	0.530 to 0.666 ***
		β_1	-0.015	0.036	-0.034 to 0.005
		β_2	-0.035	0.010	-0.041 to -0.028 ***
		β_3	-0.036	0.003	-0.043 to -0.029 ***
		β_4	-0.036	0.004	-0.043 to -0.028 ***
		β_5	-0.032	0.004	-0.043 to -0.023 ***
	Daily	β_0	0.701	0.143	0.442 to 0.980 ***
		β_1	0.158	0.099	-0.036 to 0.345
		β_2	-0.060	0.016	-0.091 to -0.029 ***
		β_3	-0.052	0.025	-0.103 to -0.004 *
		β_4	-0.046	0.017	-0.079 to -0.002**
		β_5	-0.005	0.019	-0.045 to 0.030
	Round	β_0	3.115	0.410	2.393 to 3.898 ***
		β_1	-1.879	0.500	-2.556 to -1.197 *
		β_2	-0.125	0.050	-0.198 to -0.052 *
		β_3	-0.462	0.087	-0.590 to -0.333 **
		β_4	-0.297	0.030	-0.342 to -0.253 ***
		β_5	-0.405	0.050	-0.479 to -0.329 **
Model 2	Hourly	β_0	0.595	0.036	0.526 to 0.665 ***
		β_1	-0.034	0.003	-0.040 to -0.028 ***
	Daily	β_0	0.787	0.134	0.508 to 1.042***
		β_1	-0.051	0.014	-0.078 to -0.020 ***
	Round	β_0	2.575	0.396	1.689 to 3.337 ***
		β_1	-0.252	0.039	-0.328 to -0.150 ***
Model 3	Hourly	β_0	0.295	0.008	0.276 to 0.313 ***
		β_1	1.78e-04	1.17e-04	-4.48e-05 to 4.16e-04
	Daily	β_0	0.338	0.027	0.299 to 0.382 **
		β_1	4.41e-04	9.87e-04	-1.14e-03 to 2.57e-03
	Round	β_0	0.486	0.090	0.320 to 0.651 *
		β_1	-0.004	0.004	-0.012 to 0.006

[a] Level of significance: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

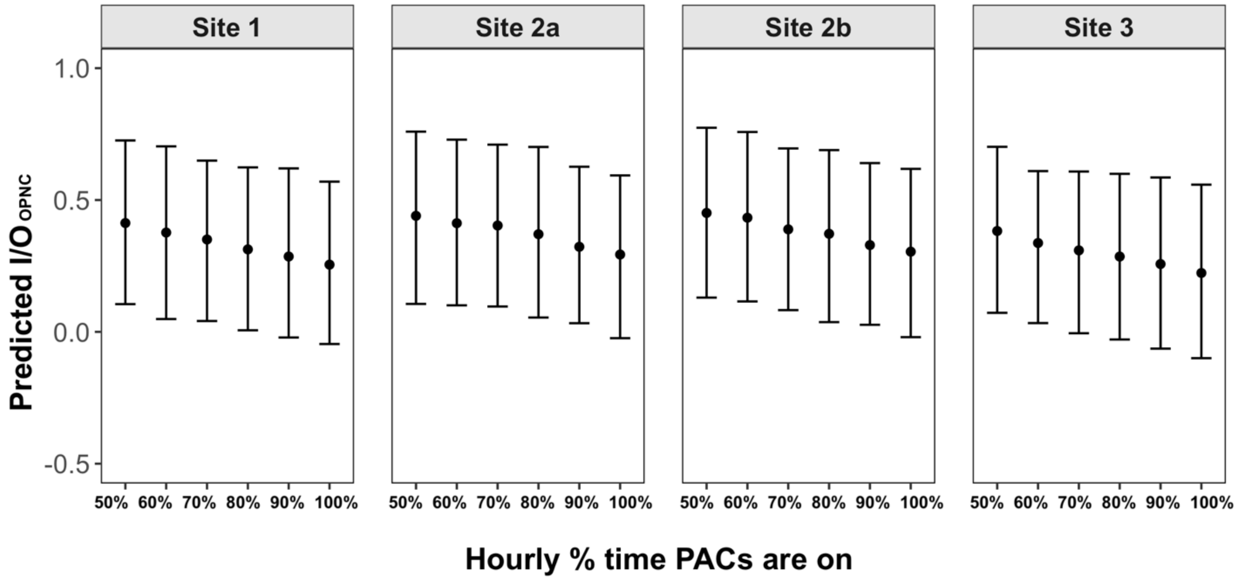

Fig. 5. Prediction of hourly I/O_{OPNC} under 50% to 100% of hourly PACs usage time at each site. The middle point represents the mean, and the top and bottom bars represent the upper and lower 95% confidence interval, respectively.

3.5 Survey results

A total of 10 clients and 12 staff from three sites participated in the post-hoc survey. Most respondents reported that cooking fumes (17, 77.3%) and cigarette smoke outdoors (17, 77.3%) were the main indoor sources of air pollution. Body and bathroom odors (2, 9.1%), vehicle exhaust (2, 9.1%), and indoor vaping (1, 4.5%) were also reported as indoor sources of air pollution. Of 22 respondents, 16 (72.7%) felt air quality was better with PACs. Among the respondents who did not feel air quality was better with PACs (4, 18.2%, 2 missing), three respondents were clients. These clients reported their ability to smell air fresheners, cigarette smoke, cooking fumes, and vehicle exhaust as the reasons they didn't feel the air quality was better. The only staff reported that air quality was not better with the PACs indicated it was due to continued smells of cooking fumes.

Regarding the maintenance and operations of PACs, half (11, 50%) of the respondents reported they hardly noticed staff cleaning PACs. Nearly 42% (5) of the staff responded that keeping the PACs running and the noise were the two primary concerns of operating the PACs. Among nine clients who responded to this question, over half (6, 66.7%) responded that they slept better with the PACs on and when the air quality was better.

4. Discussion

To our knowledge, this study is the first to examine the use of portable HEPA air cleaners and their impacts on indoor total particle concentration in homeless shelters. The results of this study suggest that using HEPA PACs (with the number of units estimated according to the ANSI/AHAM recommendation) and increasing the amount of time they are turned on, can significantly reduce indoor total OPNC compared to the outdoors, in real-world operating fan speeds of the air cleaners at homeless shelters.

A congregate living setting, by definition, is a facility or housing where people reside and share at least one common room, such as a sleeping room, bathroom, or kitchen. In homeless shelters where supportive services such as meals and housekeeping are provided, various sources of particles could have existed, such as cooking fumes, the use of vacuums, and air freshener. In this study, though PACs were found to reduce indoor total OPNC, elevated peaks (> 250 $\#/cm^3$) were still observed at each site. This highlighted the importance of source control. For example, staff and clients from site 1 and site 3 reported cooking fumes as the major indoor air pollution source, and clients from site 3 specifically mentioned that cigarette smoke from outdoors could be smelled in the sleeping dorm. This could explain the indoor total OPNC peaks observed at these two sites

(Table 2). At site 1 where the highest outdoor total OPNC was observed (20298 #/cm^3), the staff reported smoking activities happened right next to the location of outdoor particle sensors during round 2 sampling (Table 2). In addition to these common indoor particle sources, wildfire smoke is a concern generally for our region, and outdoor regional particle concentrations can reach high concentrations in the late summer-fall season. Wildfire smoke may not have been reported because of the timing of our survey which was conducted in the spring season.

Our study results show that with the use of PACs, the empirical median indoor total OPNC level was reduced by up to 84% compared to the outdoor levels. The LMER results of models 1 and 2 also supported that using PACs would result in lower indoor/outdoor total OPNC ratios. However, we did not observe significantly lower indoor/outdoor total OPNC ratios when the PACs operated under higher fan speed levels compared to low, according to the results of model 1. To further investigate this, we fit a separate LMER model to assess the effect of PACs operating at Turbo versus low fan speed level (sleep mode and speed level 1 to level 3) on indoor/outdoor total OPNC ratios (the results are presented in Table A.5). Similarly, the results show that operating PACs under Turbo level did not result in significantly lower indoor/outdoor total OPNC ratios compared to low fan speed. This is consistent with a previous study that investigated the combined use of window A/C fans and HEPA PACs in classrooms located in a non-urban setting where the background particle concentration is low (Azevedo et al., 2022). It was reported that using HEPA PACs alone at a high fan speed did not result in significantly lower $PM_{2.5}$ concentration compared to a lower fan speed. The authors suggested it was possible that the retention time of the particles was relatively short when the PAC fan speed/CADR is high, thus, resulting in lower particle removal efficiency. Nevertheless, further studies are required to investigate the flow dynamics, particle removal efficiency, and CADR of the PACs under different fan speed levels.

In model 3, the trend of regression coefficients (β_1) of model 3 was negative or close to zero, meaning that higher PACs energy consumption did not result in significant changes in indoor/outdoor total OPNC ratios. These coefficients were not statistically significant, which might be due to the noise in the data, or the variations in the energy consumption of the PACs operating at different fan speed levels were too small for the regression model to pin down the relationship between PAC energy consumption and indoor/outdoor total OPNC ratio. The energy consumption of the PACs operating at lower fan speed levels, including sleep mode, fan speed levels 1, 2, and 3 ranges from 2.8 – 10.4 and 8.7 – 21.9 wattages for the two models used in this study (Table A.1). Nevertheless, the results of model 1 and model 2 concluded that the amount of time using the PACs was associated with lower indoor/outdoor total OPNC ratios.

Care should be taken when choosing which PACs for use in homeless shelters. Consistent with the existing guidance (Centers for Disease Control and Prevention, 2021; Public Health - Seattle & King County, 2021; The American Society of Heating, 2021; U.S. Environmental Protection Agency, 2022; Washington State Department of Health, 2022a, 2022b), this study suggested selecting HEPA PACs based on the CADR ratings and recommended working room size. While the existing guidance is formulated based on the CADR and room size at the highest fan speed settings (provided by manufacturers), the results of this study suggested that keeping HEPA PACs on all the time could significantly reduce indoor particle levels, regardless of what fan speed they are on. According to the survey results, the main challenge of operating the PACs on site reported by the shelter staff was to keep them on and running. For example, staff from the participating sites reported that PACs were unplugged from the electrical outlets to plug in other or personal electronic devices. In light of this, electrical outlets should be secured to prevent PACs from being unplugged. The use of labels or signage to explain the purpose of the PACs and communicating with staff and clients to keep them plugged in or turned on would also help address this challenge. Other recommendations in the existing guidance include selecting HEPA PACs with third-party verification (e.g., CARB and AHAM) to avoid devices that could emit harmful gas (e.g., ozone) emissions. In the current study, noise was another concern that staff voiced regarding PAC use at shelter sites. There is growing evidence suggesting that noise is a major factor that affects behavior or attitude toward using PACs (Brugge et al., 2013; Huang et al., 2021). Therefore, noise level should also be considered when selecting PACs to use. Using lower settings can reduce the noise levels, so additional PACs can be helpful to provide more air changes per hour if used in a setting where the highest fan speed setting is not practical.

In addition to the challenges operating the PACs in the shelters, the survey results also suggested that odors, including cigarette smoke, bathroom smells, air fresheners, and vehicle exhaust, were perceived as the major contributors to poor indoor air quality by the shelter staff and clients. This echoes previous studies investigating perceived indoor air quality among public facilities, which reported that sensory responses (e.g., olfactory, visual, and thermal comfort) are the primary ways that humans rely on to assess air quality in indoor environments such as home (Kim et al., 2019) and sports facilities (Xie et al., 2021).

The existing guidance rarely discussed the costs of running and maintaining PACs. Based on the energy consumption data this study collected, the average monthly energy consumption per PAC ranges from ~3.4 kWh to ~17.4 kWh depending on the PAC model used and the percent time PAC operating under different fan speed levels. Other considerations include the cost and frequency of filter replacement, the need to designate staff that can clean and maintain PACs, and the design and ease of using the PACs. In this study, the PACs were brand new at the beginning of the field deployment. According to the manufacturer, the recommended HEPA lifespan of the PACs used in this study, which refers to the time of use when the CADR drops by 50%, is 12 months. Our study lasted for approximately 2.5 months, which was within the manufacturer's recommended HEPA filter lifespan. Zuraimi et al. tested the impact of artificial dust loading on the performance of a HEPA-based PAC in a controlled laboratory environment. They reported that the PAC airflow rate decreased by 49% of its initial value after 150 grams of ISO 12103-1 A1 ultrafine test dust (with particle diameter between 0.97 to 22.0 μm) was loaded on the PAC's filters (Zuraimi et al., 2017). Shaughnessy et al. reported that after 800 hours of intermittent operation in residential bedrooms, the airflow rate and CADR of HEPA-based PACs reduced by 26.5% and 25.0%, respectively (Shaughnessy et al., 1994). As neither of these studies was based on multi-zone congregational living facilities, future studies on assessing the impacts of dust loading on PACs particle removal efficiency are warranted.

This study has several limitations. First, the present study was not conducted during the wildfire season when the indoor particle concentrations would likely be higher. There may have been seasonal effects depending on the air pollution experienced at different times of the year. Therefore, the effectiveness of PACs in lowering indoor particle concentration in wildfire seasons might be different. Second, detailed time-activity information was not collected in this study, which limits our ability to characterize the impacts of sources (e.g., cooking, cleaning, window opening, etc.) on indoor particle levels. Third, compared to previous studies that relied on cross-over design, this study was observational because the air cleaners were deployed not for the study but for COVID-19 control; it would have been unethical to randomize air cleaner use or sham filtration in this situation. Fourth, the applicability of the study results might be limited. Homeless shelters are not the sole type of congregate living setting. Some other common congregate living settings include nursing homes and correctional facilities. These settings could have different characteristics such as building conditions, the density of persons, the amount of time that people share a common space, and the sources of air pollution exposures. For facilities that open overnight, the concern about using PACs might be different (e.g., noise from PACs could be an issue in a sleeping dorm). Lastly, this study did not measure air exchange rates directly, which could impact the infiltration of particles of outdoor origins (Xiang et al., 2021; Zauli-Sajani et al., 2018). This may lead to a biased comparison between the indoor and outdoor particle concentrations and the calculation of indoor/outdoor particle concentration ratios. In addition, we estimated the number of PACs deployed at each site according to the AHAM recommendations (Association of Home Appliance Manufacturers, 2013; Shaughnessy & Sextro, 2006), which were developed based on residential ventilation and particle deposition rates. In congregate living settings, the ventilation rate and particle deposition rate could have been different from residential environments. As previously mentioned, air filtration with PACs is recommended as a supplement to ventilation by various agencies, and there has been a growing interest in comparing the combined effectiveness of various ventilation and air filtration strategies. The objective of this study was not to answer such questions. Instead, our goal was to investigate the real-world effectiveness of HEPA PACs in reducing indoor particle concentration and provide qualitative insights on what factors impact the use of HEPA PACs in congregate living settings. Future studies building upon the current research and examining the effectiveness of HEPA PACs during different exposure scenarios (e.g., wildfire season) are warranted to formulate more comprehensive guidance for reducing indoor exposures. However, as discussed, our study findings suggest that short-term use of HEPA PACs is effective in reducing indoor particle levels in community congregate settings.

5. Conclusions

This study shows that portable HEPA air cleaners are an effective short-term strategy to reduce indoor particle levels in community congregate settings during non-wildfire seasons, though the overall effectiveness depended on the length of time that the portable HEPA air cleaners were used. Keeping portable HEPA air cleaners on and running was the main challenge when operating them in shelters. These findings suggested the need for formulating practical guidance for using portable HEPA air cleaners in community congregate settings.

Funding sources

This project was supported by cooperative agreement EH20-2005 funded by the Centers for Disease Control and Prevention.

Acknowledgment

The authors wish to express special thanks to King County Health Engagement Action Resource Team (HEART Team) for mobilizing rapid HEPA air cleaner deployment and facilitating connection with study sites, and PHSKC Environmental Health Services COVID Recovery Program on Indoor Air for assisting with logistics and resources.

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Supplementary Material

Assessing the effectiveness of portable HEPA air cleaners for reducing particulate matter exposure in King County, Washington homeless shelters: Implications for community congregate settings

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DOI: https://doi.org/10.1016/j.scitotenv.2023.164402

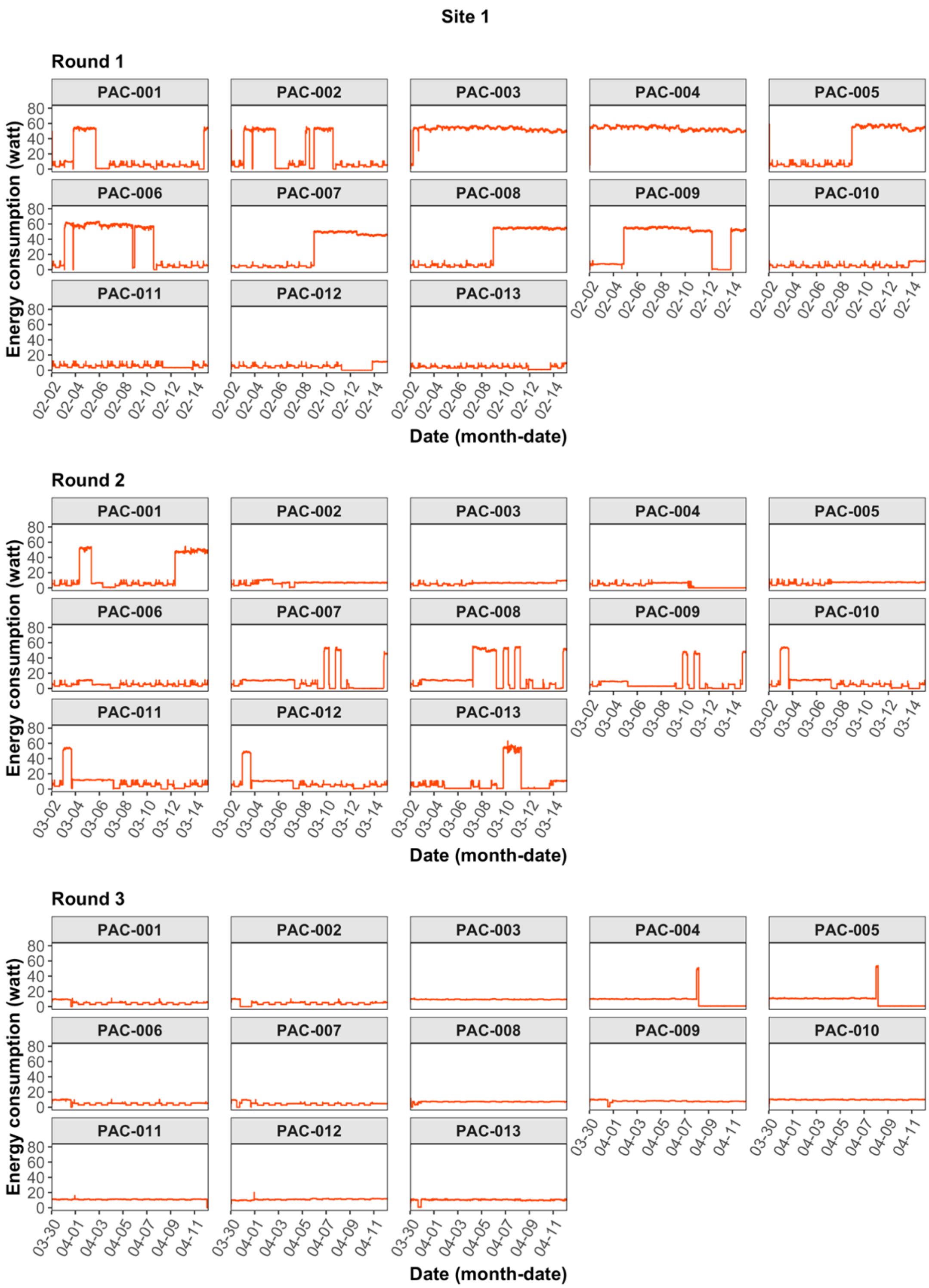

Fig. A.1. Time series of the energy consumption of the PACs deployed at site 1 during three sampling rounds.

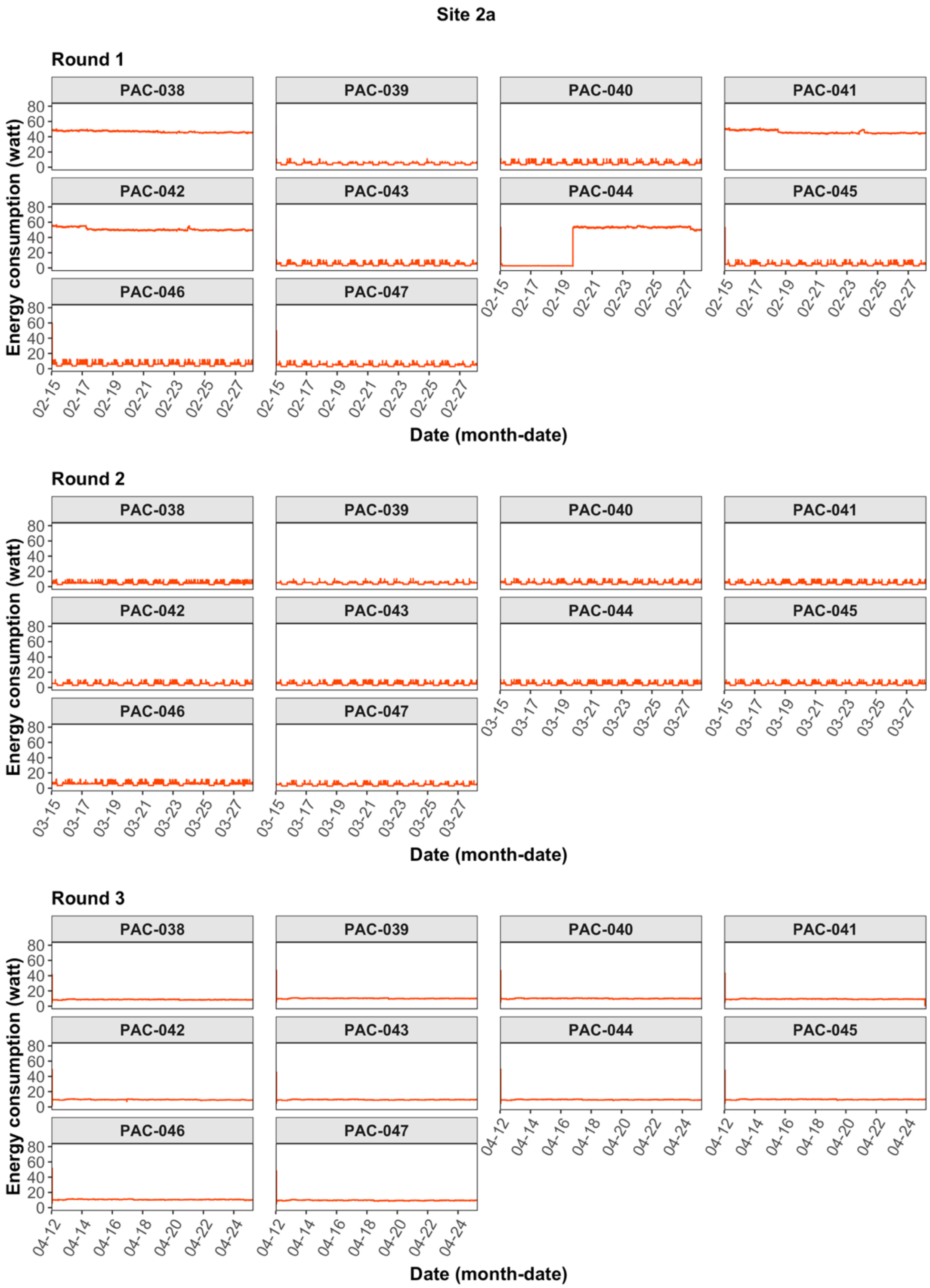

Fig. A.2. Time series of the energy consumption of the PACs deployed at site 2a during three sampling rounds.

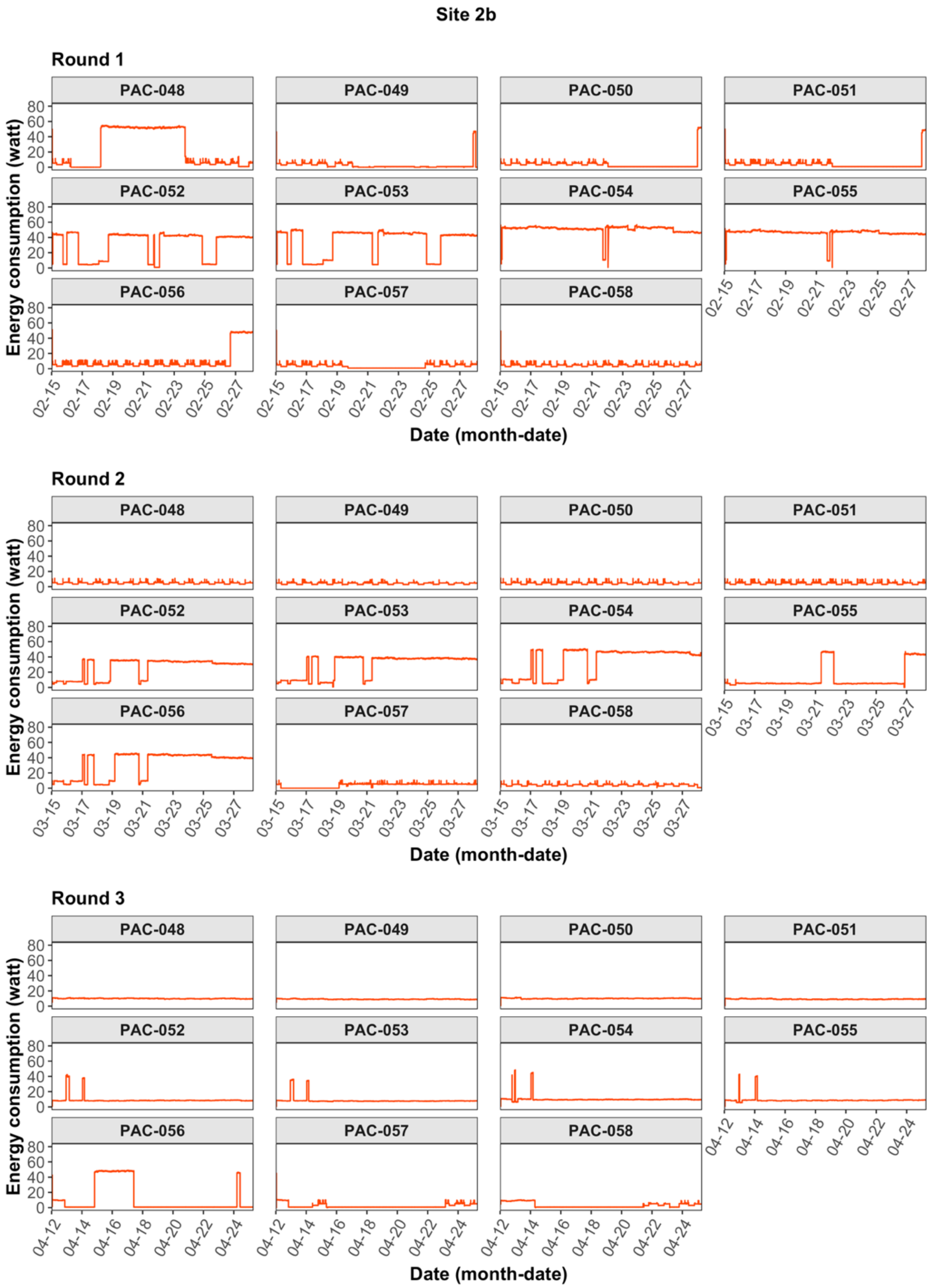

Fig. A.3. Time series of the energy consumption of the PACs deployed at site 2b during three sampling rounds.

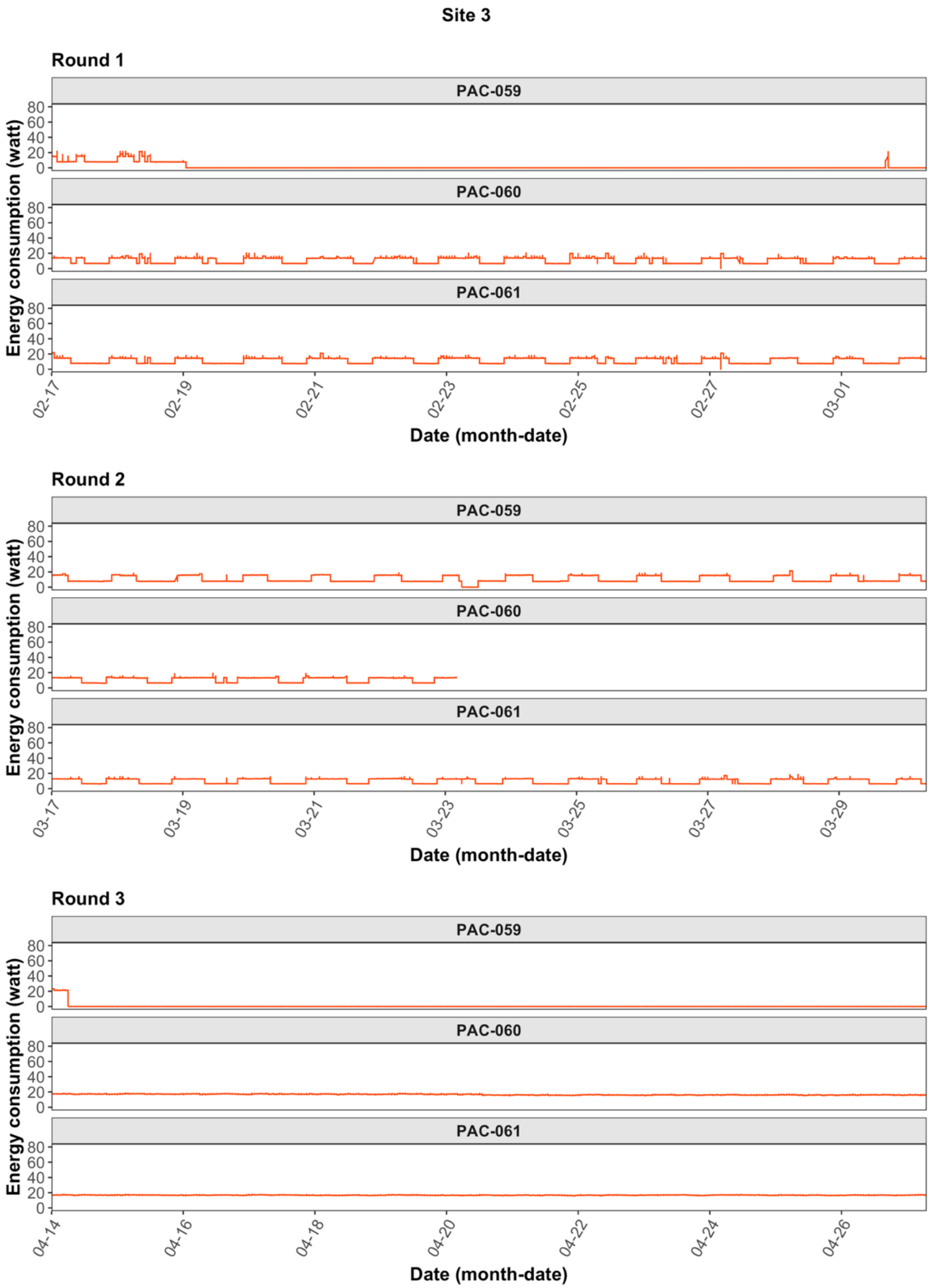

Fig. A.4. Time series of the energy consumption of the PACs deployed at site 3 during three sampling rounds.

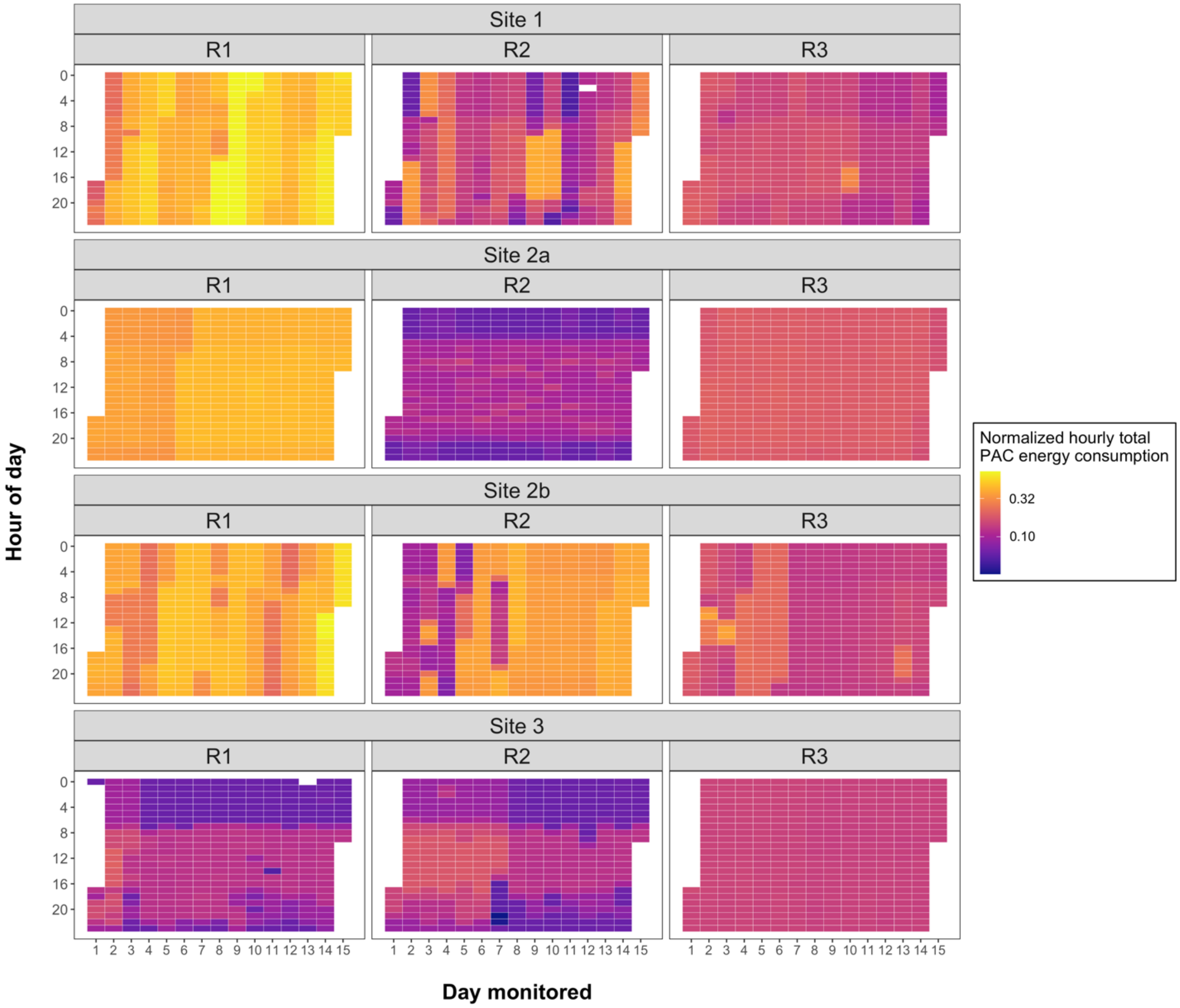

Fig A.5. Heatmap of the normalized hourly total energy consumption of the PACs deployed at each site during three sampling rounds. The normalized hourly total energy consumption at each site was calculated using the equation $\frac{\sum_j^n \sum_i^t H_{ij}}{N \times H_{max} \times t}$, where H_{ij} is the energy consumption (watt) of the jth PAC at time i (minute) at each site; N is the total number of PAC deployed at each site; H_{max} is the maximum possible PAC energy consumption (watt) (i.e., the energy consumption when the PAC operated at Turbo fan speed); t is the time (minute). The normalized total energy consumption was aggregated hourly.

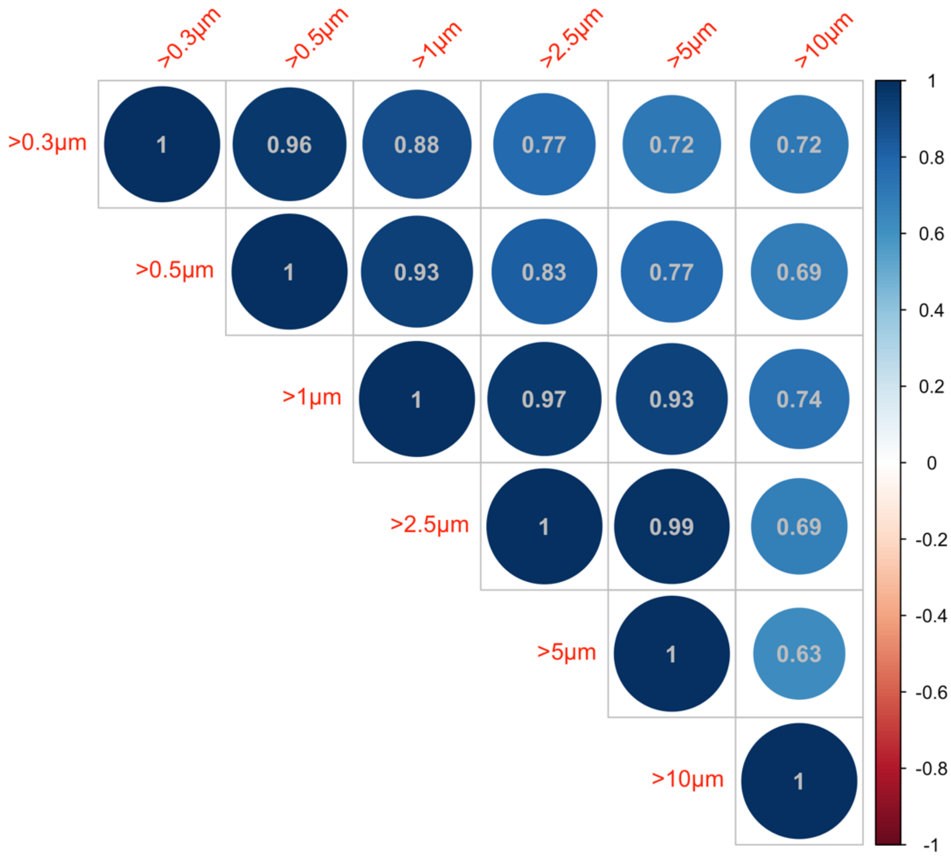

Fig A.6. Pearson correlation between each pair of the raw PurpleAir size bins (all sites pooled together).

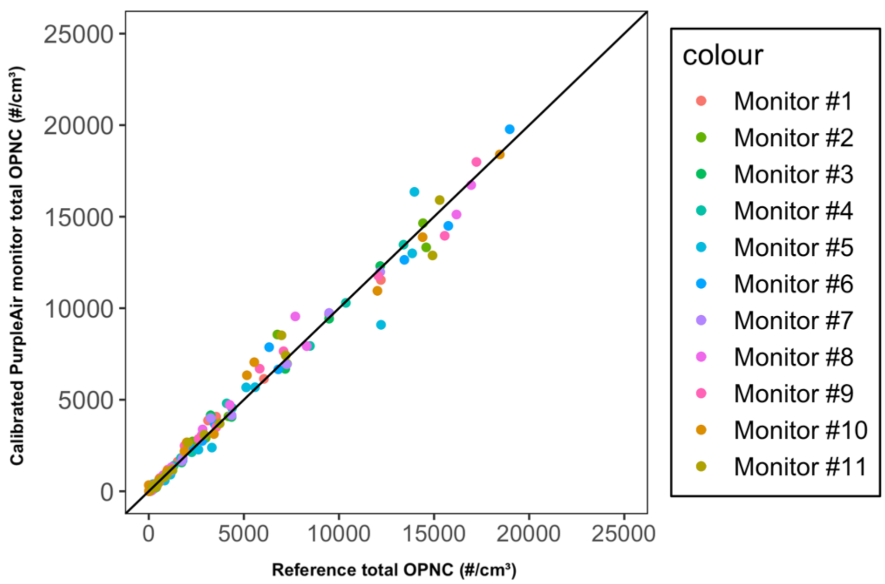

Fig A.7. Parity plot of the reference total OPNC and the calibrated optical particle counter (PurpleAir PA-II-SD) total OPNC. The color represents the data from each PurpleAir monitor. The diagonal line represents the 1:1 relationship between the reference measurement and the calibrated PurpleAir monitor measurement.

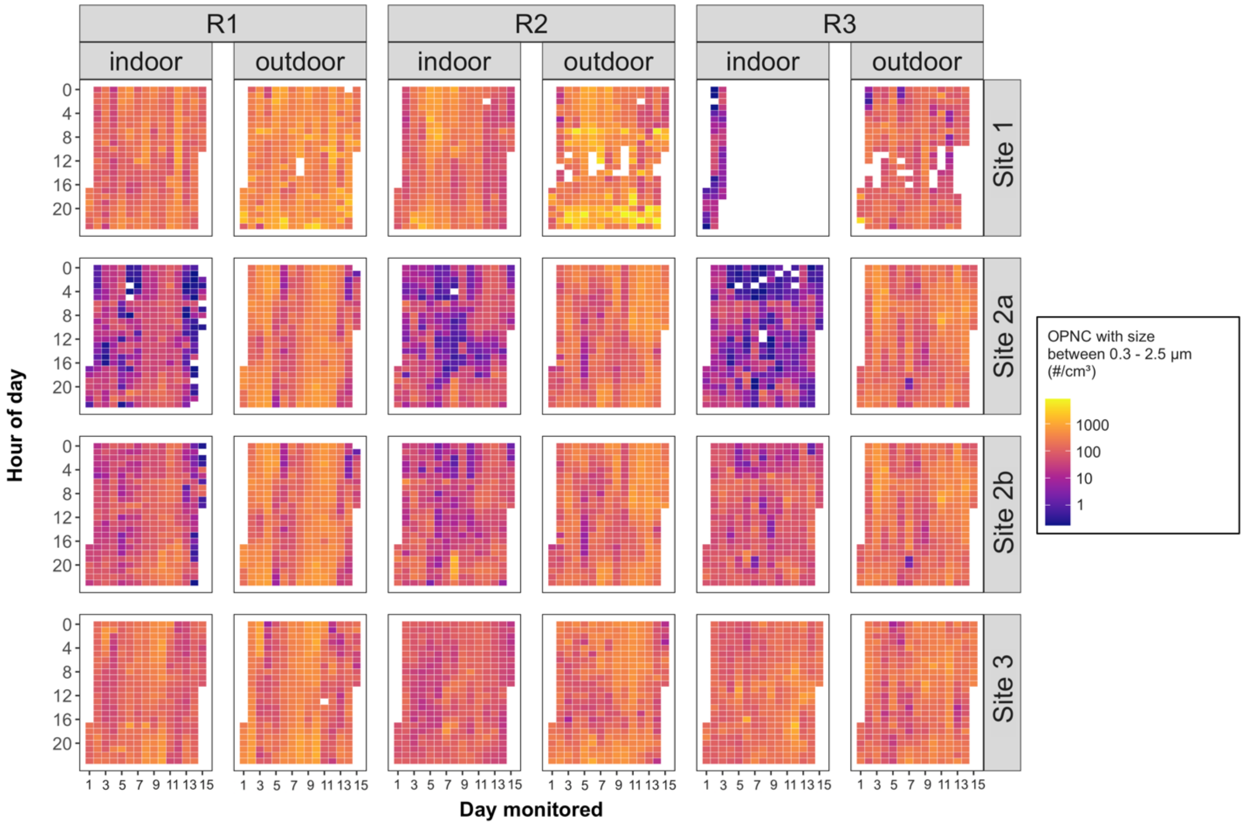

Fig A.8. Heatmap of the indoor and outdoor OPNC with size between 0.3 – 2.5 µm at each site. For sites with multiple indoor monitors (site 1, site 2a, and site 2b), the average concentrations were plotted.

Table A.1. Specifications of the HEPA PACs used in this study.

Model	Winix C535	Winix Tower XQ
CADR (dust/pollen/smoke) [a]	243/236/242	360/405/419
Energy consumption (watt) [b]		
Speed sleep mode	2.8	8.7
Speed level 1	5.4	15.6
Speed level 2	7.3	18.9
Speed level 3	10.4	21.9
Speed Turbo	50.6	76.8

[a] Manufacturer provided information.
[b] Measured.

Table A.2. Calibration coefficients [a] of the optical particle counters (PurpleAir PA-II-SD).

Monitor ID	Slope	R^2	RMSE [b]
Monitor #1	0.43	0.99	272.61
Monitor #2	1.11	0.99	461.40
Monitor #3	1.24	0.99	248.83
Monitor #4	1.15	0.99	197.85
Monitor #5	1.58	0.97	896.25
Monitor #6	1.27	0.99	486.15
Monitor #7	1.32	0.99	192.03
Monitor #8	1.21	0.99	486.16
Monitor #9	1.32	0.99	456.67
Monitor #10	0.45	0.99	450.60
Monitor #11	1.25	0.99	607.67

[a] The calibration model for each monitor was fitted in the form of $C_{TSI\ 3330} = \beta_0 + \beta_1 \cdot C_{PA} + \varepsilon$, where $C_{TSI\ 3330}$ is the particle count with the diameter ranging from 0.3 – 10 μm (#/cm^3) measured by the reference instrument (TSI optical particle sizer model 3330, TSI Inc.); C_{PA} is the raw particle count measured by the continuous optical particle counters (PurpleAir PA-II-SD; PurpleAir) in size bin >0.3 μm (#/cm^3); β_0 is the intercept; β_1 is the slope; ε is the residual. β_0 was set to zero for fitting.

[b] RMSE: root mean square error. The RMSE of the post-calibrated optical particle counters were calculated using the equation $RMSE = \sqrt{\frac{\sum_{i=1}^{N}(C_{TSI\ 3330} - C_{PA_{cal}})^2}{N}}$ where N is the number of observations; $C_{TSI\ 3330}$ is the particle count with the diameter ranging from 0.3 – 10 μm (#/cm^3) measured by the reference instrument (TSI optical particle sizer model 3330, TSI Inc.); $C_{PA_{cal}}$ is the post-calibrated particle count measured by the continuous optical particle counters (PurpleAir PA-II-SD; PurpleAir) in size bin >0.3 μm (#/cm^3).

Table A.3. Summary of the zero $PM_{2.5}$ measurements (0 μg/m^3) and zero total OPNC measurement (0 #/cm^3) based on the PurpleAir monitors' raw data by location and site.

Site	Location	Number of zero measurement (n)	Total number of measurements	% of zero measurement
$PM_{2.5}$				
Site 1	Indoor	9344	24791	37.7 %
	Outdoor	2689	18920	14.2%
Site 2a	Indoor	21867	24707	88.5 %
	Outdoor	6701	23881	28.1%
Site 2b	Indoor	27494	38091	72.2%
	Outdoor	6701	23881	28.1%
Site 3	Indoor	13505	21860	61.8%
	Outdoor	5248	21752	24.1%
Total OPNC (>0.3 μm)				
Site 1	Indoor	0	24791	0.00%
	Outdoor	0	18920	0.00%
Site 2a	Indoor	0	24707	0.00%
	Outdoor	0	23881	0.00%
Site 2b	Indoor	0	38091	0.00%
	Outdoor	0	23881	0.00%
Site 3	Indoor	0	21860	0.00%
	Outdoor	0	21752	0.00%

Table A.4. Summary of the total PAC working minutes monitored at each site.

Site	Round	Number of PAC deployed	Total PAC working minutes monitored	Missing (%)
Site 1	R1	13	256613	0.003
Site 1	R2	13	255824	0.31
Site 1	R3	13	256619	0.0004
Site 2a	R1	10	197400	0
Site 2a	R2	10	197400	0
Site 2a	R3	10	197400	0
Site 2b	R1	11	217140	0
Site 2b	R2	11	217140	0
Site 2b	R3	11	217140	0
Site 3	R1	3	59220	0
Site 3	R2	3	47979	18.9
Site 3	R3	3	59220	0

Table A.5. Summary of the LMER model [a] assessing the effect of PACs operating at Turbo fan speed versus low fan speed (sleep mode and level 1 to level 3) on I/O_{OPNC}. The estimate shows the effect of per 10% change in PAC usage time on I/O_{OPNC}.

Averaging scale	Coefficient	Estimate	Standard error	95% CI [a]
Hourly	β_0	0.593	0.035	0.526 to 0.661 ***
	β_1	-0.035	0.003	-0.041 to -0.028 ***
	β_2	-0.032	0.004	-0.039 to -0.024 ***
Daily	β_0	0.759	0.131	0.508 to 1.007 ***
	β_1	-0.055	0.014	-0.082 to -0.027 ***
	β_2	-0.019	0.017	-0.052 to 0.013
Round	β_0	2.585	0.415	1.700 to 3.361 ***
	β_1	-0.252	0.041	-0.328 to -0.152 ***
	β_2	-0.260	0.048	-0.349 to -0.138 ***

[a] The form of the LMER model is $I/O_{OPNC_{it}} = \beta_0 + \beta_1 T_{PAC-low_{it}} + \beta_2 T_{PAC-Turbo_{it}} + W_i + \varepsilon_{it}$; where β_0 – β_2 are the coefficients of the LMER models; $T_{PAC-low_{it}}$ is the percent time that the PACs were on lower fan speeds, including sleep mode, speed level 1 to level 3; $T_{PAC-Turbo_{it}}$ is the percent time that the PACs were on Turbo fan speed; W_i is the random effect factor, and ε_{it} is the residual.