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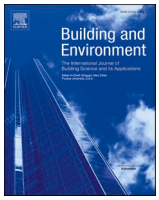

Field and laboratory evaluation of PurpleAir low-cost aerosol sensors in monitoring indoor airborne particles

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ABSTRACT

Due to the adverse health effects of residential air contaminants, there have been increased efforts to monitor indoor particulate matter (PM) concentration using low-cost sensors. However, little information is available about the performance of low-cost sensors in monitoring indoor aerosols. We established a research framework to examine the performance of a widely used low-cost sensor in the U.S. (PurpleAir) along with two research-grade light scattering sensors (Grimm 11-A, Sidepak AM520) in a laboratory chamber and a full-scale residential testbed. The results show that low-cost sensors can yield relatively high intra-model consistency for mass concentrations; however, the consistency is lower when measuring particles >1 μm than research-grade sensors. Regression analysis with research-grade sensors shows higher linearity for mass concentration than number concentration. These trends of mass and number concentrations are likely attributed to the size selectivity of Plantower PMS5003 sensor in PurpleAir that constrains the number fractions of specific particle size bins. The results also show that concentration discrepancy between the low-cost sensor and research-grade sensor increases as indoor mass concentration increases, suggesting that sensor quality assurance is needed for episodic indoor emission events that lead to elevated $PM_{2.5}$ concentrations (>100 μg m^{-3}).

1. Introduction

As people spend much more time indoors than outdoors [1,2], human exposure to indoor particles has been recognized as a major environmental health problem [3]. Human exposure to airborne particles causes adverse health effects such as respiratory and cardiovascular disease [4,5]. Some studies reported that exposure to indoor-originated particles could be much higher than outdoor-originated particles [6,7]. Furthermore, the contribution of indoor-generated particles smaller than 2.5 μm ($PM_{2.5}$) increased during and post-COVID-19 lockdown in the residential environment [8]. However, without monitoring particle concentrations, it is difficult for occupants to identify whether indoor particle concentrations are at a safe level.

Gravimetric Federal Reference Method (FRM) provided by U.S. Environmental Protection Agency (EPA) is a standard method to measure particulate matter (PM). However, FRM requires a longer sampling time than typical indoor particle emission activities. Federal Equivalent Method (FEM) enables higher time resolution (hourly or better), and it is used as a common standard for comparing the measurements with other instruments [9]. However, it requires expensive instruments, a large deployment area, and a longer sampling time, which makes it hard to be deployed in residential environments. In general, research-grade sensors can provide relatively high accuracy; however, they are still expensive and need labor and resources to set up, and some of them generate noises from sampling pumps. Hence, it may not be practical to deploy several research-grade sensors in occupied spaces and collect large amounts of detailed data in buildings. As an alternative to research-grade sensors, low-cost particle sensors have been broadly applied to outdoor and indoor aerosol monitoring [10–17]. However, researchers are still debating the performance and applicability of low-cost sensors for monitoring particles in different environments. Rai et al. [18] examined low-cost sensors under 500 US dollars and reported that a two-stage sensor calibration process is necessary to ensure data quality for measuring $PM_{2.5}$ and PM_{10}. Karagulian et al. [19] pointed out that low-cost sensors showed good agreement with research-grade sensors with a coefficient of determination $R^2 > 0.75$, and the regression slope

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close to 1.0 based on field and laboratory tests; however, calibration and inter-comparison process are recommended for monitoring $PM_{1,}$ $PM_{2.5}$, and $PM_{10.}$

Several other studies examined the performance of low-cost sensors in various environments [20–31]. Among the variety of low-cost sensors, PurpleAir has been widely used because of its advantages that are able to perform real-time monitoring of both particle mass and number concentrations. In addition, it can save time-series particle concentration data on the cloud, which makes the sensor data accessible to users. Due to this capability, previous studies employed PurpleAir for monitoring particles in ambient air at the community and city scales [8, 32–34] and evaluated the performance of PurpleAir sensor comparing with research-grade sensors under laboratory and field experiment conditions [16,32,33,35–39]. However, for indoor environment applications, relatively few studies examined the performance of PurpleAir in monitoring indoor-generated particles [14,24,39]. There are still two major questions remained about the reliability of PurpleAir: 1) Can PurpleAir have good intra-model consistency when measuring indoor-generated particles so that one can compare multiple datasets collected from different buildings? and 2) Can we trust PurpleAir's particle mass and number concentrations that vary with occupant activities in buildings?

Based on this background, the objective of this study is to examine the intra-model consistency and the performance of PurpleAir sensor against research-grade sensors for monitoring three common household indoor particles: 1) incense stick burning, 2) bacon pan frying, 3) outdoor ambient particles derived through open windows. The results will reveal how the particle monitoring performance of PurpleAir varies with indoor source emission type and concentration type (mass vs. number).

2. Methods and materials

2.1. Experimental setup

In this study, we carried out sensor collocation tests to examine the intra-model consistency of PurpleAir as well as evaluation of indoor particle monitoring performance compared to research-grade sensors. Collocation and sensor performance tests were conducted in a laboratory chamber and an apartment testbed. The laboratory chamber has a dimension of 3.4 m × 6.0 m × 2.4 m (width × length × height). All sensors were placed in the middle of the chamber and 1.2 m above the floor (Fig. 1a). Before each test, all sensors were zero-calibrated, and the sample inlets and impactors were cleaned and greased. For the particle emission source, a burning incense stick was placed 1 m away from sensors on the same height and left to burn for 7 min. During the test, all doors of the chamber were closed. Since the volume of the chamber is relatively small (40.8 m^3), air mixings were not used.

The field sensor performance tests were conducted in an apartment testbed with a floor area of 84 m^2 and a volume of 193 m^3. During each test, a heat-recovery ventilator was operating, and all PM sensors were deployed in the living room and placed 1.2 m above the floor (Fig. 1b).

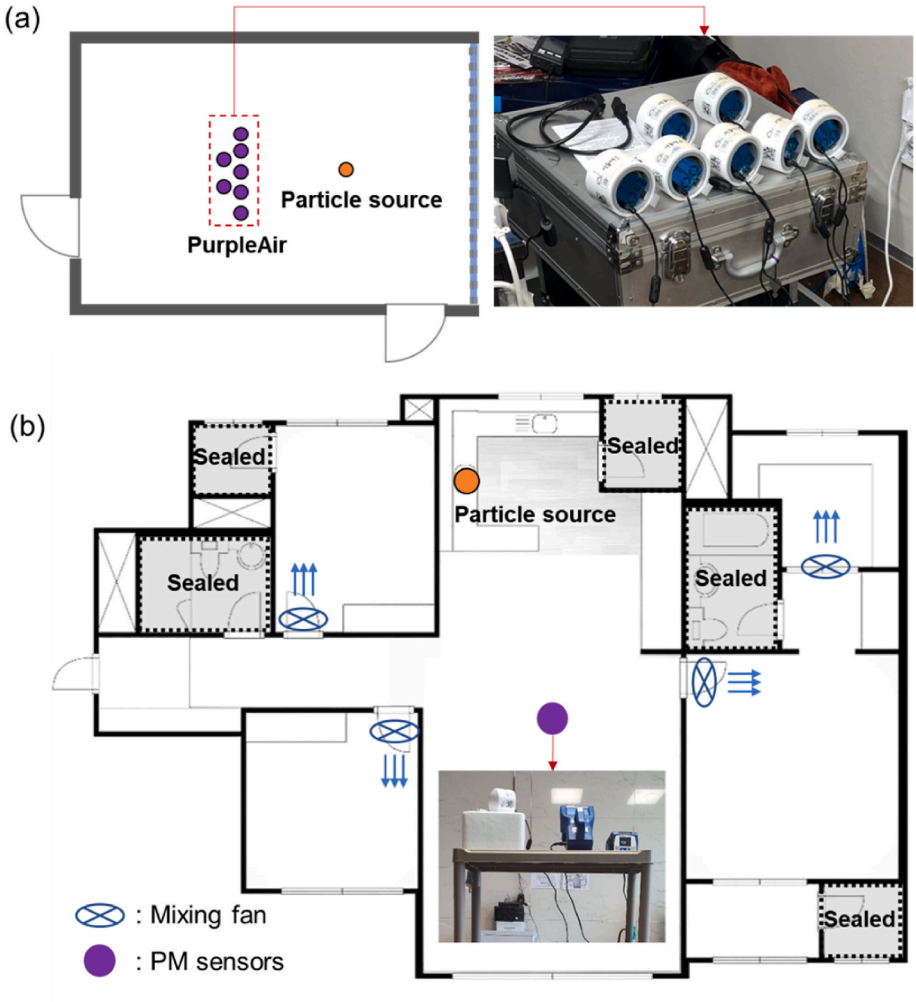

Fig. 1. (a) Description of the collocation test in a laboratory chamber, (b) Description of the sensor performance test in an apartment testbed.

Since the volume of the testbed is relatively large and the particles were generated in the kitchen, there is the possibility that the particle concentration distribution is not uniform, which can cause different particle concentration readings among sensors. To prevent this, four mixing fans were operated with an airspeed of 2 m s^{-1} to make the well-mixed condition, and all sensor inlets were placed right next to each other with a 2 cm distance. In addition, we sealed the duct joints and potential vertical air paths to minimize particle infiltration from the adjacent house units.

The tests were performed with three common household particle sources: 1) incense stick burning, 2) bacon pan frying, and 3) outdoor ambient particles. For incense stick burning, an incense stick was burnt for 7 min in the kitchen and immediately distinguished with wet tissue. For bacon pan frying, 40 g of bacon was baked in a preheated pan on an electric stove with no oil. When the surface temperature of the pan reached 230 °C, bacon was cooked for initial 3-min and turned over for another 2-min. For outdoor ambient particles, living room windows were fully opened (total dimensions of the opening is about 1.8 m × 1 m). Through the open windows, outdoor PM penetrated the apartment, resulting in the indoor PM concentration profile following the outdoor PM concentration profile in a delayed pattern. Each particle generation test was performed for 24 h after the generation except for outdoor ambient particles, for which the concentration was measured for 72 h.

During the tests, the air temperature and relative humidity (RH) were monitored using MCH-383SD. And for the field test, air change rates were measured every 10 min using the tracer gas (SF_6) concentration decay method. SF_6 was released to each room with a rate of 15 L min^{-1} until the concentration reached 50 ppm. Based on the best-fit slope to a plot of the natural log of the ratio of SF_6 concentration to the initial concentration *vs.* time, the air change rate of the testbed was estimated as 0.9 (±0.1) h^{-1}. Table 1 shows the description of the tests and Table S1 summarizes the measured air temperature and RH during the tests.

2.2. Descriptions of particle sensors

The research-grade sensors employed to measure particle mass concentrations were Grimm dust decoder model 11-A (Grimm) and TSI Sidepak personal aerosol monitor AM520 (Sidepak). Grimm, Sidepak, and PurpleAir (PA-II-SD) differ in size and number of particle size bins, features, configurations, and measurement performances. For example, Grimm can monitor particles with the size range of 0.25 μm–32 μm with 31 particle size bins, while PurpleAir measures particles in 6 size bins larger than 0.3 μm. These two sensors can report both number and mass concentrations; however, Sidepak, a photometer, can only report the mass concentration. Since Plantower PMS5003 sensor integrated in PurpleAir provides 2 min-averaged data [32], the sampling intervals for all PM sensors were set to 2-min. PurpleAir has six channels of size bin: ≥0.3 μm, ≥0.5 μm, ≥1 μm, ≥2.5 μm, ≥5 μm, and ≥10 μm. Based on these size bins, we adjusted Grimm's size bins to compare the results. Table 2 summarizes the specification of Grimm, Sidepak, and PurpleAir.

PurpleAir has two Plantower PMS5003 (Plantower.co) sensors inside the unit to check internal precision which provides sensor health and fault detection [40]. Stavroulas et al. [35] reported that PM concentrations measured by these two sensors inside the PurpleAir unit showed negligible differences of < 0.5%. In addition, PurpleAir has two inherent correction factors for mass concentration, CF = ATM and CF = 1, which were calculated using the particle count data with a proprietary algorithm proposed by the PMS5003 laser counter manufacturer [40]. According to the "Using PurpleAir Data" guide, CF = 1 is appropriate for indoor or controlled environment applications, while CF = ATM is a proprietary correction for outdoor applications. Since incense stick burning and bacon pan frying are common indoor sources, CF = 1 was chosen in this study.

Table 2
Summary of sensor specifications.

Sensors	Grimm (Grimm 11-A)	Sidepak (TSI AM520)	PurpleAir (PA-II-SD)
Notation	Grimm	Sidepak	PurpleAir
Detectable size range (μm)	0.25–32	0.1–10	>0.3
Maximum detectable concentration	3.0×10^9 m^{-3} 100 mg m^{-3}	100 mg m^{-3}	1 mg m^{-3}
Volume flow rate ($L \bullet min^{-1}$)	1.2	1.8	0.1
Operating temperature (°C)	0–40	0–50	−40–85
Operating humidity	<95%	<95%	unknown
Light source (wavelength)	Diode Laser (683 nm)	Diode Laser (650 nm)	Diode Laser (680 ± 10 nm)
Uncertainty	5% for whole range	0.001 mg m^{-3}	10% (0.1–0.5 mg m^{-3}) 0.01 mg m^{-3} (<0.1 mg m^{-3})

2.3. Data analysis

Intra-model consistency of an optical light scattering sensor was evaluated based on relative standard deviation (RSD) by comparing the mass and number concentrations of each particle size range as follows:

$$RSD_{(t)} = \sigma_{(t)/}\mu_{(t)} \quad \text{Eq (1)}$$

where $\sigma_{(t)}$ is the standard deviation at given time t and $\mu_{(t)}$ is the average particle concentration of the same model units at given time t.

Furthermore, given that the data from the low-cost and the research-grade sensors could generate a constant or proportional bias [41], regression analysis was performed to investigate the correlation between data from PurpleAir and two research-grade sensors.

3. Results

3.1. Intra-model consistency

Table 3 shows the intra-model consistency of PurpleAir that represents the agreement among different units of the same sensor. The intra-model consistency of six PurpleAir units was evaluated based on the coefficient of determination (R^2) and relative standard deviation (RSD). R^2 value indicates the linearity of pairwise units, while RSD indicates the amount of variation within a dataset; therefore, higher values of R^2 and lower values of RSD represent better intra-model consistency.

Table 1
Description of the collocation and sensor performance tests.

Test	Site	Air mixing	Source	Number of sensors			Test hours
				PurpleAir	Grimm	Sidepak	
Collocation And Sensor performance tests	Laboratory chamber (40.8 m^3)	–	Incense stick burning	6	1	5	18
Collocation test	Apartment testbed (193 m^3)	O	Bacon pan frying	4	–	–	24
Sensor performance test			Incense stick burning	1	1	1 (PM_1)	24
			Bacon pan frying			1 ($PM_{2.5}$)	24
			Outdoor particles			1 (PM_{10})	72

Table 3
Coefficient of determination (R^2) and relative standard deviation (RSD) of mass and number concentrations obtained from the collocation test.

Source	Sensor	PM	R^2			RSD		
			Min	Med	Max	Min	Med	Max
Incense stick Burning (Chamber)	PurpleAir (6 units)	PM_1	0.94	0.98	0.99	0.01	0.03	0.06
		$PM_{2.5}$	0.94	0.99	0.99	0.01	0.03	0.07
		PM_{10}	0.93	0.98	0.99	0.02	0.04	0.06
		0.3–0.5 μm	0.98	0.99	0.99	0.03	0.04	0.05
		0.5–1 μm	0.98	0.99	0.99	0.03	0.04	0.05
		1–5 μm	0.97	0.98	0.99	0.05	0.07	0.10
		5–10 μm	0.40	0.17	0.51	0.49	1.21	1.82
		≥10 μm	0.01	0.13	0.35	0.40	0.78	1.08
	Sidepak (5 units)	$PM_{2.5}$	0.97	0.99	0.99	0.05	0.06	0.08
Bacon pan frying (Testbed)	PurpleAir (4 units)	PM_1	0.97	0.98	0.99	0.01	0.12	0.29
		$PM_{2.5}$	0.96	0.98	0.99	0.01	0.15	0.25
		PM_{10}	0.93	0.94	0.99	0.01	0.32	0.70
		0.3–0.5 μm	0.98	0.99	0.99	0.04	0.06	0.10
		0.5–1 μm	0.98	0.99	0.99	0.03	0.08	0.11
		1–5 μm	0.95	0.92	0.94	0.07	0.30	0.45
		5–10 μm	0.30	0.12	0.44	0.51	1.35	1.89
		≥10 μm	0.01	0.08	0.29	0.42	0.90	1.23

Note: Min, Med, and Max denote minimum, median, and maximum, respectively.

According to the incense stick burning test (Table 3), all mass concentrations of PurpleAir PM_1, $PM_{2.5}$, and PM_{10}, have R^2 values higher than 0.93 and RSD less than 0.07; all units of PurplaAir show similar peak concentrations and the decay patterns (see Fig. S1). These values are comparable to those of Sidepak, which showed $0.97 \leq R^2 \leq 0.99$ and $0.05 \leq$ RSD ≤ 0.08. These results imply that PurpleAir has high intra-model consistency in measuring particle mass concentration from the incense stick burning. It also corresponds with previous studies reporting that particle sensors using Plantower PMS5003 show a good intra-model consistency for the particle mass concentration measurement [20,25,42].

For the bacon pan frying, the particle concentration patterns of four PurpleAir units show a good agreement with an R^2 value greater than 0.93 (Table 3 and Fig. S1). However, unlike the incense stick burning,

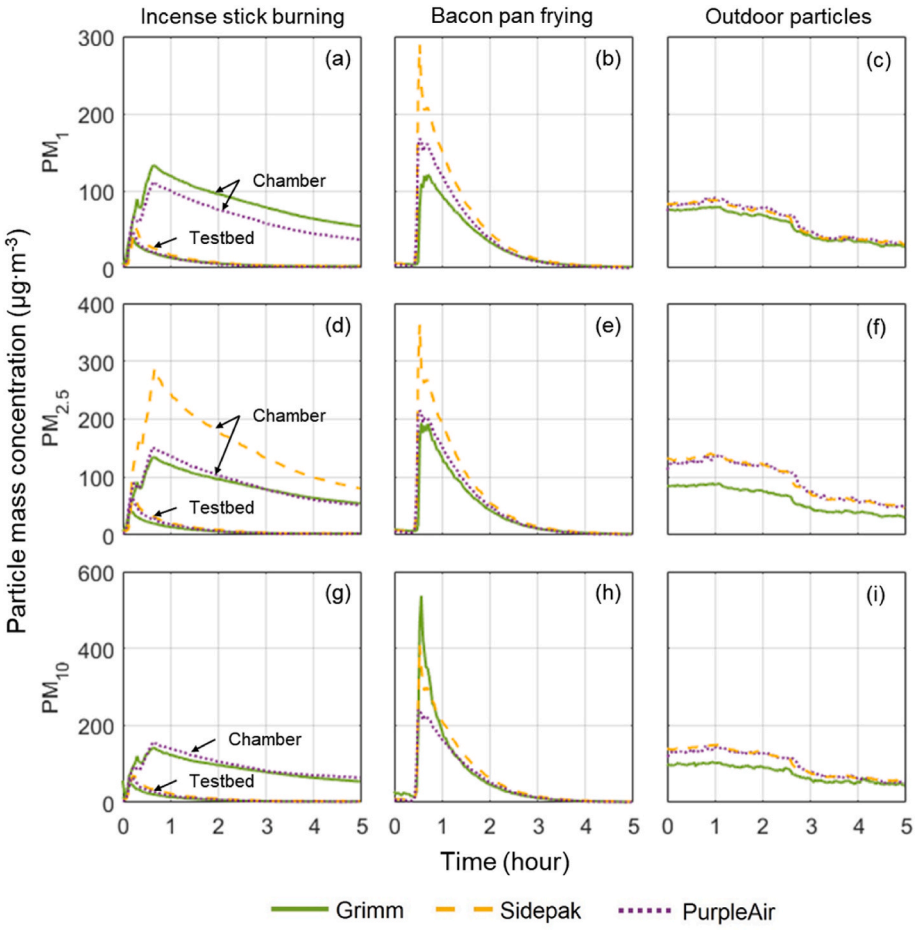

Fig. 2. Time-series particle mass concentration measured by Grimm, Sidepak, and PurpleAir. Note that (a), (d), and (g) contains the concentrations obtained from two tests, incense stick burning tests in the chamber and in the testbed. Note that the concentration of each sensor is the average time-series concentration of all units.

the bacon pan frying test shows a higher RSD ($0.01 \leq RSD \leq 0.70$), and the average RSD of $PM_{2.5}$ and PM_{10} is 5–8 times higher than the incense stick burning (Table 3). Such a trend is more pronounced as the particle size increases.

Intra-model consistency of PurpleAir in monitoring number concentration notably varies with the particle size. For both particle sources, the relatively high intra-model consistency ($R^2 > 0.98$, RSD <0.11) was observed with the particle size range from 0.3 μm to 1 μm. In contrast, the intra-model consistency sharply dropped for the particle sizes larger than 1 μm ($0.01 \leq R^2 \leq 0.99$, $0.05 \leq RSD \leq 1.89$). This trend suggests that particle number concentrations are less consistent among the units for particles larger than 1 μm. Tryner et al. [37] also observed this trend that RSD increases with monitoring coarser particles.

3.2. Particle mass concentration readings

Fig. 2 shows time-series particle mass concentration observed over the emission and decay periods with three different particle sources: 1) incense stick burning, 2) bacon pan frying, and 3) outdoor particles. Each panel illustrates mass concentrations measured by three PM sensors, Grimm, Sidepak, and PurpleAir with a sampling time interval of 2 min. The figure shows that concentration differences among three sensors notably increase as the concentration is above 100 μg m^{-3}, whereas the differences are marginal as the concentration is lower than 100 μg m^{-3}. The incense stick burning test conducted in the testbed shows that $PM_{2.5}$ concentrations of all sensors are less than 70 μg m^{-3}, and they have no notable difference (The peak concentration from the testbed is lower than from the chamber due to the large air volume and the operation of a heat recovery ventilation system that yielded an average air change rate of 0.9 h^{-1}).

In Fig. 2d, with the incense stick burning in the chamber, $PM_{2.5}$ concentration rises higher than 100 μg m^{-3}, and the concentration of Sidepak is about two times higher than that of PurpleAir. A similar trend appears when the particle source is bacon pan frying (Fig. 2b and e). At the peak concentration, PM_1 and $PM_{2.5}$ concentrations of Sidepak are about two times higher than that of PurpleAir. The difference is more pronounced (up to 280%) for PM_{10} concentration, especially at concentrations higher than 100 μg m^{-3} (Fig. 2h). With outdoor-infiltrated particles, PurpleAir and Sidepak consistently show higher concentrations than Grimm (Fig. 2f and i). The particle mass concentration monitored by each sensor varies with the concentration range, particle size, and source type. This is mainly because they affect the detection efficiency of the sensor that operate based on a light scattering method [43,44].

However, according to Table 4, PurpleAir yields the mass concentration close to Grimm for PM_1, $PM_{2.5}$ and PM_{10} concentration range of 10–100 μg m^{-3}; the mean absolute error is less than 9.7 μg m^{-3} for the concentration of 10–100 μg m^{-3}, while its range is 20.3–30.0 μg m^{-3} for the concentration >100 μg m^{-3}. This corresponds with previous study results that the concentration of PurpleAir is highly correlated to that of research-grade sensors, but the discrepancy becomes larger as the concentration increases [10,12,13]. This result implies that during episodic indoor emission events where the particle mass concentration increases dramatically (over 100 μg m^{-3} for $PM_{2.5}$), proper performance evaluation and quality control are needed as PurpleAir readings can deviate from those reported by research-grade sensors.

Fig. 3 shows time-series particle number concentrations for five different particle size bins measured by PurpleAir and Grimm. The figure indicates that the agreement between PurpleAir and Grimm in monitoring particle number concentration notably varies with the particle size and source. For bacon pan frying, PurpleAir agrees well with Grimm in monitoring particles in the range of 0.3 μm–1 μm, with a maximum difference of 33% (Fig. 4c and f). However, for the incense burning, relatively large differences up to two orders of magnitude were observed between PurpleAir and Grimm (Fig. 4a, d, and g). Regardless of the particle source type, unreasonably large discrepancies were observed for particle sizes larger than 5 μm. This result is in line with several previous studies reporting that the accuracy of PurpleAir significantly decreases for coarser particles due to the low detection efficiency [16,37,42,44]. Even though the two particle sensors share a similar working principle, the light scattering with a diode laser, the sensing performances for particle number concentrations notably vary with the particle size, concentration range, and source type. These patterns suggest cautions in reporting number concentrations associated with indoor emission sources based on PurpleAir monitoring data, especially for particle sizes larger than 1 μm.

3.3. Comparison of particle concentrations of PM sensors

Fig. 4 shows the correlation between particle mass concentrations of PurpleAir and two research-grade sensors (Grimm and Sidepak). Table S2 provides detailed information about regression slopes, intercepts, and coefficients of determination (R^2). Note that the concentration of PurpleAir is on the y-axis, so the slope less than one or higher than one means that PurpleAir underestimates or overestimates the concentration, respectively, compared to research-grade sensors. The figure reveals that the particle mass concentration of PurpleAir yields fairly high linearity ($R^2 \geq 0.86$, Table S2) with that of Grimm and Sidepak for all particle sizes and source types. However, according to Fig. 4e, the linearity between the concentrations of PurpleAir and Grimm decreases sharply when PM_{10} concentration is higher than 100 μg m^{-3}, and the regression fit is rather logarithmic. This result has been previously observed with monitoring outdoor-generated particles that Plantower PMS5003 sensor tends to report lower particle mass concentration than research-grade sensors as the concentration increases [21,25,31]. We also found that PurpleAir tends to underestimate indoor PM_{10} concentrations higher than 100 μg m^{-3}.

Fig. 5 illustrates the correlation between particle number concentrations of PurpleAir and Grimm, and the detailed information about regression slopes, intercepts, and coefficients of determination (R^2) are described in Table S3. It is apparent that the linearity of particle number concentration highly varies relative to particle mass concentration with the particle size and source type. For the particle size of 0.3 μm–0.5 μm, PurpleAir underestimates the particle number concentration compared to Grimm, and for the particle size of 0.3 μm–1 μm, it overestimates the particle number concentration (Fig. 5a and b). When the particle size is greater than 1 μm, the particle number reading of PurpleAir varies with the particle source type (Fig. 5c). Moreover, even with the same particle source, the regression slopes show a noticeable difference depending on the particle size. When the particle size is small (0.3 μm–1 μm), the

Table 4
Mean absolute and relative errors of PurpleAir compared to Grimm.

	Mass concentration range					
	<10 μg m^{-3}		10–100 μg m^{-3}		>100 μg m^{-3}	
	Absolute error (μg•m^{-3})	Relative error (%)	Absolute error (μg•m^{-3})	Relative error (%)	Absolute error (μg•m^{-3})	Relative error (%)
PM_1	2.2	51	7.3	11	20.3	18
$PM_{2.5}$	2.3	36	9.4	7	29.4	12
PM_{10}	3.5	37	9.7	9	30.0	16

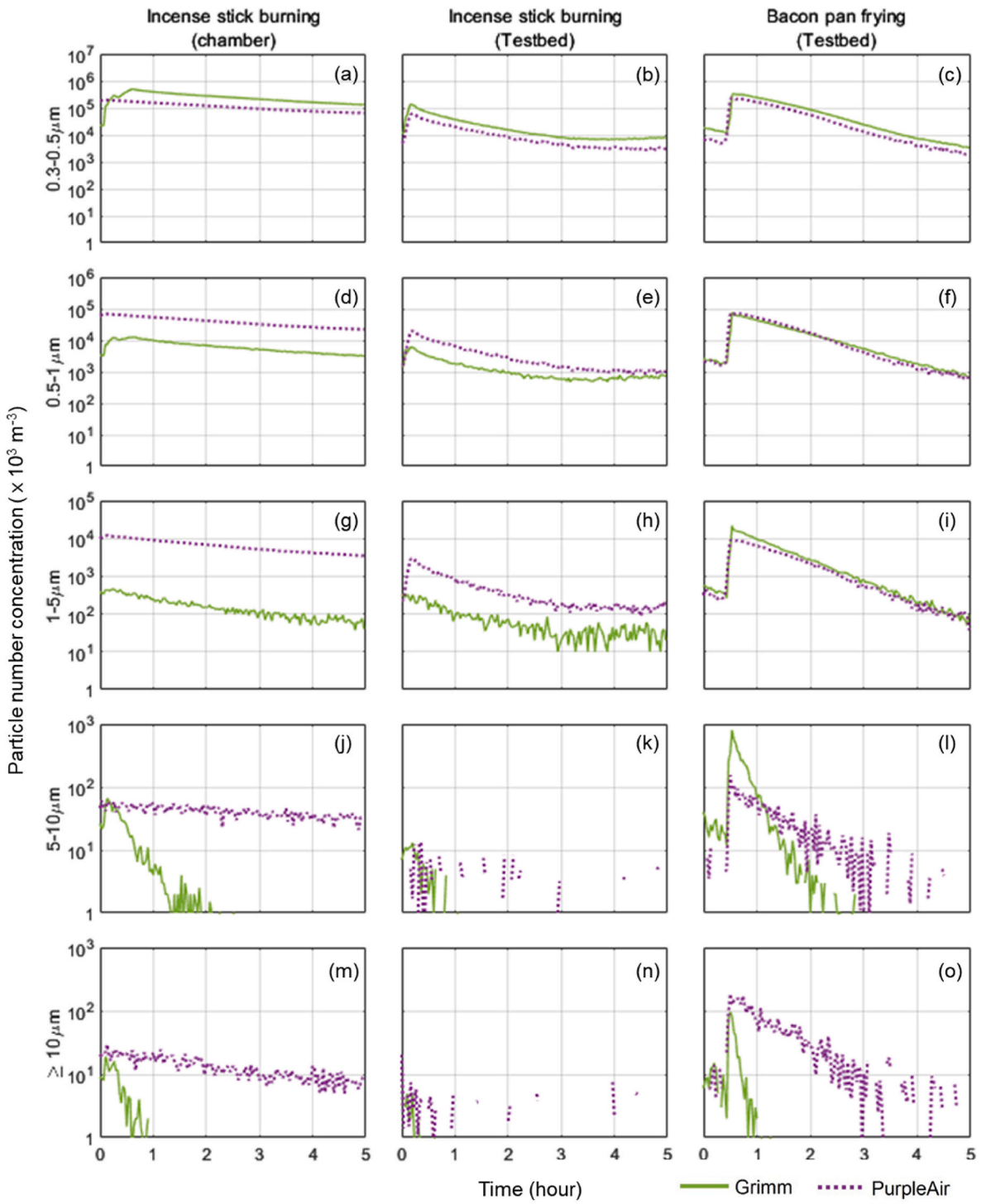

Fig. 3. Time-series particle number concentration measured by Grimm and PurpleAir. Note that the concentration of Purple is the average time-series concentration of all units. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

incense stick burning tests in the chamber and testbed yield a relatively similar trend, while for particles greater than 1 μm, the concentration from the chamber shows 3.5 times higher regression slop than from the testbed (Table S3). These results suggest that when reporting PurpleAir monitoring data, particle mass concentrations are better correlated to research-grade sensors and more consistent than particle number concentrations.

3.4. *Effect of particle size fraction*

Fig. 6 illustrates the particle size fraction of mass and number concentrations reported by Grimm, Sidepak, and PurpleAir in the present study. Grimm shows the different particle size distribution with the particle source, while Sidepak and PurpleAir show a relatively constant size distribution regardless of the particle source (Fig. 6a). Although all sensors use the light scattering method for estimating the particle concentration, specifically, Grimm and Sidepak use different methods; Grimm is a spectrometer and Sidepak is a nephelometer (also known as

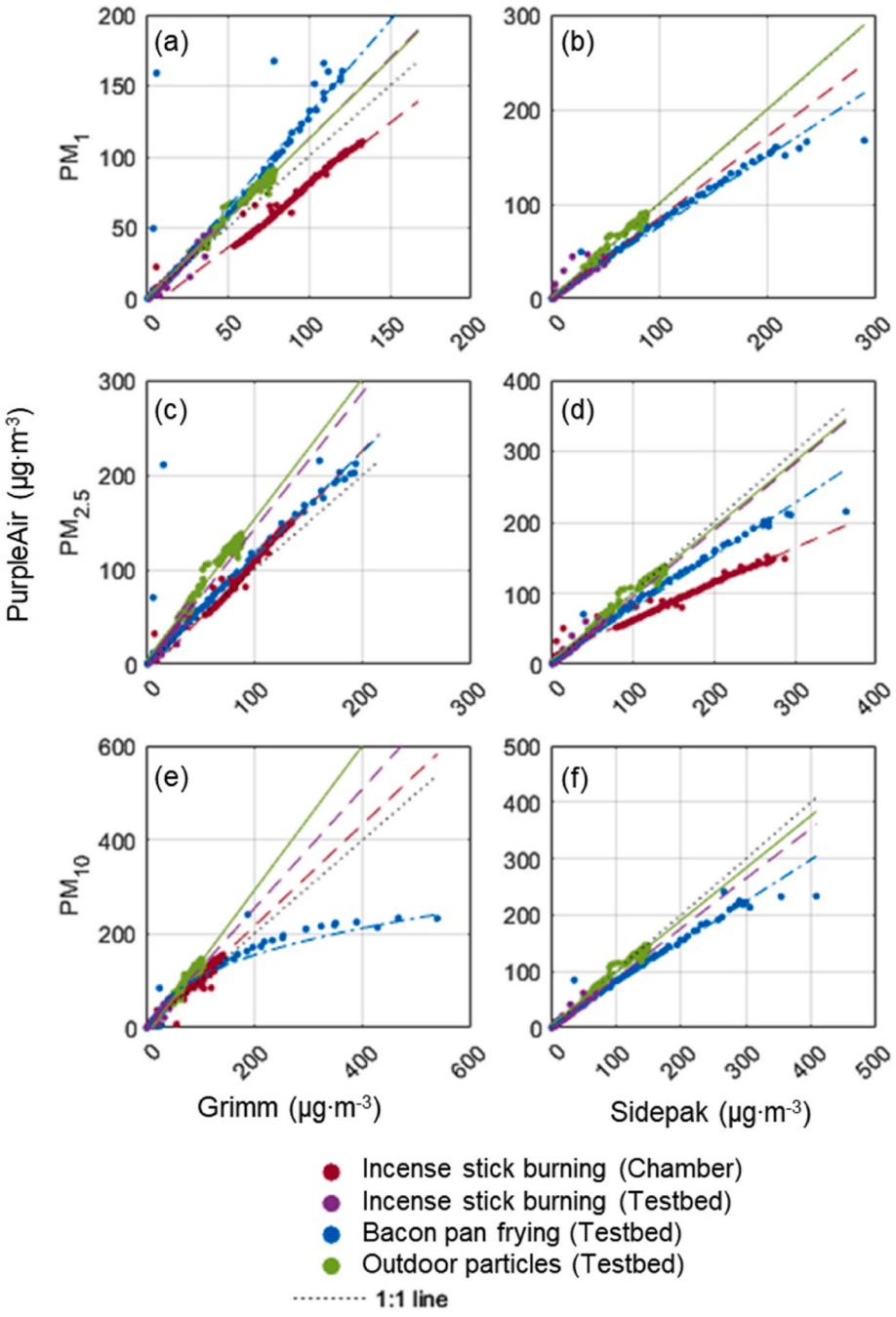

Fig. 4. The correlation between particle mass concentrations of PurpleAir and two research-grade sensors, Grimm and Sidepak.

photometer). Since Plantower PMS5003 in PurpleAir is more alike the nephelometer than the spectrometer [44,45], PurpleAir and Sidepak show the similar mass concentration fraction.

For particle number fraction, the same trend is shown (Fig. 6b); particle number concentration fraction for 0.3 μm–0.5 μm measured by Grimm changes with the particle source type, ranging from 81% to 95%. However, the concentration fraction of PurpleAir was fairly steady regardless of the particle source type, varying between 72% and 74%. The number concentration fractions of other size bins were also consistent: 23%–24% for 0.5 μm–1 μm, 2.6%–5.3% for 1 μm–2.5 μm, and less than 1% for particles larger than 2.5 μm. However, the number fraction of Grimm varied with particle size range: 4.9%–15% for 0.5 μm–1 μm, 0.26%–2.9% for 1 μm–2.5 μm, and less than 1% for particles larger than 2.5 μm. This result resonates with previous studies. He et al. [46] tested Plantower PMS5003 sensors to measure ammonium sulfate polydisperse particles in a chamber and found out that PMS5003 always shows a consistent particle size distribution, regardless of the actual particle size distribution. Tryner et al. [37] also reported the similar result that Plantower PMS5003 sensors consistently reported about 70% of particles in a size range of 0.3 μm–0.5 μm with polystyrene latex particles.

4. Discussion

In this study, we conducted collocation and sensor performance tests to assess the feasibility of PurpleAir in monitoring indoor airborne particles. According to the collocation test, PurpleAir shows a good intra-model consistency when measuring the particle mass concentrations from the incense stick burning. This result is in line with previous studies that low-cost sensors have high intra-model consistency in

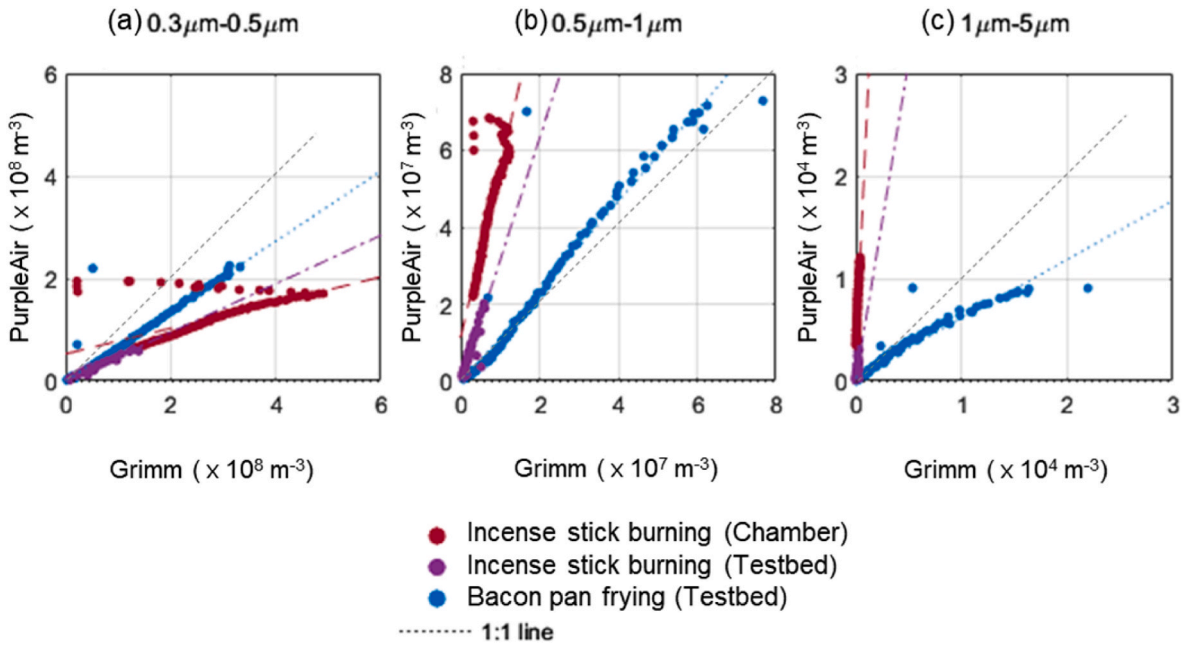

Fig. 5. The correlation between particle number concentrations of PurpleAir and Grimm.

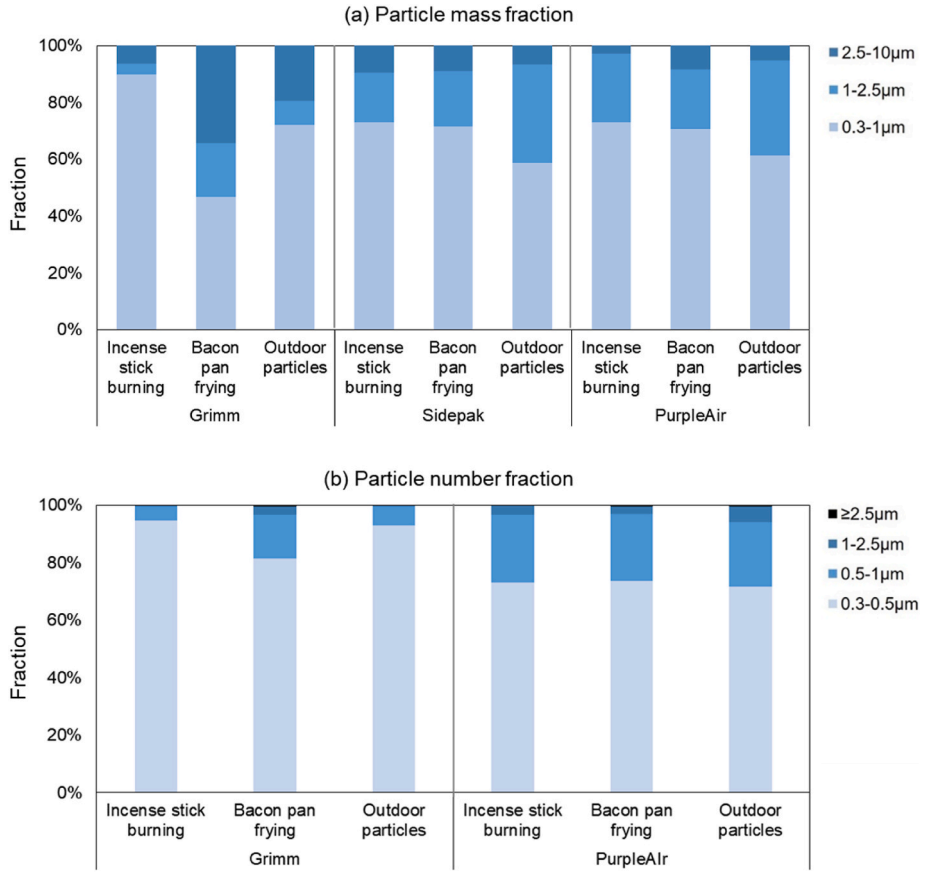

Fig. 6. Particle size fraction reported by Grimm, Sidepak, and PurpleAir. (a) Particle mass fraction, (b) Particle number fraction.

measuring ambient and indoor-generated particles [22,23,25,29,31,43]. However, our test reveals that the consistency among PurpleAir units decreases for particle sizes >1 μm, especially for bacon pan frying. This is mainly because two particle sources, incense stick burning and bacon pan frying, generate particles with different size distributions. According to the measurement by Grimm, the bacon pan frying generates about 100 times more particles (>1 μm) than the incense stick burning (Fig. S2). Considering the low detection accuracy for measuring particles >1 μm [16,28,37,44], PurpleAir can report inconsistent particle number concentrations when measuring high number

concentrations of particles >1 μm, which can influence the readings of $PM_{2.5}$ and PM_{10}.

According to the sensor performance test, PurpleAir shows fairly good agreements with Grimm and Sidepak in monitoring indoor particle mass concentration (Fig. 4 and Table S2). In this study, we used CF = 1, the correction factor for the mass concentration, and our results suggest that it is suitable for measuring indoor-generated particles. Likewise, Tryner et al. [37] reported that CF = 1 shows good linearity with a research-grade sensor. However, this correction factor in Plantower sensor has a critical drawback; it arbitrarily replaces the low concentrations with zero [16,39]. Due to such limitation, the accuracy of reading the mass concentration considerably decreases when the concentration is low (i.e., $PM_{2.5} < 40$ μg m^{-3}) [22,25,31,39]. Moreover, as the concentration increases, the linearity between PurpleAir and Grimm becomes weaker (Fig. 4). This trend is pronounced for $PM_{2.5}$ and $PM_{10} > 100$ μg m^{-3} with the bacon pan frying, which is mainly because the bacon pan frying generates more particles >1 μm where the detection efficiency of Plantower sensor is less than 15% [44]. On the other hand, Plantower sensor installed in PurpleAir has a higher sensitivity for particles <1 μm. Accordingly it consistently reports that 70% fraction of measured particles is 0.3 μm–0.5 μm as shown in Fig. 6b, [20,37,46]. Due to the predetermined size selectivity of Plantower sensor, some studies recommended not to use it for measuring PM_{10} [16,44].

To improve the accuracy of PurpleAir, new algorithms for the correction factor have been developed such as Alternative method (ALT) based on the particle number concentration [16], correlation equation including the air temperature and RH [32,42,47], and machine learning methods [48,49]. These algorithms would be appropriate for the conditions where the particle size fraction and environmental factors are relatively stable [11,42]. Meanwhile, the air temperature and relative humidity of indoor environments such as a residential building can change with time [50,51], and even occasionally, relative humidity exceeds 80% where Plantower sensor frequently reports errors [22,31]. Furthermore, they have a variety of particle sources with different particle size distributions and compositions that affect the detection efficiency of Plantower sensor [29,37]. For example, gas or electric stove mainly generates ultrafine particles [52], and human activities such as making a bed and walking generate much larger particles >3 μm [53,54]. Therefore, sensor quality assurance is necessary for the research purpose to measure particles associated with episodic indoor particle emissions.

Taken together, PurpleAir is useful for monitoring the mass concentration of indoor airborne particles because of its reasonable agreement with research-grade sensors. Our results indicate that PurpleAir yields fairly reliable data for $PM_{2.5} < 100$ μg m^{-3}. However, its detection efficiency decreases for particles >1 μm, and environmental conditions influence its performance. Also, our results reveal that PurpleAir needs careful calibration with research-grade sensors to ensure accuracy for measuring high concentrations (i.e., $PM_{2.5} > 100$ μg m^{-3}), especially for indoor environments where episodic source emissions occur.

5. Conclusions

In this study, we evaluated the performance of a widely used low-cost PurpleAir sensor for monitoring indoor particles based on the comparison with two other research-grade sensors with the light-scattering method (Grimm and Sidepak). The tests involved three common residential particle sources: 1) incense stick burning, 2) bacon pan-frying, and 3) outdoor particle infiltration through the open windows. PurpleAir showed high intra-model consistency throughout all the mass and number concentrations, although it becomes weak when measuring number concentrations for particles >1 μm. The higher the mass concentration, the larger the concentration difference between PurpleAir and other sensors was observed. This result implies that for episodic indoor emission events where higher concentrations of $PM_{2.5}$ and PM_{10} (>100 μg m^{-3}) are measured, proper performance evaluation and quality control are needed as PurpleAir readings notably deviate from those of the reference sensors. While the linearity of concentration readings of PurpleAir against other sensors shows relatively high R^2 values for mass concentration, using particle number concentrations measured by PurpleAir does not seem practical or possible for evaluating indoor exposure to airborne particles.

Note that this study mainly focused on only three types of anthropogenic emissions, i.e., two indoor sources (bacon frying in pan and incense burning) and the outdoor air pollution. Future studies are warranted to examine the sensor performance for other common indoor aerosol emission sources considering building operating conditions in schools and offices [54,55].

CRediT authorship contribution statement

Seongjun Park: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **Shinhye Lee:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Myoungsouk Yeo:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Conceptualization. **Donghyun Rim:** Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110127.

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