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Characterizing Particle Number Size Distributions and Source Contribution for Public Elementary School Classrooms in Bangkok

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Abstract

This study provides crucial information on indoor air pollution in public elementary schools in Bangkok, highlighting the substantial impact it has on the health and learning conditions of students, particularly in view of the city's rapidly urban expansion. The research examines particle size distributions (PSD) in four urban schools using the scanning mobility particle sizers (SMPS) and the optical particle sizers (OPS) to cover particle size range of 10 nm to 10 microns. Measurement covered class hours on weekdays and experiments on the weekends. Throughout the study, outdoor particle number concentration (PNC) was significantly higher than indoor levels. On weekdays, the indoor 1-hour mean PNC at Site S4 reached 23,182 cm^{-3} as a highest level among others, classified as a High PNC level according to WHO good practice guidelines. This suggests substantial internal sources, inadequate ventilation, and the impact of nearby traffic and school activities. Similarly, during weekend measurements, Sites S1 and S3 also reached High PNC levels, with concentrations of 27,663 cm^{-3} and 29,534 cm^{-3}, respectively. Peaks in PNC were directly linked to the use of cleaning products containing volatile chemicals, underlining the pronounced impact of these activities on indoor air quality. The weekday indoor particle number size distribution (PNSD) exhibited a single-mode distribution, significantly influenced by routine class activities and student movements. Over the weekend, the indoor PNSD across all sites showed fluctuations corresponding to various experimental setups involving changes in ventilation and cleaning activities. This study underscores the necessity of strategic indoor air quality management in schools, aiming to reduce exposure to high PNCs, improve indoor air quality in classrooms, and provide better educational settings for children in increasingly urbanized regions. Effective strategies might include enhanced ventilation, controlled cleaning practices, and real-time monitoring of PNC and PNSD to maintain a healthy educational environment.

Keywords : indoor air quality; particle size distribution; ultrafine particle; urban schools; air pollution mitigation; environmental health

Introduction

The rapid expansion of cities like Bangkok brings numerous social and economic benefits but also creates environmental challenges. Among these, air pollution poses a substantial threat affecting the health of millions of people. For the context of urban schools, the combination of pollution from external sources and insufficient ventilation in public schools has become crucial [1]. In addition, the World Health Organization (WHO) emphasizes the importance of indoor air quality since it connects to several public health issues [2]. As per guidance of United Nations Sustainable Development Goals (UN SDGs), namely intending to contribute to the well-being (Goal 3), education quality (Goal 4), and sustainability (Goal 11) of urban areas, inside school air quality management activities plays critical role. Among the air quality issues, fine particulate matter still remains for a challenge; on top of that, ultrafine particles (UFPs) deserve a spotlight. Due to the ability of UFPs in evading the immune system, it can lead to serious respiratory diseases [3]. Up to now, the lack of comprehensive guidelines regarding UFPs highlights a significant lapse in our efforts to combat air pollution, especially in small rooms like school classrooms. Since significant amounts of time are spent by students and teachers inside classrooms, the pollutants in the air might disrupt health and learning capabilities [4]. To provide the baseline information to support decisions to tackle UFPs in Bangkok's public elementary school classrooms, first we must determine the concentration of these particles.

Understanding the conditions that lead to poor indoor air quality is essential for establishing effective risk-mitigation measures, especially the schools that require immediate action. Even though studies on indoor particle number size distribution. in schools have been conducted in various locations like Hanoi, Vietnam [5], Brisbane, Queensland, Australia [6], China [7], and Korea [8], no previous data has been recorded for Bangkok's schools hence there is lacking of such data relavant to distinct meteorological, infrastructural, and urban development patterns of Bangkok.

In Bangkok, most previous research and monitoring infrastructure have focused on ambient air quality while there has been a lack of studies investigating the air quality within school buildings. The present study therefore aimed to provide critical indoor pollution data in Bangkok's public elementary schools. By means of identifying sources of indoor pollution, assessing the influence of outdoor air quality, and analyzing the impact of environmental conditions on particle levels, the results could favor not only to illuminate the current state of classroom air quality but also to support decisions for actionable strategies to ameliorate. Our study could eventually contribute to healthier and supportive learning environments for vulnerable children of Bangkok in line with aforementioned SDGs.

Methodology

Sampling Sites: The study was conducted in Pathumwan District, a central business district in Bangkok. Four elementary schools, namely, Wat Chaimongkol School (S1), Wat Pathum Wanaram School (S2), Wat Daung Khae School (S3), and Suan Lumphini School (S4), were chosen based on their varied urbanization features and proximity to high-traffic roads as shown in Figure 1. The classrooms chosen for the study are kindergarten level equipped with air conditioner to keep cool and allow closed room condition especially during high $PM_{2.5}$ days. These rooms are also equipped with air treatment devices donated to the schools. The devices operate by releasing atomized water particles containing hydroxyl radicals to eradicate viruses and bacteria. Site S1, S2, and S3, each have an air treatment device installed on the ceiling. Site S4 has the same technology with a different setup, an air conditioner integrated with the disinfecting particle generating device.

Instrumentation: The Scanning Mobility Particle Sizers (SMPS) TSI 3910 was used to measure particle size distribution covering a size range of 10 nm to 420 nm across 13 size channels. Secondly, Optical Particle Sizers (OPS): The TSI 3330 measured particles within the 300 nm to 10,000 nm range. Next, TESTO 440 Flow Meter was positioned near the classroom door to measure the air flow into or out of the classroom [9]. An airthinX sensor for measuring temperature, pressure, humidity, $PM_{2.5}$ and PM_{10} was installed inside the classroom and employed for the outdoor measurement simultaneously [10]. All instruments used in this study are demonstrated in Figure 2.

Measurement conditions: Measurements were conducted inside and outside the classrooms simultaneously. Figure 3 depicts the measurement spots which are similar for all sites. The study included weekdays and weekends measurements under two different settings. During weekdays, we conducted measurement during regular school hours to capture the typical air quality conditions without any intervention. However, weekend measurements were conducted during the same hours without any class activities but with varying experimental conditions to examine air quality under varying influencing factors, namely, air conditioning, electric ceiling fan, ventilation (windows and doors opening), cleaning activity, and, finally, the use of air treatment system. Table 1 tabulates the 12 experimental setups conducted to investigate the effects of influencing factors on indoor air quality.

(a)

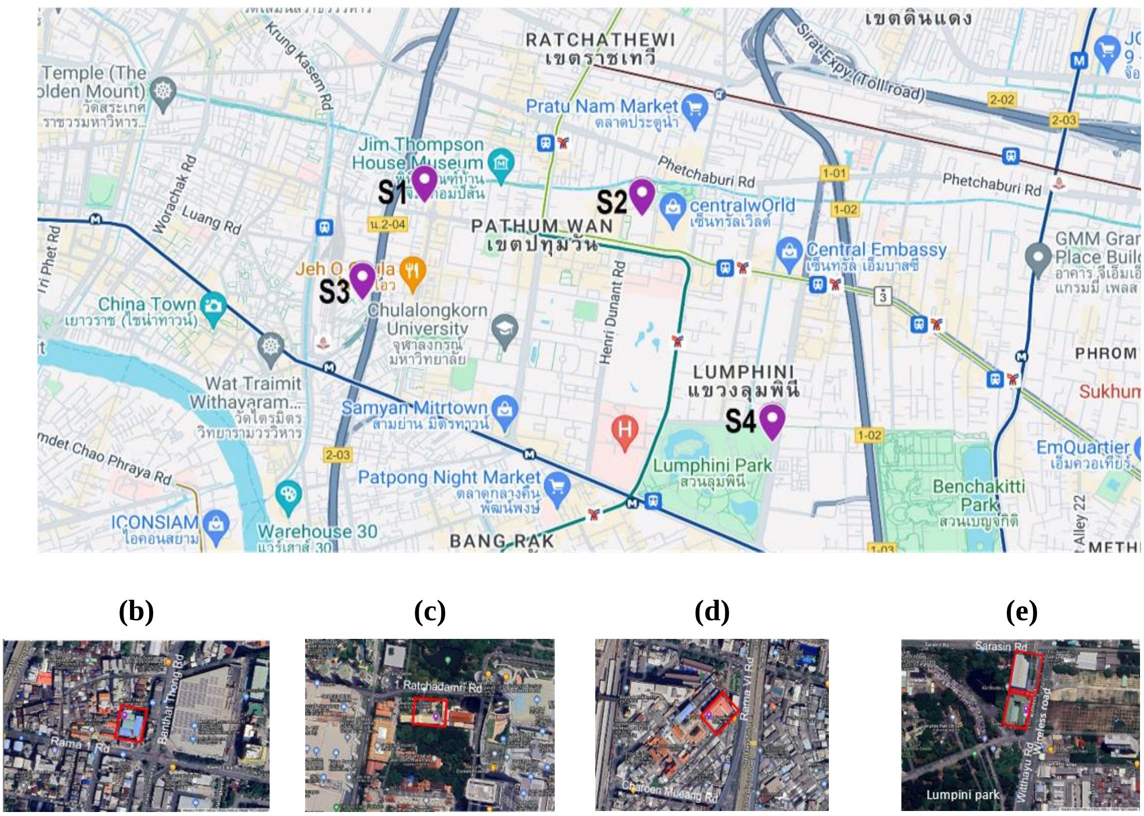

Figure 1 Map of sampling sites (a) overview map, (b) S1-Wat Chaimongkol School, (c) S2-Wat Pathum Wanaram School, (d) S3-Wat Daung Khae School, and (e) S4-Suan Lumphini School. The red inserts indicate school buildings and the placemarks identify the classroom location

(a) (b) (c) (d)

Figure 2 Instruments used for the onsite measurements: (a) Scanning Mobility Particle Sizer (SMPS, Model 3910 TSI), (b) Optical Particle Sizer (OPS, Model 3330 TSI), (c) an air flow meter (TESTO 440) and (d) AirthinX sensor

(a) (b)

Figure 3 Measurement setup for a) outside and b) inside of the classrooms

Table 1 Experimental setup for weekend measurements

Condition	Fan	Air condition	Window and door	Cleaning	Air treatment
C1	On	Off	Open	No	On
C2a	Off	Off	Open	No	On
C2b	Off	Off	Open	Yes	On
C3	On	Off	Open	No	Off
C4a	Off	Off	Open	No	Off
C4b	Off	Off	Open	Yes	Off
C5	On	On	Closed	No	Off
C6a	Off	On	Closed	No	Off
C6b	Off	On	Closed	Yes	Off
C7	On	On	Closed	No	On
C8a	Off	On	Closed	No	On
C8b	Off	On	Closed	Yes	On

Results and Discussion

Classroom weekday measurement results

The 1-hour average of outdoor particle number concentration (PNC) in the weekdays revealed 11.46 x 10^3 #/cm^3, 9.86 x 10^3 #/cm^3, 17.59 x 10^3 #/cm^3, and 13.33 x 10^3 #/cm^3, at sites S1, S2, S3, and S4, respectively. And then, the 1-hour mean of indoor PNC was 10.22 x 10^3 #/cm^3, 16.14 x 10^3 #/cm^3, 18.71 x 10^3 #/cm^3, and 23.18 x 10^3 #/cm^3 in each respective site. According to the WHO global air quality guideline, the indoor PNC at site S4 exceeded the high PNC level of 20,000 #/cm^{-3} for 1-hour mean value. This high PNC can be a result of students having lunch in the classroom followed by cleaning activities with some use of cleaning products; unlike other sites where students went for lunch outside the classrooms. Table 2 shows the statistics of outdoor and indoor total PNC in each school during the weekday measurement. The weekend results are not shown as the experiments do not represent actual PNC that students usually are exposed to. The correlation analysis of indoor and outdoor PNC during the weekdays was conducted and moderate correlations were observed in S1, S3 and S4 with the coefficients, R^2 of 0.47, 0.31 and 0.66, respectively. However, S2 revealed low correlation (R^2 = 0.04) because the outdoor measurement was in a building corridor with walls and doors that may lead to accumulation unlike measurement in open corridors at other sites.

Distinct patterns in particle number size distributions (PNSD) were influenced by both interior activities and outdoor environmental conditions [11]. The time-series PNSD of the weekday classroom of the four sites exhibit similar features thus only that of S1 is presented in Figure 4. The indoor PNSD features a stable one-mode size distribution which is related to the fact that classroom windows were closed throughout the operating hours. An abrupt change of indoor PNSD at midday is consequential of movement of all students leaving for lunch and re-entering afterwards thus the exchange of outdoor air. In contrast, the outdoor PNSD exhibits greater variability. The peak in the morning is related to the morning traffic rush hours. Then the PNSD progressively diminished as atmospheric conditions becoming more unstable with increasing solar radiation and traffic congestion ease up during the midday and afternoon periods [12]. The identified difference and relatedness of the indoor and outdoor PNSD underscore the necessity for focused indoor air quality management, particularly in periods of heightened activity that may result in intermittent deterioration of air quality. The characteristics of the PNSD can be depicted as multi-modal lognormal particle number size distribution plots as shown in Figure 5. Since the PNSD exhibits one mode for most of time with only some occasion of two modes, only two selected instances are shown. The plots in Figure 5 are accompanied by Table 3 presenting the parameters of the size distribution, namely, number concentrations (N) in #/cm3, geometric mean ($\overline{D}_{pg}$) in nm, and geometric standard deviation ($\boldsymbol{\sigma}_g$) in nm.

Table 2 Summarizing statistics of outdoor and indoor 1-hour averaged total PNC in each school during weekday measurement

Schools	Measurement condition	Descriptive statistics for total PNC (x 10^3 #/cm^3)					
		Mean ± Std.Dev	Minimum	25th Percentile	Median	75th Percentile	Maximum
S1	Indoor	10.2 ± 3.57	6.02	6.31	9.78	13.7	22
	Outdoor	11.4 ± 3.30	3.69	7.55	10.8	15.4	36.8
S2	Indoor	15.7 ±9.72	6.84	7.31	11.5	28.1	47.1
	Outdoor	10.1 ± 3.94	3.74	6.96	8.95	11.7	33.7
S3	Indoor	18.7 ± 3.58	4.82	13.2	3.58	21.5	31.8
	Outdoor	17.6 ± 8.18	5.83	10.6	8.18	20.4	66.2
S4	Indoor	21.7 ± 7.27	10.5	14.4	19.4	25.1	56.9
	Outdoor	14.0 ± 5.33	7.5	8.17	12.6	17.7	40.1

Std.Dev = standard deviation.

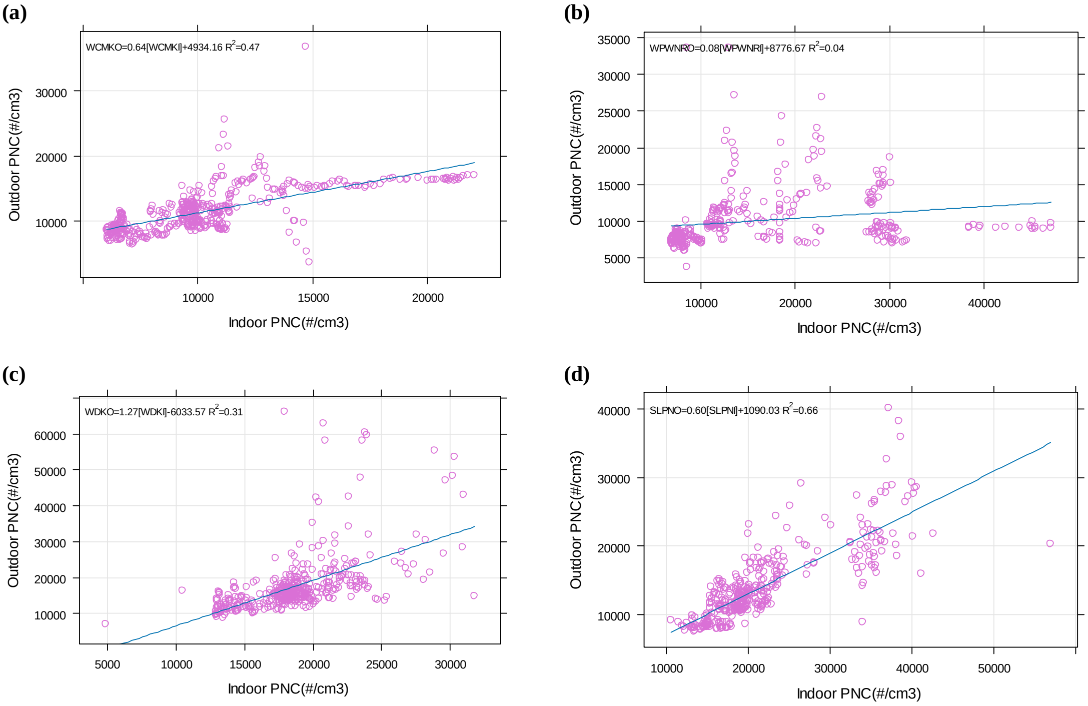

Figure 4 Scatter plot of linear regression analysis of weekday outdoor and indoor PNC in (a) S1, (b) S2, (c) S3 and (d) S4, respectively

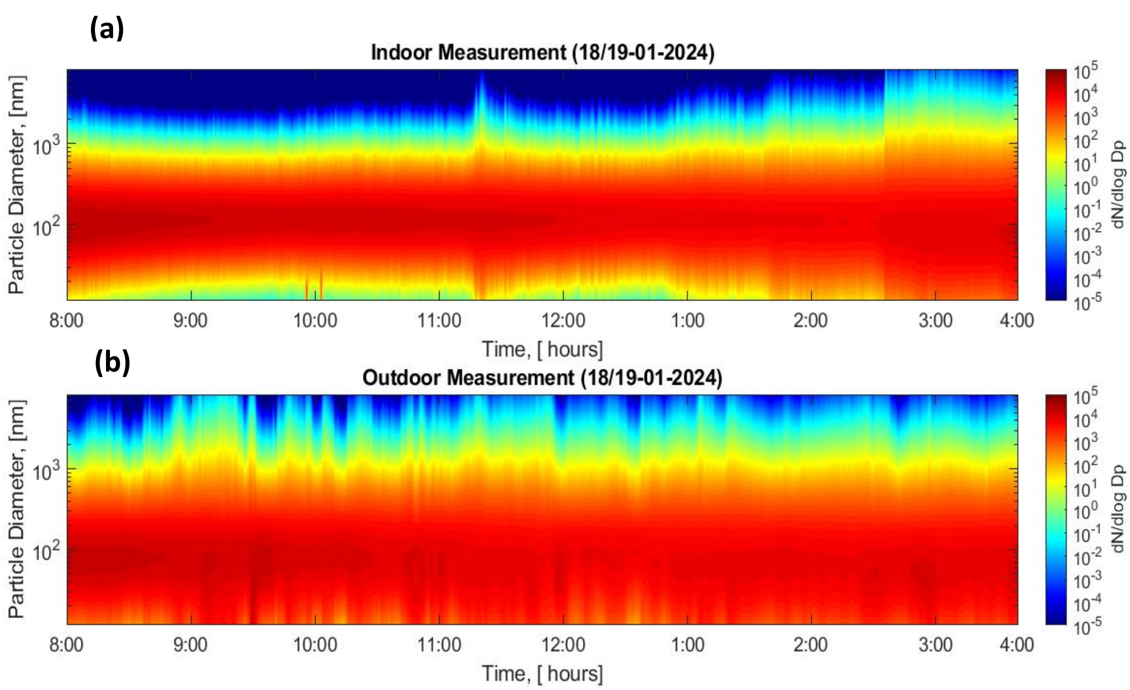

Figure 5 Particle number size distribution time series during weekday measurement for a) indoor and b) outdoor

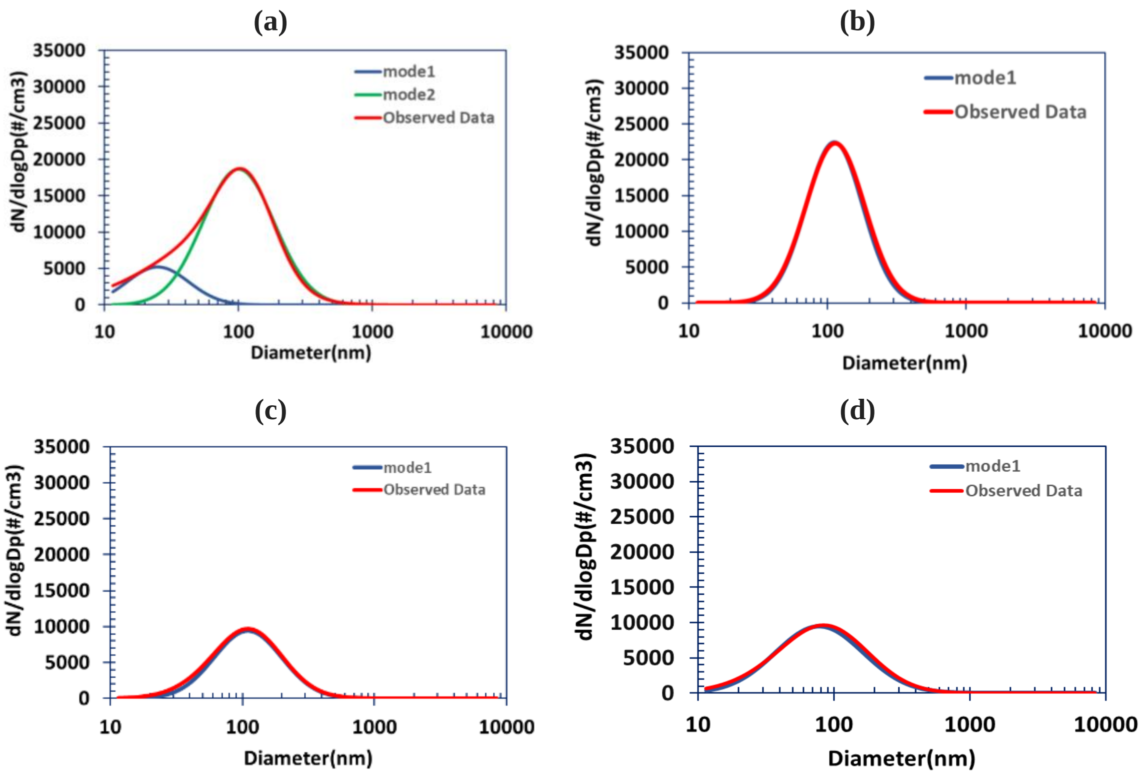

Figure 6 Multi-modal number size distribution plots of the weekday measurement for S1 for selected hours. a) outdoor 9-10 am, b) indoor 9-10 am, c) outdoor 2-3 pm, and d) indoor 2-3 pm. The lines are fitted mode 1 (blue), fitted mode 2 (green) and measured (red)

Table 3 Multi-modal number size distribution parameters of the weekday measurement for S1 for selected hours (1)9-10 am and (2)2-3 pm

	Fitted mode 1			**Fitted mode 2**		
	N (#/cm^3)	**Dpg (nm)**	σ_g (nm)	**N (#/cm^3)**	**Dpg (nm)**	σ_g (nm)
Out (1)	3000	23	1.7	12,000	100	1.9
In (1)	_	_	_	11,500	112	1.6
Out (2)	_	_	_	7,700	78	2.1
In (2)	_	_	_	6,500	110	1.8

As shown in Table 3, the existence of two separate modes indicates a combination of fresh emissions and aged particles from various sources in an outdoor environment. The lower concentration and smaller size of Mode 1 might be possible because of recently emitted particles from nearby traffic or other sources [13]. On the other hand, the bigger particles and greater concentration of Mode 2 are suggestive of aged particles that have grown in size over time after being emitted from sources such as transportation. Upon comparing the indoor PNSD with the outdoor PNSD at the same time as shown in Table 3, indoor shows that distributions center at bigger diameters and are narrower; this would be due to aging of outdoor particles. Even though the ventilation of the classroom is most of the time prevented with closed doors and windows, the indoor PNSD showed a sustained and stable distribution that can be due to introduction of outdoor particles into the room at the beginning of the day together with the air purification device that generates disinfecting particles which operated throughout the operating hours [14].

Figure 7 shows the analysis of indoor/ outdoor (I/O) hourly particle concentration ratios at four sites for weekday measurement. Particularly at sites S2 and S4, the ratios are consistently higher than 1. The elevated I/O ratio at site S2 may be attributed to its location situated far from the main road, implying a lower impact from outdoor vehicular emissions. The fact that there is less exposure to external contaminants in this setting indicates that interior sources or activities may have a greater impact on indoor air quality [14]. As for the site S4, the reason could be a combination of factors that the indoor purification system here differs from rest of the sites and also the fact that the road adjacent to the school (Wireless Road) is relatively less busy than the main road (Rama 4 road).

Weekend experiment results

The 1-hour average of outdoor particle number concentration (PNC) in the weekend analysis was 11,000 #/cm^3, 6,380 #/cm^3, 16,586 #/cm^3, and 11,627 #/cm^3 in S1, S2, S3 and S4, respectively. And then, the 1-hour mean of indoor PNC was 27,663 #/cm^3, 6,167 #/cm^3, 29,534 #/cm^3, and 13,977 #/cm^3, in each respective site. Although all outdoor PNC results showed the low PNC situation when comparing the WHO good practice for PNC [2], the indoor PNC of S1 and S3 revealed as the high PNC (>20,000 #/cm^3) during the cleaning activities.

The experiment was conducted during the weekend as tabulated in Table 1. The time-series PNSD are shown in Figure 8 for site S1. The indoor PNSD features fluctuation caused by the changing experimental setups while the outdoor PNSD exhibits similar features as that of the weekdays. Major change of the indoor PNSD can be seen at midday as the setup changes from open windows and doors to closed windows and doors. Obvious hotspots on the contour coincide with the cleaning activity with the use of cleaning agents containing volatile chemicals. The period right after cleaning also shows lingering particles undergoing microphysical growth. The PNSD of the interesting period with cleaning, namely, C4 and C6, are chosen to display the multi-modal size distribution in Figure 9 and the size distribution characteristics are presented in Table 4. The contrast between the indoor two-mode and the outdoor single-mode during cleaning activities highlights the influence of cleaning activities such as spraying cleaning agents and the use of volatile chemical products in mopping the floor.

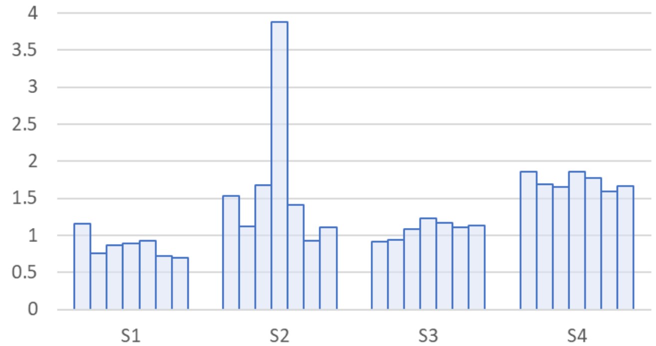

Figure 7 Weekday I/O ratios. Each bar presents hourly average value

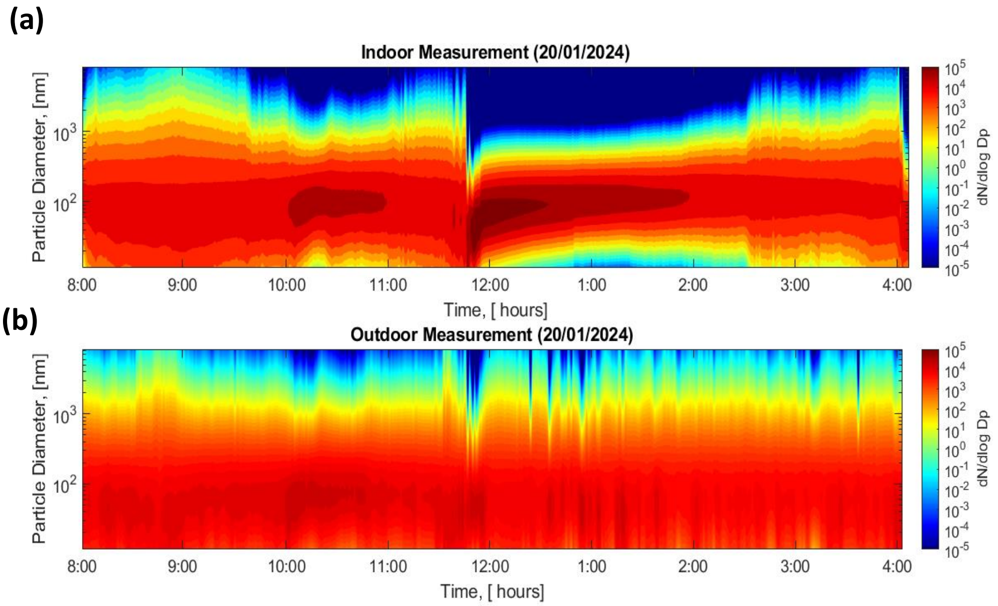

Figure 8 Particle number size distribution time series during weekend measurement for a) indoor and b) outdoor

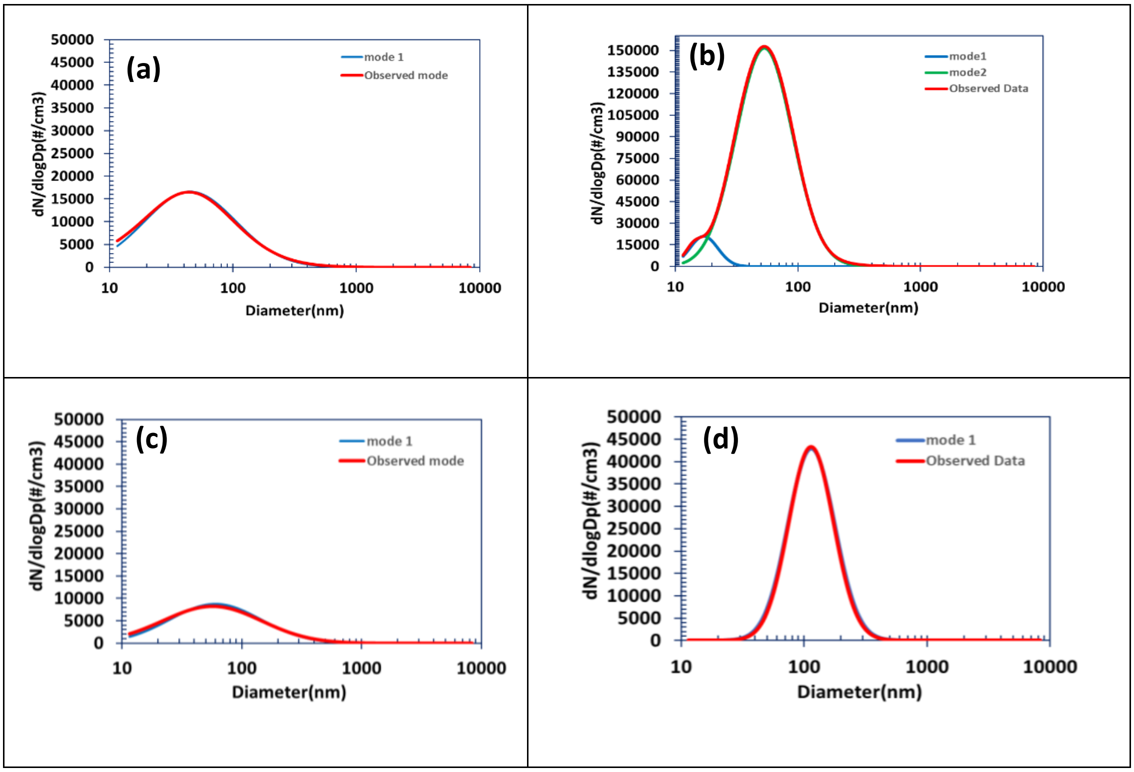

Figure 9 Multi-modal number size distribution plots of the weekend measurement for S1 for selected hours. a) outdoor 11:30-12:00 pm, b) indoor11:30-12:00 pm, c) outdoor 1:30-2:00 pm, and d) indoor 1:30-2:00 pm. The lines are fitted mode 1 (blue), fitted mode 2 (green) and measured (red)

The selected periods presented in Table 4 also highlight the difference between the open-window (C4b) and close window (C6b) conditions. It is speculated that open-window condition allows free flow of outdoor air that replenishes and supplies air with oxidation capacity thus the more likelihood of reactions of volatile organic compounds (VOCs) to become lower volatility products and secondary particles. The C6b condition shows lower number concentration and larger diameter population that may be explained by a combination of lower oxidation with the lack of outside air and the presence of the air purifying particles leading to coagulation growth. Nevertheless,[3] (1-hour average) that the WHO guideline specifies as high PNC condition.

When studying the particle number levels in classrooms under various cleaning and ventilation conditions, it was observed that stations S1 and S2 had the highest particle counts during C4b cleaning periods. The increase in pollutant levels can be due to the open windows, [15] which enable external air pollutants to enter. However, in C5, even though the cleaning process was finished, and the window was closed with the AC running, a higher level of particle number was still found. This indicates that the particles and precursor gas that linger in the indoor air and later contained by shutting down ventilation can lead to heighten concentrations. On the other hand, the particle number levels at station S4 reached their highest point in the morning, at the same time as the processes for opening windows. This provides evidence that natural ventilation has an important influence on the levels of particles indoors. The results highlight the complex connection between cleaning activities, HVAC system performance, and natural ventilation in affecting the indoor air quality in school environments [16]. Figure 10 presents the indoor/outdoor (I/O) hourly particle concentration ratios at four sites for weekend measurement. The ratios for S1 and S3 peak at condition C5 as discussed above. The reasoning why the peaking pattern of sites S1 and S3 were not replicated at sites S2 and S4 remains unclear and will need more in-depth investigation in future works.

Table 4 Multi-modal number size distribution parameters of the weekend measurement for S1 for selected condition

	Fitted mode 1			**Fitted mode 2**		
	N (#/cm^3)	**Dpg (nm)**	**$\sigma_{g\ (nm)}$**	**N (#/cm^3)**	**Dpg (nm)**	**$\sigma_{g\ (nm)}$**
Out -C4b	_	_	_	10500	45	2.3
In – C4b	6000	17	1.3	87500	53	1.7
Out- C6b	_	_	_	5700	97	1.5
In – C6b	_	_	_	20500	115	1.6

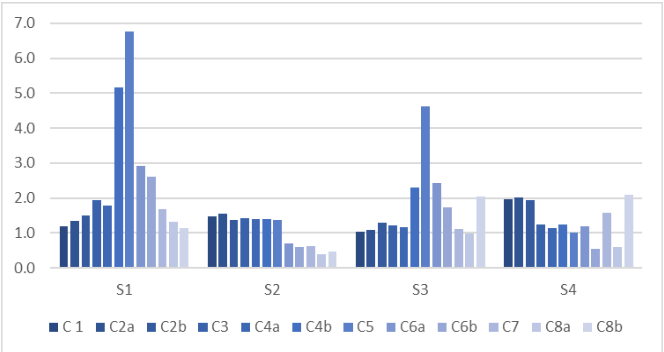

Figure 10 Weekend I/O ratios. Each bar presents the average value of each experiment condition

Conclusions

A comprehensive investigation of hourly average PNC from four schools in Bangkok central business district during regular weekday schedules indicated significant variation related to outdoor concentrations. The size distributions were observed to be unimodal for most of the study period. The particle number size distributions inside classrooms show connection to the outdoor particles that are influenced majorly by traffic emissions and size growth. The experiments conducted in the study indicated that cleaning activity indoors can cause surge of PNC likely due to cleaning agents. One school site revealed an average of the 1-hour mean PNC exceeding the high PNC level recommended by WHO. The results emphasize the need for intervention to improve air quality to safeguard the well-being of young children, particularly during periods of high indoor activity and cleaning procedures. This research helps establish the baseline information about ultrafine particles for future urban environmental policy, therefore preparing the way for sustainable school settings in increasingly urbanizing areas.

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