CHARACTERIZATION OF SIZE-RESOLVED PARTICLES AND CHEMICAL COMPOSITION AT TWO ELEMENTARY SCHOOLS IN HANOI, VIETNAM

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ABSTRACT

Indoor and outdoor ultrafine, accumulation mode, and coarse fractions collected at two elementary schools (S1 and S2) in Hanoi capital, Vietnam were characterized in terms of mass, number concentrations, particle morphology, and chemical composition to assess the indoor air quality at the examined schools. The sampling campaigns were performed simultaneously indoors and outdoors for three consecutive weeks at each school. Indoor average concentrations of CO_2 and CO at both schools were below the limit values recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (1000 ppm for CO_2) and World Health Organization (7 mg/m³ for CO). Indoor mass concentrations of PM_{10} and CO_2 at S1 and S2 were strongly influenced by the presence of children and their activities indoors whereas the number concentration of particles seemed not to be impacted by occupants' activities. Water-soluble ions commonly presented unimodal distribution for indoor and outdoor airborne particles at S1 and S2, which accounted for typically a proportion of around 3.5-5% of the total mass of particles. Oxygen (O) was the most abundant element in all fractions, followed by carbon (C) for indoor and outdoor particles.

KEY WORDS: Indoor air quality, Young children, Ultrafine particles, Morphology, Water-soluble ions, Elemental distribution.

INTRODUCTION

People in modern society are spending more and more time indoors, so indoor air quality has a direct impact on human health, especially children, because theyspend a considerable amount of time in their school days indoors where, in certain cases, air is more polluted than outdoor (Tran, *et al.,* 2014; Pallarés, *et al.,* 2019; Tran, *et al.*, 2012; Tofful and Perrino, 2015). Moreover, children are more sensitive to atmospheric pollutants than adults, due to their not-fully developed respiratory system and high rates of acute respiratory infections (WHO, 2004);

hence, their exposure to indoor airborne particles can result in negative health impacts. Recent studies have increasingly focused on fine airborne particles ($PM_{2.5}$, PM_1), nanometer-sized ultrafine particles ($PM_{0.1}$) and their chemical composition as these are important agents effectinghuman health and the environment (WHO, 2004). The health effects of airborne particles (PM) depend strongly on their size, specific surface area, number, and chemical composition, such as their heavy metal contents (Frampton, *et al.*, 1999; Pope, *et al.*, 2002). These potentially toxicelements could be emitted by various sources, such as industries (Tran, *et al.*, 2012;

Mbengue, *et al.*, 2014; Mbengue, *et al.*, 2017), road traffic (Tran, *et al.*, 2012; Tofful and Perrino, 2015; Mbengue, *et al.*, 2017; Rivas, *et al.,* 2014; Oliveira, *et al.,* 2016), and biomass combustions (Ruggieri, *et al.* 2019; Viana, *et al.,* 2013; Hussein, *et al.*, 2020). Fine and ultrafine particles can penetrate deeply into the humanrespiratory system, and hence may cause more adverse impacts on human health (WHO, 2004; Pope, *et al.*, 2002) . In addition, ultrafine and fine particles are very high in numbers, and have higher surface area than larger particles, which promote them to adsorb, retain, and release toxic substances in the pulmonary system (Frampton, *et al.*, 1999; Viana, *et al.*, 2013; Hussein, *et al.,* 2020). Previous studies showed that most of the airborne particles from combustion are composed of chain-aggregated masses of fine carbonaceous spheres, and adverse organic compounds such aspolycyclic aromatic hydro-carbons (PAHs) and quinones (WHO, 2004).

In general, school environments do not present typical indoor emission sources of airborne particles such as heating combustion, smoking, and cooking. However, airborne particle concentrations and their elemental contents are strongly influenced by several factors, such as the number of occupants andtheir indoor activities (Tran, *et al.*, 2014; Tran, *et al.,* 2012; Tran, *et al.,* 2015), ventilation systems (Lai, 2002; Nazaroff, 2004), air exchange rates (Tran, *et al.,* 2015; Nazaroff, 2004; Thatcher and Layton, 1995), indoor furniture,painting and building materials (Babich, *et al.,* 2020; Wolkoff, *et al.,* 2006), outdoor particles' penetration capacity, and resuspension ofdeposited particles (Tran, *et al.*, 2015; Nazaroff, 2004).

The increasingly rapid urbanization and industrialization in Hanoi, Vietnam, has been suspected to induce problems to environments, including air pollution issues. The study on the air quality in Hanoi is stilllimited, though there have been some studies carried out on roadsides for outdoor air pollutants (Tran, *et al.,* 2015; Vo and Nguyen, 2007). Potential emission sources of airborne particles and their associated contents in Hanoi could be traffic, construction and demolition activities, and biomass burning in winter. To the best of our knowledge, there is no research on mass and number concentration, water-soluble ions of size-resolved airborne particles in school environmentsin Hanoi, Vietnam.

The main objectives of this study are to identify the sources of airborne particles in class rooms and to determine the influence of the children's activities to the elemental distribution for different particle size fractions at two preschools in Hanoi, Vietnam, where young children who are among themost sensitive to air pollution spend most of their time indoors.

MATERIALS AND METHODS

School characteristics

Two elementar schools were selected in the Hanoi capital, Vietnam (Figure 1). The climate of the regionis characterized by a high level of humidity,
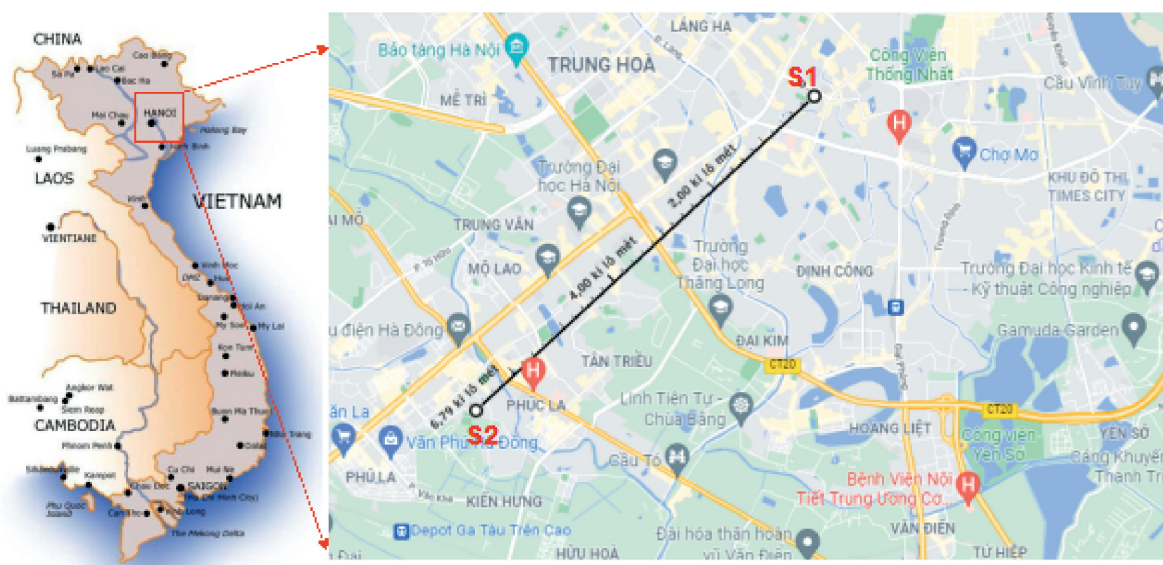

Fig. 1. Location of the two examined elemental schools in Hanoi, school 1 (S1), school 2 (S2).

four seasons around the year. Hanoi is the second largest Vietnamese city by population (8.41 million as of 2021) after Ho Chi Minh City, with a density of up to 40,300 inhabitants/km^2 in the center district compared with the average figure of 2398 inhabitants/km^2 for the wholecity. This is causing traffic congestion in many parts of the city, and consequently, airpollution. The two elemetary weres elected to match two close types of environments: urban center (school 1 (S1)) and urbanperiphery (school 2 (S2)). The spatial distance between the two schools is about 7 km (Figure 1). The schools were also selected for the study based upon edifice characteristics such as ventilation system, internal covering including flooring, wall, and ceiling, windows structure, and building age, which are summarized in Table 1.

School 1 (S1), built in 2005 and made of brick, is located in close proximately to a main road conjunction of the city, where there are high traffic density roads, with a lot of vehicles commuting at almost all times of the day. A large gas station is located about 500 meters from the school. School 2 (S2) built in 2015, is a three-level brick building situatedin proximity to ring road N0.4. There is parking nearby and a gas station at a distance of about 350 meters. Cleaning at the two schools is conducted on a daily basis using cleaning products.

Sampling and measurement stratergy

The 4-week sampling campaigns for each school were divided into two periods: during teaching hours and in the absence of children in the classrooms. The occupied periods consisted of teaching hours during five school days, from Monday to Friday. The unoccupied periods included all nights (from 7 p.m to 6 a.m of the next day) of the weekdays and weekends to avoid resuspended particles due to occupants' activities during the class (Tran, *et al.*, 2014), the teaching hours started at 08:00 and finished at 16:00. The sampling campaigns were simultaneously conducted indoors and outdoors of the two schools. They were conducted successively at each school, from 01March to 30Appril 2020 under relatively cool and stable meteorological conditions during each campaign. Two identical particle samplers (Nanosampler II, KANOMAX) were deployed to collect different size fractions of airborne particles, which were then subjected to mass concentration, morphology, and chemical composition determination. Comfort parameters such as temperature, relative humidity, CO, and CO2 gases were monitored indoors and outdoors during the campaigns using two identical Qtrak, TSI. All equipment was calibrated prior to being deployed for the sampling campaigns. In addition, information about daily school activities in the studied classrooms (number of pupils present, closing/opening state of doors and windows, cleaning method and products used) were collected by questionnaires. Some chemicals identified among the cleaning products used at S1 and S2 were polyacrylic acid, triethanolamine, ethoxylated alcohol, benzisothiazolinone, methylchloroiso-thiazolinone, methylisothiazolinone, and other preservatives, dyes, and fragrances, which were not given specific names by producers. Details on sampling strategy were presented in previous work

Table 1. List of main characteristics of the monitored schools.

Monitored preschools	Description
School 1	Located in a central district of Hanoi, in proximity to a filling station.
	Surrounded by high-rise buildings, residential buildings, and houses.
	Serrounded by dense traffic roads.
	Numerous green plants within the school's premises.
	Buildings built in 2010. No recent important renovation.
	Laminate Flooring.
	Naturally ventilated.
	40 children present in the surveyed classrooms of 68 m^3.
School 2	Located in a peripherical area of Hanoi, directly exposed to a street.
	Proximity to a ring road (about 300 m).
	Numerous green plants within the school's premises.
	New tables and chairs at the sampling periods.
	Buildings built in 2015.
	Flooring tiles.
	Mechanical ventilation by ceiling fans.
	42 children present in the surveyed classroom of 80 m^3.

(Tran, *et al.*, 2012).

Aerosol sampling, morphology, and ion-soluble analysis

Aerosol samples were simultaneously collected indoors and outdoors on Zefluor filters (Pall Corporation, 0.45 µm porosity) by impaction (for each stage) and filtration (for backup filter) using five-stage cascade impactors, Nanosampler II (Kanomax Japan Inc.) at a constant flow-rate of 40 L/min to collect different particle size fractions, i.e., between 10 and 2.5 µm, between 2.5 and 1 µm, between 1.0 and 0.5 µm, and between 0.5 and 0.1 µm. Teflon filters were selected as they are nonhygroscopic and chemically inert, have low blanks, and therefore, improve the analytical quality of the analyses. To assess concentrations and composition of PM_{10}, $PM_{2.5}$, PM_1, $PM_{0.5}$, and $PM_{0.1}$, successive fractions collected on the cascade impactor stages (filter substrates) were summed. The sampling flow-rate was calibrated by a TSI 4040 mass flow-meter before and after each sampling campaign.

In order to examine the impact of the presence of occupants and their activities at school on pollutants' còncentrations, ten indoor and ten outdoor particle samples were collected during occupied periods (during the class) and unoccupied periods (no occupants in the classrooms) at each school. Regarding occupied periods, each sample was collected during 2 school days, corresponding to 16 hours. The same numbers of samples were collected during unoccupied periods at each school: over two nights or 24 hours for school days, and 48 h during weekends (two complete days). In total, 70 airborne particle samples were sampled at the two schools.

The collected airborne particles were kept in clean Petri dishes and stored in a temperature (20 ± 1 °C) and relative humidity (45%–50%) controlled room for 48 h before weighing according to the standard reference method (EN 12341:2014). Each filter was weighed four times before and after exposure with a microbalance (Mettler-Toledo UMT2, Switzerland) with a 0.1 mg reading resolution. The difference in weighed mass and the sampled air volume were used to calculate PM mass concentrations.

The concentrations of five anions (Cl^-, NO_3^-, and SO_4^{2-}) and five cations (Na^+, NH_4^+, K^+, Mg^{2+} and Ca^{2+}) were determined in aqueous extracts of the sample filters. To extract the water-soluble ions from the filters, the portions of the filters used for the gravimetric analysis were placed in separate 12 ml vials containing 10 ml of distilled–deionized water (18.2 MW resistivity). The vials were placed in an ultrasonic water bath and shaken with a mechanical shaker for 1 h toextract the ions. The extracts were filtered through 0.45 µm pore size microporous membranes, and thefiltrates were stored at 4 °C in clean tubes before analysis. A Dionex-1100 Ion Chromatograph (Dionex Inc., Sunnyvale, CA, USA) was used for determiningboth the cations and anions in the aqueous extracts of the air filters. For the cation analyses, the instrument was equipped with an IonPacCS12A column (20 mmol/l methanesulfonic acid asthe eluent), while an ASRS-4num column (25 mmol/l KOH as the eluent) was used for anions.

The measurements were taken under the following conditions: column temperature: 30 °C; flow rate: 1.0 ml/min; injection volume: 20 µL; flow precision < ± 0.1%; flow rate maximum error 0.1%. Detectionlimits were 4.2 mg l^{-1} for Na^+, 3.5.0 mg l^{-1} for NH_4^+, 9.0-9.3 mg l^{-1} for K^+, Mg^{2+} and Ca^{2+}, 0.7 mg l^{-1} for and Cl^-, 12 mg l^{-1} for and NO^{3-}, and 18 mg l^{-1} for SO_4^{2-}. Standard reference materials produced by the National Research Center for Certified Reference Materials (NIST, USA) were analyzed for quality control and assurance purposes. Data from blank samples were subtracted fromthe corresponding sample data after analysis.

Particle morphology and composition of $PM_{0.1}$, $PM_{0.5}$, PM_1, $PM_{2.5}$, and PM_{10} were analyzed using a JEOL JSM-6400 high-vacuum SEM with a tungsten filament operating at 20 kV accelerating voltage coupled with an Energy-Dispersive X-ray Spectroscopy (EDS). SEM provides images of a sample while the chemical composition is analyzed by an energy-dispersive X-ray spectroscopy coupled with SEM.

RESULTS AND DISCUSSION

Indoor, outdoor variation of CO, CO_2 concentrations and comfort parameters

Results on indoor, outdoor CO, CO_2 concentrations, and comfort parameters are presented in Table 2. It is noted that indoor and outdoor average CO concentrations obtained during the class and when the classrooms were empty at S1 and S2 were clearly lower than the 8 hour and 24 h guidelines for indoor air (10 mg/m³ or 8732 ppm and 7 mg/m³ or 6113 ppm, respectively) set by the World Health

Table 2. CO_2, CO concentration, and comfort parameters measured indoors and outdoors at the surveyed preschools (n = 74, average ± standard deviation, between parentheses areranges of values).

Schools	During teaching hours		During unoccupied period	
	S1	S2	S1	S2
Indoor				
CO_2 (ppm)	795±256	601±152	457±41	425±55
	(398-1886)	(395-1918)	(401-684)	(377-912)
CO (ppm)	2.9±1.9	1.3±0.8	2.6±1.4	0.7±0.5
	(0.5-9.1)	(0.3-7.1)	(0.5-9.2)	(0.2-5.8)
°C	25.7±2.3	24.8±3.3	24.8±1.9	25.4±2.3
	(20.4-28.9)	(20.6-29.7)	(21.5-27.7)	(18.7-32.1)
RH (%)	54.7±14.7	71.6±16.3	54.4±13.9	59.7±9.3
	(25.8-80.2)	(54.8-82.2)	(27.8-77.3)	(41.8-79.5)
Outdoor				
CO_2 (ppm)	461±47	412±19	449±28	414±22
	(387-672)	(366-627)	(412-604)	(356-587)
CO (ppm)	1.9±1.4	1.7±0.6	1.4±1.2	1.4±0.7
	(0.4-11.3)	(0.8-7.6)	(0.3-19.8)	(0.4-9.5)
°C	23.8±3.1	22.9±3.4	23.3±2.6	19.6±4.1
	(17.6-27.8)	(17.9-32.1)	(21.4-29.2)	(14.1-38.2)
RH (%)	52.6±15.3	71.2±8.4	58.5±16.4	78.5±9.1
	(21.9-81.5)	(29.1-89.3)	(30.6-89.3)	(30.2-91.3)

Organization (2010). During teaching hours, indoor concentrations of CO at S1 varied in the range of 0.5 to 9.1 ppm, averaging 2.9 ppm, whilst those values at S2 were in the range of 0.3–7.1 ppm, averaging 1.3 ppm (Table 2). There were no significant differences in indoor and outdoor CO levels at S1 and S2 between the two periods during teaching hours and when the schools were vacant (p > 0.05). This implies that there were no significant indoor emission sources of CO at S1 and S2. As regard CO_2, indoor average concentrations of CO_2 obtained during the class at S1 (795 ± 256) and S2 (601 ± 152) were relatively higher than those obtained when the rooms were empty (457 ± 41) for S1 and 425 ± 55 for

S2) due to children's respiration (Table 2). However, there were no significant discrepancies between outdoor CO_2 levels obtained during classes and those obtained when the classrooms were vacant for both the schools (p > 0.05). All indoor and outdoor average concentration of CO_2 at S1 and S2 were below the recommended value of 1000 ppm set by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2013), although there were certain moments where indoor CO_2 levels during teaching hours exceeded 1000 ppm (Figure 2). Those levels of indoor CO_2 were lower than several results of research conducted in classrooms, especially in cold climate countries
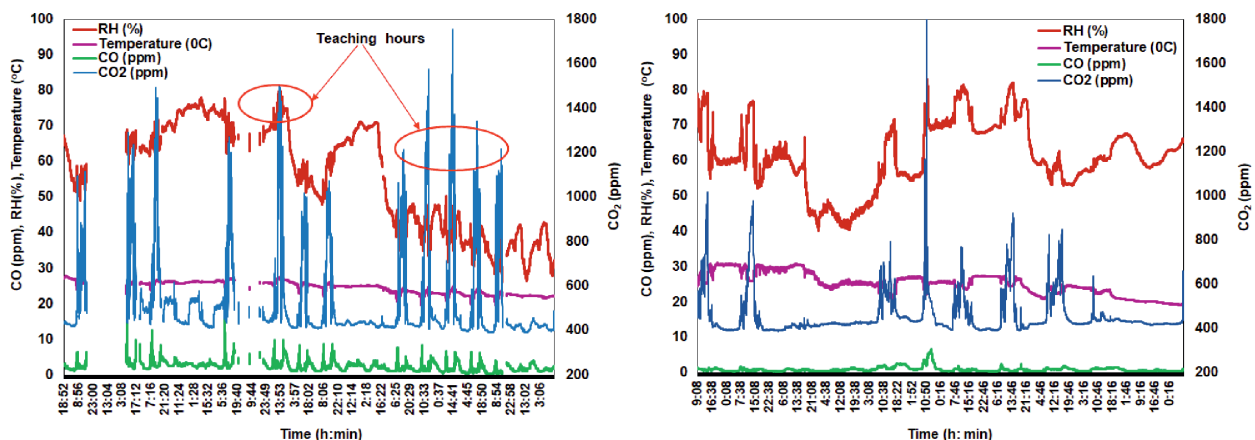

Fig. 2. Variation of indoor CO, CO_2 concentrations and comfort parameters at S1 (left) and S2 (right).

where doors and windows are frequently closed to avoid the cold (Tran, *et al.*, 2015; Peng, *et al.*, 2017; Mainka and Zajusz-Zubek, 2015).

Regarding comfort parameters (RH% and temperature), it was observed that indoor temperature and relative humidity less varied compared to the outdoor ones, although indoor values were correlated with outdoor figures (Table 2 and Figure 2). For instance, indoor temperature at S2 varied from 20.6 to 29.7 °C whereas this value for outdoor air at the same period was in the range of 17.9-32.1 °C. Similar trend was observed with relative humidity (54.8-82.2% for indoor vs 29.1-89.3% for outdoor air). This could be attributed to the building envelops that helped to maintain indoor temperature and humidity.

Regarding the variation of outdoor CO, CO_2 concentrations and comfort parameters, CO and temperature at S1 and S2 were repatively stable while relative humidity fluctuated as a function of time due to large change in climatic conditions. This suggested that outdoor emission sources of CO close to the S1 and S2 were negligible. Regarding the concentration of CO_2, there were sharp signals of CO_2 concentration (Figure 3) could be attributed to the fact that children played in the courtyard and in proximity to the gas analyzers, which might make CO_2 concentration increase.

Indoor, outdoor variation of particle mass and number concentrations

The variation in mass concentrations of $PM_{1.0}$; $PM_{2.5}$; and PM_{10} at S1 was presented in Figure 4. As shown in Fig. 4, duringteaching hours, the mass concentration ofindoor PM_2 and PM_1 was slightly higher than that measured outdoor whereas in absence of occupants in the classrooms, it was

theopposite. The evolution of indoor fine particles did not seem to becorrelated to outdoor ones. It was also observed some relatively small peak of these fractions observed during teaching hours. It could be associated with occupant's activities in classrooms (walking, sitting, and playing), giventhat during school days, the doors and windows were sometimekept open which should have led to similar concentrations indoorand outdoor. The larger peaks were linked to sweeping activitieson the floor at the end of the school day. The variation of indoor concentrations of the coarse particles (PM_{10}) related to occupant's activities in classrooms was more noteworthy (Fig. 4). Indeed, this fraction sharply increased as soon as the arrival of occupants (at about 8:00 AM) and phased out quickly during both the breaks (at about 10:00 and 14:30), lunch time, and the end of the class in weekdays (Fig. 4). The most intense peaks of PM_{10} concentrations were observed during the cleaning routine after the class. This type of activity could result in an increase of 40-60 times the indoor PM_{10} concentrations compared
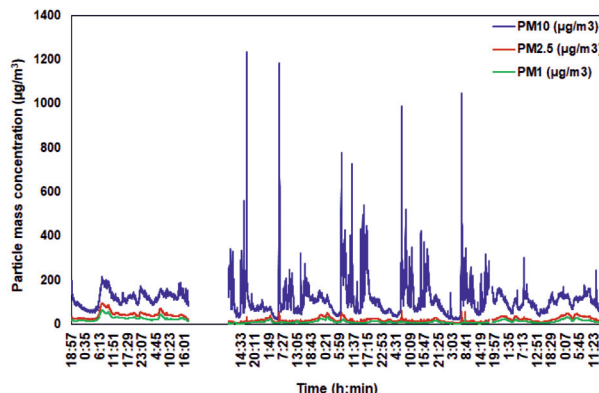

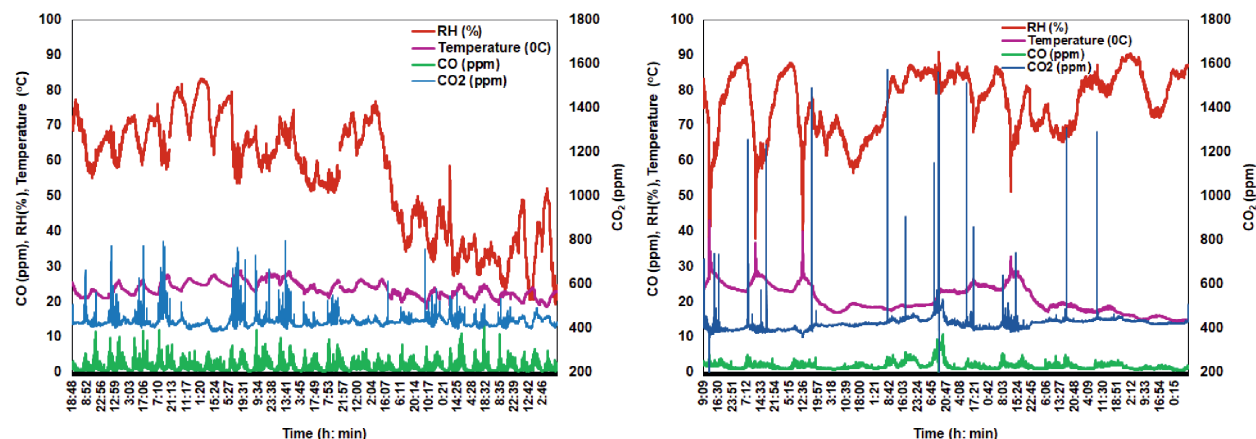**Fig. 4.** Variation of indoor particle mass concentration at S1.

Fig. 3. Variation of outdoor CO, CO_2 concentrations and comfort parameters at S1 (left) and S2 (right).

to unoccupied period (Fig. 4).

Regarding outdoor, the variation of PM_1 and $PM_{2.5}$ was slightly sharped by the teaching period where relatively high peaks of PM_1 and $PM_{2.5}$ was not as significant and sometimes was anti-correlated with indoor ones, particularly during the breaks and lunch time when the pupils played in the courtyards and close to the monitoring instruments. As for PM_{10}, the impact of occupants' activities outdoor was sharped by several strong peaks of PM_{10} concentration during school days although those peaks lasted for a short time (Fig. 5). This implied that although the outdoor activities of children might cause an increase in particle concentration, ambient fresh air could be the factor diluted particle concentration outdoor.
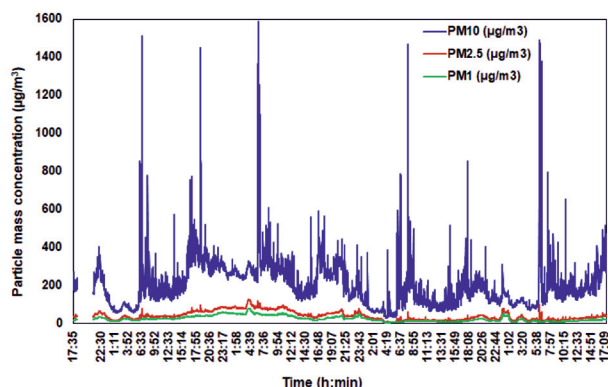

Fig. 5. Variation of outdoor particle mass concentration at S1

The outdoor and indoor particle average number concentrations ranged from 2.8×10^6 to $8.7\times 10^9 P/cm^3$ for S1 and from 2.0×10^6 to $3.5\times10^9 P/cm^3$, respectively. Those results were higher than the findings reported by Mullen *et al.* (2011) in schools in California, who showed that the average outdoor

particle number concentration levels were consistently higher than the indoor (classroom) ones (outdoor: 9.0×10^3–$2.6\times10^4 P/cm^3$; indoor: 5.2×10^3–$1.7\times10^4 P/cm^3$). Such results are supported by the average daily trends of indoor, outdoor and background particle number concentration levels concerning the three schools. The outdoor-peak concentrations for S1 and S2 occurred at the start of school hours (07:30; Fig. 6, 7), this is due to heavy traffic in proximity to school at pick up and drop off zones: in fact, S1 was surrounded by trafficked and congested urban roads.

It is noted that unlike mass concentration, fine and ultrafine number concentration accounted for almost 100% indoor and outdoor PM_{10} (Fig. 6 and 7). This confirms that although ultrafine particles represent a large number in PM_{10}, their mass might not be significant.

Particle concentrations measured outdoors was higher than the background concentrations, except at S3. The submicrometer particle concentrations were usually higher outdoors than indoors, because no indoor sources were detected. Indeed, human presence and related activities, constitute a significant source of supermicrometer particles in indoor micro-environments, whereas, submicrometer particles concentrations are mainly associated with outdoor particle levels (Zollner, *et al.,* 2007; Tippayawong, *et al.*, 2009).

When looking at ondoor/outdoor (I/O) ratio regarding fine and coarse particle number concentration, ones could conlude that the presence of occupants in the classrooms seemed not to lead to significant increase in number of particles (Fig. 8), inversely to the case of mass concentration of particles, which resulted in strong increase in mass concentration of coarse fraction. This again confirms
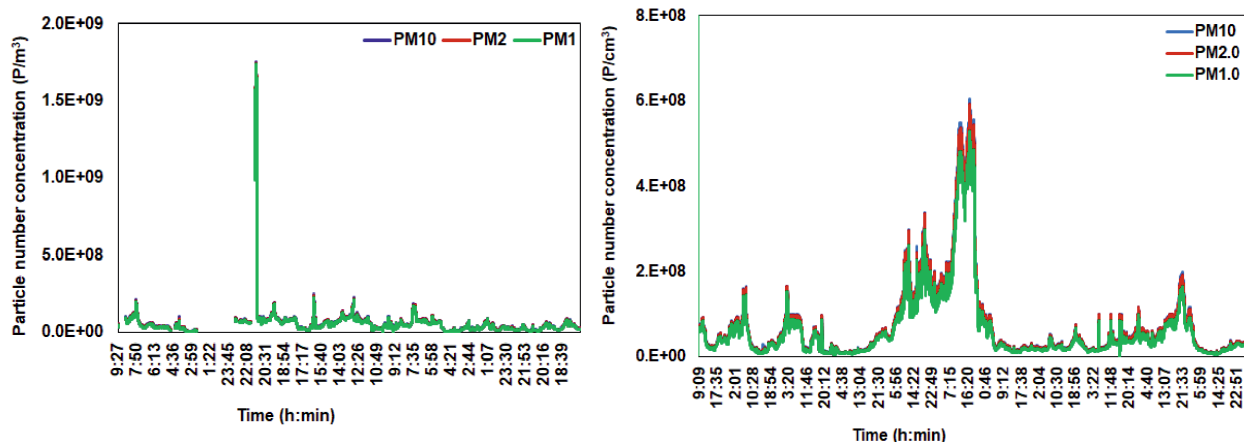

Fig. 6. Variation of indoor particle number concentration at S1 (left), and S2 (right).
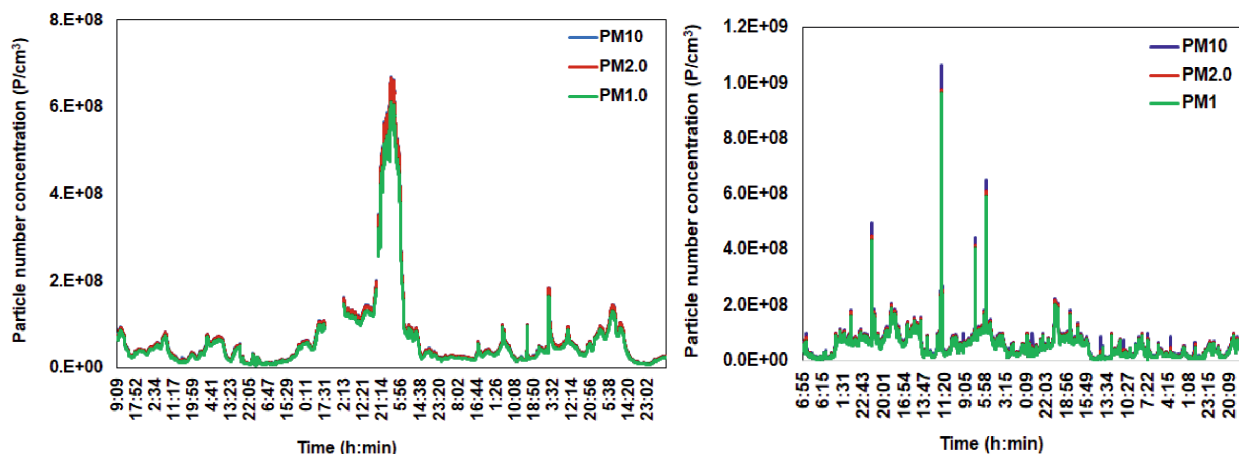
Fig. 7. Variation of outdoor particle number concentration at S1 (left) and S2 (right).
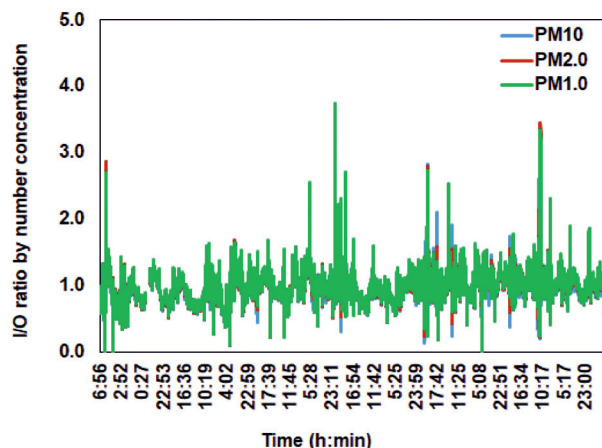

Fig. 8. Variation of I/O ratio by particle number concentration at S1.

the importance of mass of coarse fraction.

Indoor, outdoor soluble ions of size-resoved airborne particles

The indoor and outdoor mass concentrations of ultra fine, fine, and coarse particles are summarized in Table 3. Daily indoor PM_{10} concentrations obtained during teaching hours at S1 ranged from30to 102 µg/m³, averaging 58.3 ± 30 µg/m³. This was largely higher than during the period when there were no children in the classrooms (17.8 ± 18.1 µg/m3), which fluctuated from 10.7 to 47.6 µg/m3.

This suggests that children and their activities at school result in an increase in indoor PM_{10} concentration. Regarding outdoor, there was no significant discrepancy between the two periods regardless of the presence or absence of children in the class rooms (p > 0.05). For instance, out door average concentrations of PM_{10} collected during class and when the school was vacant were 164 ±

46.6 and 134.6 ± 52.2 µg/m³, respectively (Table 3). Similar trends were observed at S2 where indoor PM_{10} concentrations varied within the range of8.7– 12.7 µg/m³ during classes and 2.5–10.5 µg/m³ when the class rooms were empty. These observations can be explained by occupants' physical activities in the classroom (running, playing with toys, movements...) which would contribute to a strong increase in coarse factions. For instance, averag indoor concentration of $PM_{2.5-10}$ fraction sampled during the lesson was 10.5 ± 8.2, ranging from 2.0 to20.8 µg/m3, where as those values obtained without children in the classrooms were 1.7 ± 0.8, ranging rom 1.0 to 3.0 (Table 3). In contrast, when there were no occupants in the classrooms, the building envelope of S1 andS2 prevented the penetration of the coarse fraction from outdoors owing to their filtration capacity (Tran, *et al*., 2014; Oliveira, *et al*., 2016; Tran, *et al*., 2015). Outdoor average concentrations of PM_{10} for occupied and unoccupied periods at S2 were 226 ± 20.7 µg/m³ and 175 ± 36.6 µg/m³, respectively (Table 3). They largely exceeded the daily limit (50 µg/m³) recommended by the World Health Organization (WHO) and were relatively higher than Vietnam 24 h exposure regulations (150 µg/m³) for ambient air. Indoor PM_{10} concentrations measured during teaching hours slightly surpassed the daily limits (50 µg/m³) set by WHO for indoor air. It is noted that there are no guidelines for indoor air in Vietnam.

Similarly, indoor concentrations of $PM_{2.5}$ at S1 and S2 were strongly influenced by the presence of children and their activities within the classrooms. Average $PM_{2.5}$ levels obtained during the lesson at S1 and S2 were 49.4 ± 41.0 µg/m³ and 7.9 ± 1.8 µg/m³, while those values obtained when the rooms were

Table 3. Indoor and outdoor size-resolved air borne particle concentrations at S1 and S2 (n = 10 for each parameter, with a total of 70 samples, average ± SD, in parent heses are min–max values).

Schools	During teaching hours		During unoccupied period	
	S1	S2	S1	S2
Indoor				
$PM_{0.1}$	3.4±1.5	2.4 ± 0.8	1.8±1.6	1.8 ± 0.8
	(1.7-5.4)	(1.8–3.0)	(0.4-3.9)	(0.9–2.9)
$PM_{0.5}$	8.3±6.8	4.6 ± 1.2	4.9±3.0	3.0 ± 1.8
	(2.2-14.8)	(3.0–5.8)	(1.9-7.4)	(1.5–4.9)
PM_1	27.7±20.4	7.2 ± 1.6	11.2±10.3	4.7 ± 2.7
	(5.7-60.3)	(5.4–8.9)	(2.7-26.6)	(2.1–8.4)
$PM_{2.5}$	48.8±18.7	9.9 ± 2.4	14.5±18.0	7.2 ± 3.6
	(28.6-79.0)	(6.7–11.0)	(2.9-40.4)	(3.5–11)
PM_{10}	58.3±24.9	11.1 ± 2.5	17.8±18.1	9.1 ± 2.6
	(30.1-102)	(9.6–13.6)	(10.7-47.6)	(5.5–13.5)
Outdoor				
$PM_{0.1}$	16.2±2.4	13.0 ± 2.4	17.1±3.5	12.6 ± 3.4
	(14.4-19.7)	(10.5–15.2)	(11.7-21,6)	(9.0–14.2)
$PM_{0.5}$	33.7±5.6	38.9 ± 4.9	45,1±10,3	37.1 ± 10.2
	(27.8-41.5)	(35.5–41.2)	(37.4-58.9)	(26.1–45.0)
PM_1	75.4±22.8	106 ± 10.1	88.7±25.6	99.8 ± 29.0
	(44.6-101)	(98.8–117)	(64.6-123.2)	(56.5–125)
$PM_{2.5}$	105±39.0	168 ± 23	134.5±31.8	149 ± 31.3
	(58.9-148)	(153–201)	(96.7-169.2)	(108–172)
PM_{10}	132.2±67.1	220 ± 21.2	164.6±45.8	170 ± 38.3
	(89.1-180)	(203–251)	(110-209)	(125–217)

vacant were 15.7 ± 19.0 µg/m³and 4.2 ± 3.0 µg/m³, respectively (Table 3). Indoor PM_{10} and $PM_{2.5}$ at S1 were higher than at S2, which could be explained by the fact that the number of children presente in the examined classroom at S1 was almost twice as high compared to the classroom at S2 (43 at S1versus 20 at S2), while the classroom's volume was lower than at S2 (68 m³ at S1 versus 80 m³ at S2). Given that S2 was located in close proximity to the ring road N0.4, emissions from both mechanical (road surface abrasion, resuspension of road dusts, brake wear) and thermal processes (exhaust from vehicles) were expected to contribute to higher concentrations of outdoor coarse and fine particles at S2, which will be analyzed in detail in the subsequent section.

Only indoor average concentration of $PM_{2.5}$ collected in the presence of children at S1 located in Hanoi center largely exceeded the limit value (25 µg/m³ for 24 h exposure) recommended by WHO.However, all the outdoor concentrations of PM2.5 at S1 and S2 were largely higher than the WHOguideline for ambient air, and they also largely exceeded the Vietnam standard (50 µg/m³ for 24 hexposure). The outdoor average concentrations of $PM_{2.5}$ collected during class at S1 were 107 ± 40.0 and the corresponding value at S2 was 177 ± 20.2,

respectively (Table 3). This is in accordance withresults on $PM_{2.5}$ obtained from a monitoring station of United States Environmental Protection Agency (US EPA) located in Hanoi (Alves, *et al.*, 2013). However, until now, there have been no large-scale campaigns in Hanoi capital to gather a large enough dataset in order to draw conclusions on such phenomena.

Interestingly, school situation and number of children and their activities could lead to discrepancies inindoor PM_{10} and $PM_{2.5}$ concentrations at S1 and S2, but ultrafine particles seemed not to be influenced by those factors. In fact, indoor average concentrations of $PM_{0.1}$ in the presence of children at S1 and S2were 3.1 ± 1.3 µg/m³ and 2.2 ± 0.6 µg/m³ respectively, while those values obtained when there were nochildren in the classrooms at S1 and S2 were 1.4 ± 1.2 µg/m³ and 1.1 ± 0.6 µg/m³, respectively (Table 3). The differences in indoor and outdoor concentrations of ultrafine particles between S1 and S2 were in significant (p > 0.05). $PM_{0.1}$ (ultrafine particles or particulate matter with an aerodynamic diameter < 0.1 µm); $PM_{0.5}$ (particulate matter with an aerodynamic diameter < 0.5 µm); PM_1 (particulate matter with anaerodynamic diameter < 1 µm); $PM_{2.5}$

Table 4. Indoor water-solubleion size-resolved air borne particle concentrations collected during the class at S1 and S2 (n = 10 for eachion, with a total of 70 samples, average ± SD, in parentheses are min–maxvalues).

	$PM_{0.1}$	$PM_{0.5}$	PM_1	$PM_{2.5}$	PM_{10}
S1					
Na^+	0.56±1.78	2.14±1.08	3.93±2.30	5.20±3.03	6.16±3.32
	(0.45-0.74)	(3.20-6.82)	(6.43-1.19)	(8.31-1.52)	(9.28-1.97)
K^+	2.62±2.62	3.65±4.36	5.57±6.69	6.51±7.62	7.18±7.64
	(1-5.64)	(1.91-9.94)	(4.25-15.1)	(6.56-16.6)	(1.92-9.36)
Mg^{2+}	2.82±2.74	3.36±2.91	6.20±5.86	7.79±7.24	7.90±9.40
	(1.11-5.98)	(3.32-7.23)	(6.75-13.8)	(8.37-17.6)	(12.2-20.1)
Ca^{2+}	1.14±1.52	1.24±1.05	2.83±2.90	4.20±3.88	5.22±4.38
	(0.78-3.58)	(1.70-2.67)	(2.90-7.53)	(3.40-9.96)	(8.87-11.4)
Cl^-	0.80±0.46	2.39±0.35	4.22±1.46	6.44±1.37	8.16±1.37
	(0.43-1.32)	(2.1-3.0)	(2.91-6.52)	(5.13-8.36)	(6.8-9.96)
NO_3^-	0.58±0.45	3.32±2.50	6.02±5.57	8.19±7.3	9.01±7.34
	(0.22-1.10)	(0.31-5.80)	(0.44-14.6)	(0.89-18.84)	(1.85-19.61)
SO_4^{2-}	0.60±0.29	5.64±4.90	10.1±9.80	11.44±10.98	12.45±11.51
	(0.29-0.86)	(0.70-12.5)	(1.12-20.3)	(2.18-25.08)	(3.53-29.76)
S2					
Na^+	0.90±0.23	2.0±0.23	2.82±0.68	3.5±0.07	4.23±1.25
	(0.87-0.92)	(1.85-2.14)	(2.76-2.88)	(3.5-3.55)	(4.15-4.49)
K^+	2.73±0.41	6.14±0.39	7.64±0.44	11±0.5	13.1±1.82
	(2.44-3.02)	(6.42-5.86)	(7.95-7.32)	(11.3-10.6)	(14.4-11.8)
Mg^{2+}	7.1±3.13	12.8±3.35	17.2±3.22	23±0.81	25.8±1.8
	(4.89-9.31)	(15.1-10.4)	(19.5-15)	(23.5-22.4)	(27.1-24.5)
Ca^{2+}	3.16±2.39	8.94±4.09	12.8±3.49	16.9±3.57	19.4±5.49
	. (1.47-4.85)	(11.8-6.05)	(15.2-10.3)	(19.5-14.4)	(23.3-15.6)
Cl^-	2.86±0.18	5.93±0.43	8.87±0.24	12.5±1.37	14.8±0.25
	(2.74-2.99)	(5.63-6.23)	(8.69-9.04)	(11.5-13.5)	(14.6-15)
NO_3^-	0.71±0.15	1.56±0.38	2.33±0.96	2.81±1.34	3.13±1.13
	(0.6-0.82)	(1.28-1.83)	(1.65-3.01)	(1.86-3.76)	(2.33-3.93)
SO_4^{2-}	0.37±nd	0.98±0.01	1.54±0.21	2.14±0.55	2.81±0.72
	(0.37-0.38)	(0.98-0.99)	(1.39-1.68)	(1.75-2.53)	(2.31-3.32)

(particulate matter with an aerodynamic diameter < 2.5 µm); $PM_{2.5}$ (particulate matter with an aerodynamic diameter < 10 µm); $PM_{2.5-10}$ (fraction of particulate matter with an aerodynamic diameter in the range of 2.5-10 µm).

Descriptive statistics for water-soluble ions in indoor and outdoor PM at the two sampling sites can be found in Table 4 and Table 5. All cation and anionsconcentrations were higher than LoD in all particle size fractions at the two schools. Of all the ions detected, nitrate was the dominant constituent of all particles which was followedclosely by sulfate.

Particulate nitrate is formed through the photo oxidation of nitrogen dioxide emitted from combustion processes (Ho, *et al.*, 2003). Sulfate aerosols are formed through the heterogenous or homogenous reactions of sulfur dioxide (Cheng, *et al.*, 2000). Contribution of ions to the total water-soluble ions andmass concentrations of indoor and outdoor PM_{10}, $PM_{2.5}$, PM_1 and $PM_{0.1}$ for each sampling site are given in Table 4 and 5, respectively. Regardless from indoor or outdoor and sampling site, secondary inorganic aerosols (sum of sulfate, nitrate, and ammonium) were the main water-soluble ions, and their percentage increased with decreasing PM size. In fact, they accounted for about 60-80% of the mass of water-soluble ionsin PM_{10} (5-20% of PM_{10} mass), 75-85% in $PM_{2.5}$ (20-40% of $PM_{2.5}$ mass), and more than 90% in PM_1 (25-45% of PM_1 mass). Our study, thus, adds the evidence that the smaller the particle, the higher the percentage of secondary inorganic aerosols. This study also suggests that sea-salt species (sodium and chloride) and crustal elements (potassium, magnesium, and calcium) are mainly found incoarse particles. High levels of secondary inorganic aerosols indicate a high degree of anthropogenic pollution in this area. They aremost likely formed secondarily from NO_x and SO_2 gases. It is noticeable that the high values of sodium, potassium, magnesium, and calcium

Table 5. Indoor water-solubleion size-resolved air borne particle concentrations collected during the class at S1 and S2 (n = 10 for eachion, with a total of 70 samples, average ± SD, in parentheses are min–max values).

	$PM_{0.1}$	$PM_{0.5}$	PM_1	$PM_{2.5}$	PM_{10}
S1					
Na^+	1.21±0.19	3.36±0.52	5.77±2.08	7.12±3.35	7.81±3.67
	(1.05-1.42)	(2.45-3.72)	(3.60-7.82)	(3.8-10.8)	(4.58-11.8)
K^+	3.64±2.80	9.27±7.02	12.6±10.1	14.0±11.6	14.7±11.6
	(1.96-6.87)	(3.42-20.1)	(5.35-24.1)	(5.85-27.2)	(6.73-28.0)
Mg^{2+}	2.75±2.05	5.31±2.71	11.7±3.67	13.7±5.06	15.1±5.93
	(0.39-3.97)	(0.56-7.09)	(9.46-16.0)	(10.60-19.6)	(11.3-22.0)
Ca^{2+}	1.43±0.70	2.79±0.31	5.54±1.44	7.95±2.19	9.91±2.53
	(0.66-2.04)	(2.35-3.19)	(4.65-7.21)	(6.59-10.5)	(8.45-12.8)
Cl^-	1.18±0.71	2.55±0.7	5.72±1.2	8.97±1.55	11.3±2.14
	(0.37-1.71)	(1.85-3.6)	(4.38-7.51)	(6.5-10.6)	(8.38-14)
NO_3^-	1.85±0.64	5.28±2.01	12.8±8.4	18.7±11	21.3±12.6
	(1.2-2.48)	(2.34-7.15)	(3.39-24.7)	(7.07-33.8)	(7.83-38.3)
SO_4^{2-}	4.07±0.54	11.3±2.81	23.4±13.5	26.5±14.6	28.4±15.2
	(3.48-4.55)	(7.56-14.9)	(11.2-45.3)	(12.3-49.7)	(13.5-52.0)
S2					
Na^+	0.98±0.39	2.39±0.71	5.26±0.83	7.93±0.58	8.65±1.60
	(0.70-1.25)	(1.89-2.90)	(4.68-5.85)	(7.52-8.35)	(7.52-9.79)
K^+	0.65±0.19	5.20±3.23	11.9±2.08	14.6±2.31	15.3±1.34
	(0.52-0.77)	(2.92-7.48)	(10.5-13.4)	(13.0-16.2)	(14.3-16.2)
Mg^{2+}	1.13±0.59	2.91±1.12	9.71±9.10	16.7±11.3	19.9±6.91
	(0.71-1.55)	(2.12-3.70)	(3.28-16.1)	(8.75-24.7)	(15.0-24.8)
Ca^{2+}	0.664±4.00	1.62±0.15	4.01±0.65	9.15±1.50	11.3±1.61
	(0.38-0.95)	(1.52-1.72)	(3.56-4.47)	(8.09-10.2)	(10.2-12.5)
Cl^-	2.61±1.17	7.27±2.69	19.7±5.48	31.3±1.42	38.4±1.33
	(1.79-3.44)	(5.36-9.17)	(15.8-23.6)	(30.3-32.3)	(37.5-39.4)
NO_3^-	1.93±0.44	7.7±2.22	24.1±5.12	38.3±6.1	44.2±5.51
	(1.62-2.24)	(6.12-9.27)	(20.5-27.7)	(34-42.6)	(40.3-48.1)
SO_4^{2-}	1.91±0.81	8.18±2.81	26±4.12	34.4±1.21	40±0.85
	(1.34-2.48)	(6.18-10.2)	(23.1-28.9)	(33.6-35.3)	(39.4-40.6)

detected for indoor PM_{10} in the school dormitory may indicate resuspension of soil deposited on the floor and other surfaces such as beds, benches, and shoes.

It is shown that water-soluble ions in ultrafine fraction accounted for around 5%–35% of their content in PM_{10}, while their concentration in fine particles ($PM_{2.5}$) made up a range of 75% to 80% of indoorand outdoor PM_{10} at S1 and S2. Those major elements seemed to be slightly more enriched in coarse fraction ($PM_{2.5-10}$) compared to ultrafine fraction (5-35% for ultrafine fraction vs 79-98% for coarse fraction). A similar trend was observed with the case ofindoor particles at S1 and for outdoor particles at S1 and S2. Indoor activities of occupants seemed not to influence the elemental distribution in indoor particles compared to outdoor ones (Table 4 and 5). Our results were in accordance with reported work (Tran, *et al.,* 2015; Lai, 2002), carried out in school environments.

Water soluble ions commonly presented unimodal distribution for indoor and outdoor airborne particles at S1 and S2 (Fig. 9), with the dominant peak occurring in the particle diameter range (Dp) = 0.5–1 µm at S2 and 1–2.5 µm at S1. The average accumulative proportions of examined elements indoor and outdoor at S1 and S2 accounted for about 67–93% of their total mass in PM_{10} (Fig. 10). The appearance of unimodal distribution for all elements might be associated with the limited resolution of the cascade impactor (only one fraction in coarse particles - $PM_{2.5-10}$), which probably masked the elemental distribution within thecoarse mode.

Indoor, outdoor particle morphology and elemental analysis

SEM imagesof indoor $PM_{0.1}$, $PM_{0.1-0.5}$, $PM_{0.5-1}$, $PM_{1-2.5}$, and $PM_{2.5-10}$ sampled during the teaching hoursat S1and S2 are presented in Figures 11 and 12,
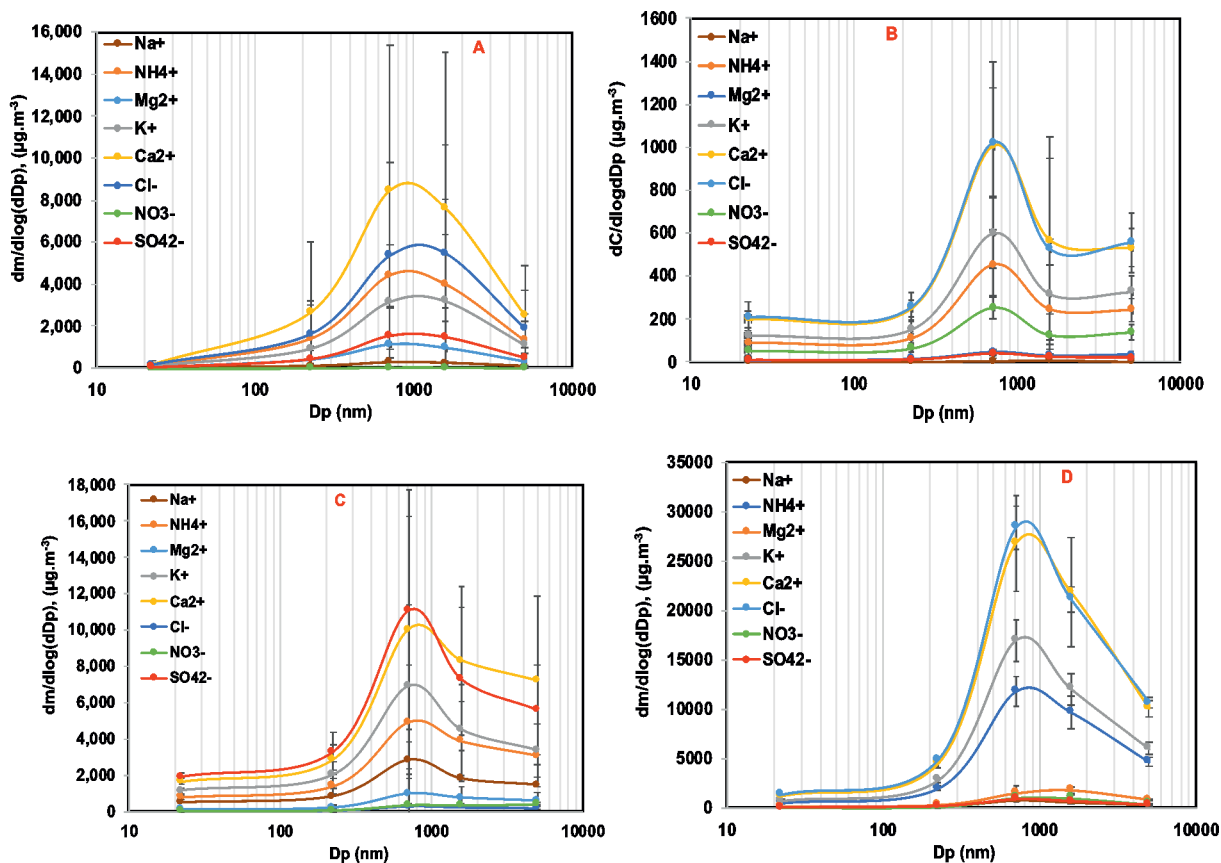
Fig. 9. Average size-resolved water-soluble ion distributions ofindoorairborne particles sampled during the class at S1 (A) and S2 (B). C, D are respectively velues for outdoor particles at S1 and S2. n = 70, average ± SD.

respectively. Interms of particle morphology, indoor and outdoor particles collected at S1 presented similar forms for each particulate fraction. Particles within the largest fraction (PM$_{2.5-10}$) did not have regular forms but most of them displayed the cubic-like shape, while smaller fractions tended to aggregate to form clusters with fine structures. The sub micronfractions (PM$_{0.5-1}$and PM$_{0.1-0.5}$) presented the largest population, which were aggregated more tightly, resulting in the formation of blocks of particles with much lower porosity compared to other factions.
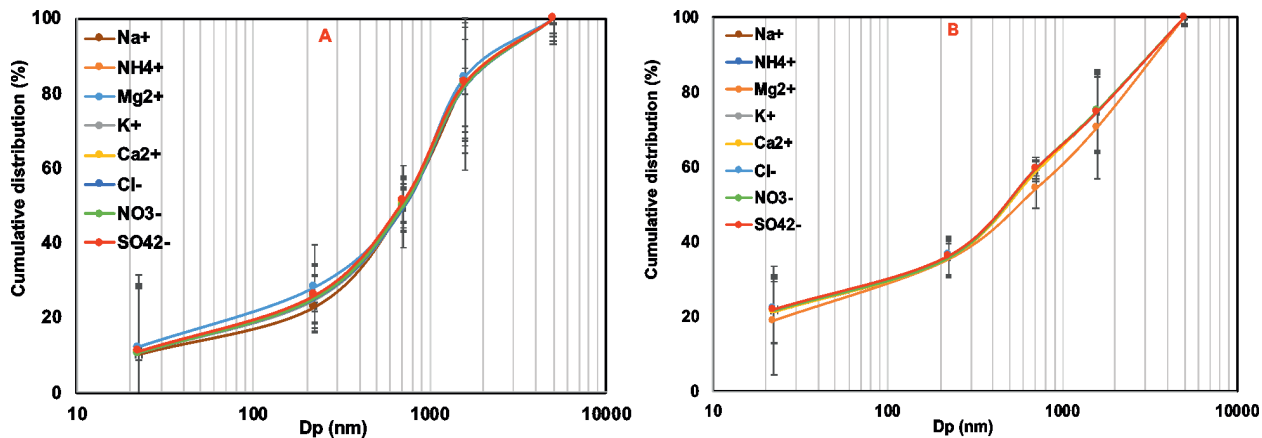
Fig. 10. Cumulative size-resolved elemental distributions of indoor airborne particles sampled duringthe class at S1 (A) and S2 (B). n = 70, average ± SD.

PM$_{0.1}$ PM$_{0.1-0.5}$ PM$_{0.5-1.0}$

PM$_{1.0-2.5}$ PM$_{2.5-10}$

Fig. 11. SEM images of indoor particles (PM$_{0.1}$; PM$_{0.1-0.5}$; PM$_{0.5-1.0}$; PM$_{1-2.5}$; PM$_{2.5-10}$) collected during teaching hours at S1.

PM$_{0.1}$ PM$_{0.1-0.5}$ PM$_{0.5-1.0}$

PM$_{1.0-2.5}$ PM$_{2.5-10}$

Fig. 12. SEM images of indoor particles (PM$_{0.1}$; PM$_{0.1-0.5}$; PM$_{0.5-1.0}$; PM$_{1-2.5}$; PM$_{2.5-10}$) collected during teaching hours at S2.

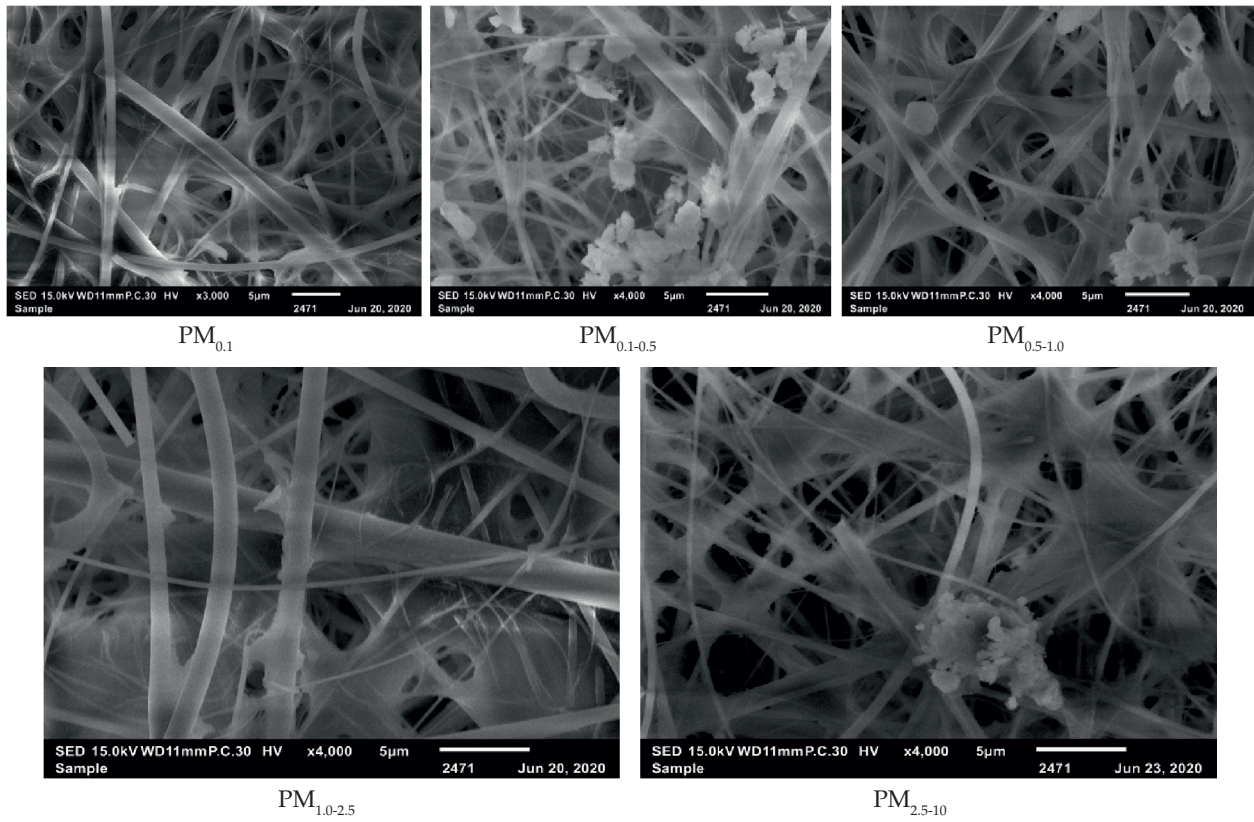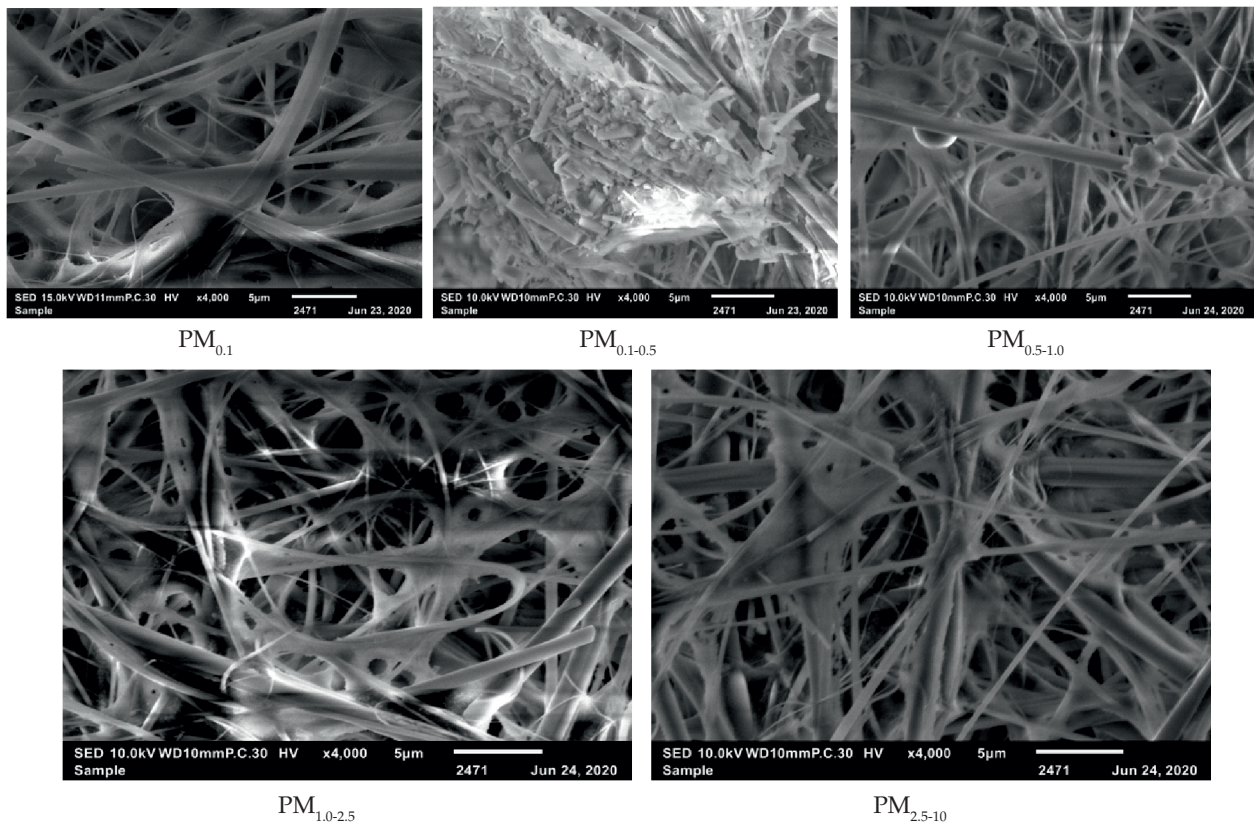The SEM results suggested that the presence of young children in the class led to increases the concentration of fine particles whereas the concentration of ultrafine particles were not much impacted by children's presence and activities (Fig. 11 and 12). This suggests that fine dust accounts for the majority of PM_{10} particles in indoor air of the examined schools.

Table 6 and 7 show elemental composition of indoor $PM_{0.1}$, $PM_{0.1-0.5}$, $PM_{0.5-1}$, $PM_{1-2.5}$, and $PM_{2.5-10}$ sampled during teaching hours at the same schools, respectively. The obtained results revealed that oxygen was the most abundant element, accounted for (1.23-3.98% by total mass of different particle fractions), followed by Si element (0.62-2.11%) and carbon (0.64-1.90%). It was observed that those major elements were presented more in larger particles (PM_{10}). As the presence of carbon and oxygen elements might be linked with the matrix of the filter, we only calculated the percentage of other major elements (Na, Al, Si, K, Ca, Ba), and found that they accounted for 0.94% in $PM_{0.1}$ while this value was 3.74% in PM_{10} at S1 (Table 6). Similarly,

those figures for S2 were respectively 4.6 and 4.8 for indoor $PM_{0.1}$ and PM_{10}.

It is noted that EDS measurement did not provide accurate results for element having a content less than 0.5%. As a results, attention should be paid for the elements with their mass proportions under 0.5% of the total mass of the sample.

CONCLUSION

This work performed at 2 elementary schools in Hanoi, Vietnam, is focusing on mass, number concentration of indoor/outdoor airborne particles and their chemical composition, morphology, and elemental distribution, which provides insights into the context of air quality in at school environment in Hanoi. The results showed that the average concentrations of indoor and outdoor CO and CO_2 were below the limit values recommended by WHO and ASHRAE for 24 h exposure. Indoor average concentrations of PM_{10} and $PM_{2.5}$ were below the limit values recommended by WHO at S2, where as they exceeded these recommendations at S1. The

Table 6. Concentration of major elements in indoor ultrafine, fine, and coarse fractions collected during teaching hours at S1.

	$PM_{0.1}$	$PM_{0.1-0.5}$	$PM_{0.5-1.0}$	$PM_{1.0-2.5}$	$PM_{2.5-10}$
C	1.54	1.16	0.68	0.64	1.90
O	1.37	1.67	3.98	1.23	3.93
Na	0.19	0.16	0.49	0.22	0.55
Al	0.07	0.10	0.59	0.06	0.23
Si	0.62	0.66	0.80	0.66	2.11
K	0.06	0.09	0.05	0.07	0.23
Ca	nd	0.12	0.19	nd	0.14
Ba	nd	nd	nd	nd	0.48
Total	3.85	3.96	6.78	2.88	9.57

nd: non-detectable

Table 7. Concentration of major elements in indoor ultrafine, fine, and coarse fractions collected during teaching hours at S2.

	$PM_{0.1}$	$PM_{0.1-0.5}$	$PM_{0.5-1.0}$	$PM_{1.0-2.5}$	$PM_{2.5-10}$
C	7.55	3.12	1.28	1.21	1.62
O	9.40	1.48	1.44	1.73	2.18
Na	1.40	0.09	0.21	0.28	0.38
Al	0.33	0.16	0.09	0.09	0.13
Si	3.21	1.22	0.73	0.84	1.12
K	0.29	0.21	0.08	0.09	0.11
Ca	0.15	0.12	0.05	nd	nd
Ba	0.52	0.53	nd	nd	nd
Total	22.85	6.93	3.88	4.24	5.54

nd: non-detectable

presence of children and their activities strongly influenced the concentration of fine $PM_{2.5}$ and PM_{10} factions, whereas they did notseem to have significant impacts on ultrafine particles. Althouth occupants' activities indoors and outdoors have impacts on [article mass concentration, particle number concentration seems not be influenced by such activities.

Regarding elemental composition and morphology of airborne particles sampled at S1 and S2, it was shown that the coarse fraction (2.5–10 μm) did not present regular shapes, while smaller factions tended to aggregate to form clusters with fine structures. The submicron fractions ($PM_{0.5–1}$ and $PM_{0.1–0.5}$) presented the largest population, which were aggregated more tightly. Oxygen (1.3%–9.4%) was the most abundant element, followed by C (0.6%-7.2%) and then Si in indoor and outdoor airborne particles. A mass proportion of major and minor elements could make up to around 5.0%. Water-soluble ions and major elements presented unimodal distribution.

Data Availability All data generated or analyzed during this study are included in this published article.

Conflict of interest The authors declare no conlicts of interest.

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