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The underpinning factors affecting the classroom air quality, thermal comfort and ventilation in 30 classrooms of primary schools in London

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ABSTRACT

The health and academic performance of children are significantly impacted by air quality in classrooms. However, there is a lack of understanding of the relationship between classroom air pollutants and contextual factors such as physical characteristics of the classroom, ventilation and occupancy. We monitored concentrations of particulate matter (PM), CO_2 and thermal comfort (relative humidity and temperature) across five schools in London. Results were compared between occupied and unoccupied hours to assess the impact of occupants and their activities, different floor coverings and the locations of the classrooms. In-classroom CO_2 concentrations varied between 500 and 1500 ppm during occupancy; average CO_2 (955 ± 365 ppm) during occupancy was ~150% higher than non-occupancy. Average PM_{10} (23 ± 15 μgm^{-3}), $PM_{2.5}$ (10 ± 4 μgm^{-3}) and PM_1 (6 ± 3 μg m^{-3}) during the occupancy were 230, 125 and 120% higher than non-occupancy. Average RH (29 ± 6%) was below the 40–60% comfort range in all classrooms. Average temperature (24 ± 2 °C) was >23 °C in 60% of classrooms. Reduction in PM_{10} concentration (50%) by dual ventilation (mechanical + natural) was higher than for $PM_{2.5}$ (40%) and PM_1 (33%) compared with natural ventilation (door + window). PM_{10} was higher in classrooms with wooden (33 ± 19 μg m^{-3}) and vinyl (25 ± 20 μgm^{-3}) floors compared with carpet (17 ± 12 μgm^{-3}). Air change rate (ACH) and CO_2 did not vary appreciably between the different floor levels and types. $PM_{2.5}/PM_{10}$ was influenced by different occupancy periods; highest value (~0.87) was during non-occupancy compared with occupancy (~0.56). Classrooms located on the ground floor had $PM_{2.5}/PM_{10}$ > 0.5, indicating an outdoor $PM_{2.5}$ ingress compared with those located on the first and third floors (<0.5). The large-volume (>300 m^3) classroom showed ~33% lower ACH compared with small-volume (100–200 m^3). These findings provide guidance for taking appropriate measures to improve classroom air quality.

1. Introduction

Indoor air quality has a substantial effect on human health, well-being and performance (Becerra et al., 2020), specifically in children, who are more vulnerable and sensitive to the presence of indoor air pollutants (Meiboudi, et al., 2016). Children's lung development can be negatively impacted by air pollution, which may also raise their chance of developing respiratory infections (Gehring et al., 2013). Around ten million pupils attend school in the UK, and they spend roughly 70% of their school days in a classroom (~30% of their life) (Han et al., 2015; Jainn et al., 2020). As a result, classrooms are classified as the second-most significant indoor place for children after their home. In England, there are over 7800 schools situated in locations where the average $PM_{2.5}$ in 2017 was higher than the recommended WHO standard (10 g/m^3) (Osborne et al., 2021). London also had ~800 schools where the annual average NO_2 concentrations exceeded the UK standard value (40 g/m^3) (Brook and King, 2017). Since children spend considerable time (7–11 h daily) in schools (Almeida et al., 2011), it is vital to evaluate pollutants exposure and assess thermal comfort factors in classrooms.

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Children may experience increased personal exposure since they usually engage in more outdoor activity for longer periods and breathe higher air (volume/minute) than adults (Osborne et al., 2021). Both indoor-generated and incoming outdoor air pollutants, the latter normally linked to road traffic, are classified as classroom air pollutants. Due to the proximity of major roads to schools in urban and rural areas, traffic emissions are a significant source of PM in schools (Abhijith et al., 2022; Kumar et al., 2020). For instance, around 2000 nurseries and schools in the UK are positioned within 150 m of roads with high air pollution and traffic density (Irvin, 2018). All factors, such as proximity of traffic density, car idling, flow profile on nearby roads and streets, and children's drop-off and pick-up timings, play crucial roles in determining the extent of outdoor pollution related to traffic emission, and that ingresses into classrooms and effect on the indoor air quality (Kumar et al., 2020; Abhijith et al., 2022). For example, the ingress of road traffic pollutants during morning drop-off times caused a two-fold increase in $PM_{2.5}$ concentration in a classroom (Kumar et al., 2020). Local pollutant levels are also impacted by urban development surrounding schools. For instance, greenery around schools and densely populated regions are linked to low and high levels of pollution, respectively (Dadvand et al., 2015; Amato et al., 2014).

Addition to in-classroom air pollutants, other perspectives of the indoor environment, as measured by other factors like ventilation with fresh air, thermal comfort, classroom volume, and RH, also significantly affect the health and wellbeing of children. As a result, IAQ can have an impact on their attendance at school, learning performance and productivity (Annesi-Maesano et al., 2013) and thermal comfort (Ervasti et al., 2012). Owing to the majority of time spent indoors, indoor CO_2 levels and related health risks have become gradually substantial. CO_2 levels higher than 1000 ppm are linked with low ventilation rates (VRs) in classrooms, more frequently occurred headaches, increased lack of attention, respiratory patterns, and a higher possibility of asthma attacks among students (Haddad et al., 2021; Cai et al., 2021). Low ventilation rates, low relative humidity and high temperatures adversely influence the cognitive ability of pupils in the classes (Bakó-Biró et al., 2012; Teli et al., 2017). Strong links between high indoor temperatures and inadequate ventilation, causing worsening in IAQ, have been shown in earlier studies (Vornanen-Winqvist et al., 2020). Thus, appropriate consideration of various aspects of the indoor environment, beyond only IAQ, is required in controlling indoor environmental conditions in schools to allow for effective learning and to ensure the wellbeing and the mental and physical health of children.

In-classroom exposure studies mostly focus on a single parameter or a single school, restricting the potential of generalisation at the city scale. Also, very limited studies have been performed on in-classroom exposure-related experimental studies in the UK, and the data are often for short durations or inconsistent, with inconsistent sampling methods (Table S1). An overview of relevant previous studies showed a lack of work using an integrated approach to evaluate in-classroom PM and CO_2 exposure in different schools within London (Table S1). Thus, this work aims to fill this gap by monitoring in-classroom PM and CO_2 exposures in five schools in the London area, which comes under the Ultra Low Emission Zone (TFL, 2022). We focused on the exposure to airborne particles ($PM_{10,}$ PM_1, and $PM_{2.5}$), and CO_2 concentrations across classrooms in these schools where inadequate studies are presently available as demonstrated by the summary of previous studies (Table S1). The overall goal is to examine the factors that impact in-classroom CO_2, aerosol with thermal comfort in 30 classrooms across five schools in London. We discuss the variation of the in-classroom aerosol and CO_2 concentrations, thermal comfort and ventilation conditions amongst the 30 classrooms in reference to variations in classroom condition, specifically in relation to ventilation, volume of classroom, floor location, floor type and occupancy; and finally, we examine ACH and ventilation rates to provide the practical recommendations and scientific evidence base, to improve in-classroom indoor environment in schools across the UK.

2. Methodology

2.1. School sites

Thirty classrooms were monitored across two secondary urban and three primary and schools, which are referred to as S1–S5 (Fig. 1). Six classrooms were monitored per school during the winter season. Continuous in-classroom monitoring of PM (PM_{10}, PM_1 and $PM_{2.5}$) and CO_2, relative humidity (RH) and temperature was carried out for two weeks (weekends included) in each of the designated schools. Table 1 shows the characteristics of the monitored classroom. Out of 30 monitored classrooms, the majority (76%; 23) had natural ventilation (door, window and skylight openings), 10% (3) had mechanical ventilation and 13% (4) had a combination of both systems (dual ventilation). The volume of monitored classrooms varied between 138 and 1755 m^3. In addition, 50% (15), 37% (11) and 13% (4) of classrooms were located on the ground, first and third floor, respectively. In-depth questionnaires were conducted to obtain qualitative data regarding school building and occupancy levels, including ventilation, volume of classroom, floor area, and dimensions, status of windows and doors (closed or open), cleaning frequency and flooring type (Tables S2-S6).

Owing to understand in-classroom air quality as a function of ventilation, classrooms were divided into six ventilation types: (1) T1: Natural ventilation (NV): high ceilings and adaptable window openings (e.g. high level and low-level openings); (2) T2. NV: medium ceiling height: single side ventilation: limited opening options; (3) T3. Same as (T2) but with cross ventilation e.g., to a corridor; (4) T4. NV: Low ceiling: single sided; (T5) Mechanical ventilation (MV); (6) T6. Mixed natural and mechanical ventilations (DV_{mn}).

2.2. Data collection

Data were collected between January 10, 2022 and April 01, 2022 for 72 days, including weekends. The collected data from all instruments was consolidated, cleaned and then averaged to a 1-min interval. The cleansed dataset was then subjected to data analysis using R (R Core Team, 2022) and Microsoft Excel with the assist of the openair package (Carslaw and Ropkins, 2012). School-opening hours were considered to be 08.00–18.00 h, while the rest of the period was termed as non-school hours. The six different classrooms were monitored simultaneously in each school using the same monitoring setup, as described in Section 2.3.

2.3. Instrumentation

The monitoring setup consisted of CO_2 monitors (Q-TRAK; TSI Inc., model 7575) and an optical particle counter (Alphasense OPC-N3). The Q-TRAK measured CO_2 levels in the range of 0–5000 ppm, with an accuracy of ±50 ppm. They also measured RH and temperature. The monitoring range of RH and temperature was 5–95% and -10-60 °C, with an accuracy of ±3% and 0.5 °C, respectively. The CO_2 monitors were factory calibrated before being used in this study. As a proxy of the ventilation condition, the CO_2 was measured and also utilised to estimate the ACH and ventilation condition in each classroom (Section S1). The OPC-N3 measured PM (PM_1, $PM_{2.5}$, and PM_{10}) levels. These were successfully used in previous indoor and outdoor monitoring studies (Kumar et al., 2022c, 2023; Mills et al., 2023). These measures segregated particle numbers into 24-size bins between 0.35 and 40 μm. More details about OPC-N3 can be found in previous studies (Kumar et al., 2023; Sousan et al., 2016).

2.4. Quality assurance and control

All the instruments used were either factory-calibrated (Q-TRAK monitors) or new (Alphasense OPC-N3). To ensure the PM data quality, we carried out two days of co-located experiments (before starting the

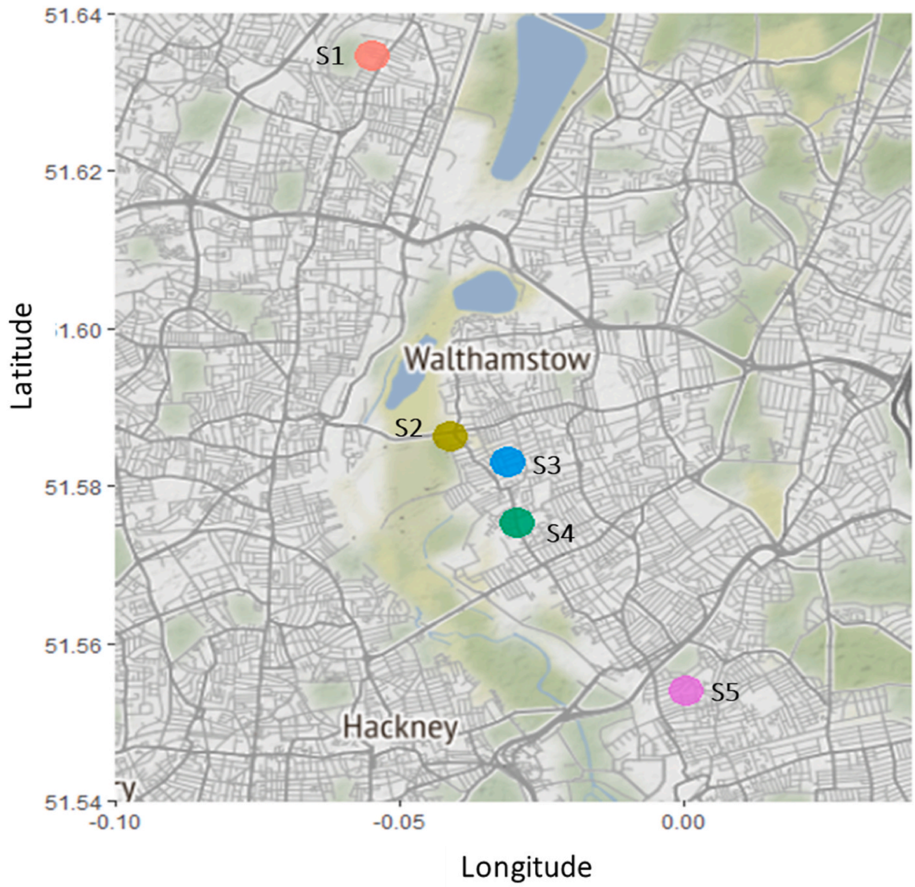

Fig. 1. Location map showing the five schools (S1, S2, S3, S4 and S5) monitored in London, UK.

campaign) with a research-grade OPC (GRIMM model 11-C). During colocation, all OPC-N3 sensors were co-located along with the GRIMM under normal conditions in a laboratory where 1% NaCl solution (by weight), produced by a nebulizer, was utilised to create various-sized aerosols (flow rate, 6 l min^{-1}) (Kumar et al., 2023). Data were recorded in 1-min intervals. The Pearson correlation coefficient revealed high agreement across all aerosol monitors between GRIMM and OPC-N3 was larger than ~0.87 (PM_{10}), 0.91 ($PM_{2.5}$) and 0.96 (PM_1). Figure S1 shows the cross-comparison among OPC-N3 units and they showed a good correlation which is larger than ~0.96 (PM_{10}), 0.97 ($PM_{2.5}$) and 0.98 (PM_1). The Q-TRAK CO_2 monitors were tested using a similar methodology. The CO_2 measured by the Q-TRAK monitors at night time (01–02 h, local time) in the classrooms was utilised as a background concentration in order to assess CO_2 monitor performance (Kumar et al., 2023). The concentration disparity between the Q-TRAK CO_2 device was smaller than the measurement error (±50 ppm).

2.5. Estimation of ACH and VR

Air change rate (ACH) is calculated using CO_2 (tracer gas) and categorised based on occupancy and CO_2 level derived utilising three methods: build-up; steady-state and decay (Batterman, 2017; Ramalho et al., 2013; Kumar et al., 2022b). We applied two methods (decay and build-up) for calculating the ACH in these 30 classrooms, as used by previous classroom works (Abhijith et al., 2022; Stabile et al., 2016). More details on both these methods can be found in SI section S2.

3. Results and discussion

3.1. Classroom characteristics

The CO_2, PM, RH and temperature data collected from 30 classrooms were separated into six groups: ventilation type, classroom volume, occupancy, floor level, floor type and schools (Fig. 2a). During school hours, 33%, 30%, 13%, 13%, 7% and 3% of the classrooms fell into the ventilation category T4 (NV), T1 (NV), T2 (NV), T6 (MV), T5 (MV) and T3 (NV), respectively (Fig. 2b). Broadly, 80%, 13% and 6.7% of the classrooms used NV, MV, and DV_{mn}, respectively (Fig. 2c).

The average classroom volume was 245 m^3 with ranges ~138 and 1755 m^3; 53%, 40% and 7% of the classroom fell within V1 (100–200), V2 (200–300) and V3 (>300) m^3, respectively (Fig. 2d). As for the floor level, 50%, 37% and 13% of classrooms were located at the ground, first and third floor, respectively (Fig. 2e). In addition, 83%, 10% and 7% of classrooms had carpet, vinyl and wooden flooring, respectively (Fig. 2f). All schools had more than 95% occupancy level during school hours. To better understand and allow comparison, the occupancy has been classified into: high occupancy (26–30 occupants), low occupancy (up to 4 occupants in the classroom) and zero occupancy (demonstrating vacant classroom) for each classroom. The above classroom characteristics were used to understand their effect on the variations in PM concentration (Section 3.2), CO_2 (Section 3.4) and RH and temperature (Section 3.5).

3.2. In-classroom PM concentrations

Table S7 shows the statistics of PM concentrations which varied widely across classrooms. During school-opening hours, average PM_1, $PM_{2.5}$ and PM_{10} levels in the classrooms were 5 ± 2, 10 ± 2 and 20 ± 11

Table 1
Characteristics of the monitored classrooms. The classrooms were classified into three ventilation categories: (i) NV (T1-T4); (ii) MV (T5); and (iii) DVmn (T6). Sampling was carried out between January and April 2022 for all schools, i.e., S1 (10–27 January); S2 (27 January- 11 February); S3 (17 February- 4 March); S4 (7–18 March), and S5 (21 March- 1 April).

Classroom ID	Classroom dimension (m): L × W × H (volume; m^3)	Ventilation	Floor place	Floor type	Year group
S1C1	6.7 × 6.6 × 3.3 (146)	T1	Ground	Carpet	Second
S1C2	6.7 × 6.6 × 3.3 (146)	T3	Ground	Carpet	Second
S1C3	7.2 × 7.8 × 4.3 (241)	T1	Third	Carpet	Third
S1C4	7.2 × 7.8 × 4.3 (241)	T1	Third	Carpet	Third
S1C5	7.3 × 8.0 × 4.6 (269)	T1	Third	Carpet	Fourth
S1C6	7.3 × 8.0 × 4.6 (269)	T1	Third	Carpet	Fifth
S2C1	2.6 × 6.4 × 9.1 (151)	T4	Ground	Carpet	Seventh
S2C2	2.6 × 6.4 × 8.1 (135)	T4	Ground	Carpet	Ninth
S2C3	2.6 × 5.7 × 11.5 (170)	T4	Ground	Carpet	Eighth
S2C4	2.6 × 5.7 × 9.4 (139)	T4	Ground	Carpet	Ninth
S2C5	4.1 × 5.7 × 9.6 (224)	T2	First	Carpet	Tenth
S2C6	2.7 × 5.7 × 9.4 (145)	T4	First	Carpet	Eleventh
S3C1	2.7 × 7.1 × 9.2 (176)	T4	Ground	Carpet	Sixth
S3C2	2.7 × 6.9 × 9.2 (171)	T4	Ground	Carpet	First
S3C3	2.7 × 7.1 × 9.2 (176)	T4	Ground	Carpet	First
S3C4	3.2 × 7.1 × 9.2 (209)	T2	First	Carpet	Second
S3C5	3.2 × 7.3 × 9.2 (215)	T2	First	Carpet	Fourth
S3C6	3.2 × 7.2 × 9.2 (212)	T2	First	Carpet	Fourth
S4C1	2.7 × 9.3 × 9.6 (241)	T5	Ground	Vinyl	Eighth
S4C2	6.3 × 7.3 × 7.6 (349)	T6	Ground	Carpet	Seventh
S4C3	2.7 × 7.3 × 7.6 (150)	T6	Ground	Carpet	Seventh
S4C4	2.7 × 7.3 × 7.6 (150)	T6	First	Carpet	Ninth
S4C5	2.7 × 7.3 × 7.6 (150)	T6	First	Carpet	Ninth
S4C6	2.7 × 5.8 × 8.8 (138)	T5	First	Carpet	Ninth
S5C1	2.5 × 24.8 × 28.3 (1755)	T4	Ground	Vinyl	Reception
S5C2	4.1 × 6.4 × 7.7 (202)	T1	First	Carpet	Fourth
S5C3	4.1 × 6.5 × 8.4 (224)	T1	Ground	Vinyl	First
S5C4	4.4 × 6.8 × 6.9 (206)	T1	Ground	Wooden	Second
S5C5	4.3 × 6.1 × 7.4 (194)	T1	First	Wooden	Third
S5C6	2.6 × 7.2 × 8.0 (150)	T4	First	Carpet	Fifth

μg m^{-3}, respectively (Table S7). As expected, PM_{10} level showed the highest (20 ± 11 μg m^{-3}) due to the resuspension by children's and teachers' movement and classroom activities (Kumar et al., 2023). The PM_1 and $PM_{2.5}$ variations, which are typically associated with outside sources such as traffic emissions and combustion processes (Carrion-Matta et al., 2019; Hama et al., 2020; Kumar et al., 2021), were lower than PM_{10} during the school-opening periods since the studied classrooms are placed away from busy roads. The highest PM_{10} range was found for classrooms in S1, which was 16–41 μg m^{-3} (Fig. 3a), while the lowest was found for classrooms in school S2 (10–15 μg m^{-3}). These results are relatively lower with average $PM_{2.5}$ (∼17 μg m^{-3}) and PM_{10} (∼25 μg m^{-3}) than those found in previous school studies in London (Abhijith et al., 2022; Broeksstra et al., 2019).

Fig. 3b shows the average PM_{10} concentrations for the specific types of natural ventilation during school-opening hours. The highest average in-classroom PM_{10} concentration was found in classrooms with high ceilings and adaptable window openings ventilation (T1, PM_{10} ~ 23 μg m^{-3}), followed by cross and single-sided ventilation types, i.e., T3 (22), T2 (17) and T4 (17 μg m^{-3}). Figures S2b and S3b show the $PM_{2.5}$, and PM_1 levels for the specific types of natural ventilation, respectively. The trend of the average $PM_{2.5}$, and PM_1 level was similar to PM_{10} variation. The T1 type showed the highest PM_{10} concentration (12), followed by T3 (10) and T2 (8 μg m^{-3}). According to three different types of ventilation (Fig. 3c), the average PM_{10} concentration was as follows: NV (20) >MV (17) >dual (DVmn) ventilation (10 μg/m). The average $PM_{2.5}$ (or $PM_{1.0}$) concentration followed the same order as the PM_{10} based on the ventilation types (Figures S2c and S3c). However, the total reduction of PM_{10} concentration (50%) by dual ventilation was significantly higher than $PM_{2.5}$ (40%) and PM_1 (33%) when compared with natural ventilation.

Regarding the effect of volume, the average PM_{10} concentrations were 17 ± 14, 20 ± 13 and 22 ± 20 μg m^{-3} for V1, V2 and V3, respectively (Fig. 3d). The above findings confirmed the impact of other factors (such as occupancy) to be more impactful than the volume factor on in-classroom PM_{10} concentration. Figures S2d and S3d depict the average PM_1 and $PM_{2.5}$ for various sizes of classrooms. Average $PM_{2.5}$ ($PM_{1.0}$) levels were 9 ± 3 (5 ± 2), 10 ± 4 (6 ± 3) and 11 ± 5 (7 ± 3) μg m^{-3} for V1, V2 and V3, respectively (Tables S9 and S10). We noted that $PM_{2.5}$ and PM_1 follow the same trend as PM_{10} across the studied classrooms.

Fig. 3e shows the average PM_{10} concentrations for different floor levels during school-opening hours. The average PM_{10} concentrations were 18 ± 15, 19 ± 14 and 20 ± 12 μg m^{-3} for ground, first and third floor, respectively (Table S8). Figures S2e and S3e show the $PM_{2.5}$ and PM_1 in various floor levels, respectively. Average $PM_{2.5}$ and PM_1 followed the same trend as PM_{10} across the studied classrooms (Table S8), indicating that other factors discussed above and below might have a higher impact since the PM vertical profile relies on various factors other than the height of the building such as the geometry of the surrounding buildings and local meteorological conditions.

Fig. 3f shows the average PM_{10} concentrations for the different types of floors in all classrooms. The average PM_{10} concentrations were 17 ± 12, 25 ± 20 and 33 ± 19 μg m^{-3} carpet, vinyl and wooden, respectively. Figures S2f and S3f exhibit average $PM_{2.5}$, and PM_1 concentrations for various floor type in classrooms. Average $PM_{2.5}$ (PM_1) levels were 9 ± 3 (5 ± 2), 12 ± 6 (7 ± 4) and 14 ± 5 (9 ± 4) μg m^{-3} for carpet, vinyl and wooden, respectively (Tables S9 and S10). Interestingly, in-classroom PM concentrations showed the highest for wooden and vinyl floor types (hard floors), while we found the lowest PM concentrations for classrooms which had carpet floors (soft floors). This might be associated with particle resuspension from wooden and vinyl floors (Adamová et al., 2020; Bamai et al., 2014). A previous work indicated that the PM_{10} resuspension rate was ∼2.5 times higher than the $PM_{2.5}$ for wood and carpet floors (You and Wan, 2015). Although carpet classrooms showed the lowest PM concentrations, they can act as a repository of more dust and allergens compared with hard floors and may also become resuspended during cleaning activities such as hoovering or vacuuming (He et al., 2022; Becher et al., 2018; Bergmans et al., 2022), and therefore wall-to-wall carpets in the classrooms are not recommended. We also found that the RH level has a significant effect on the resuspension rate of PM_{10} concentration in indoor areas. For instance, the resuspension rate of PM_{10} under low humidity levels (RH = 41%) were 3- and

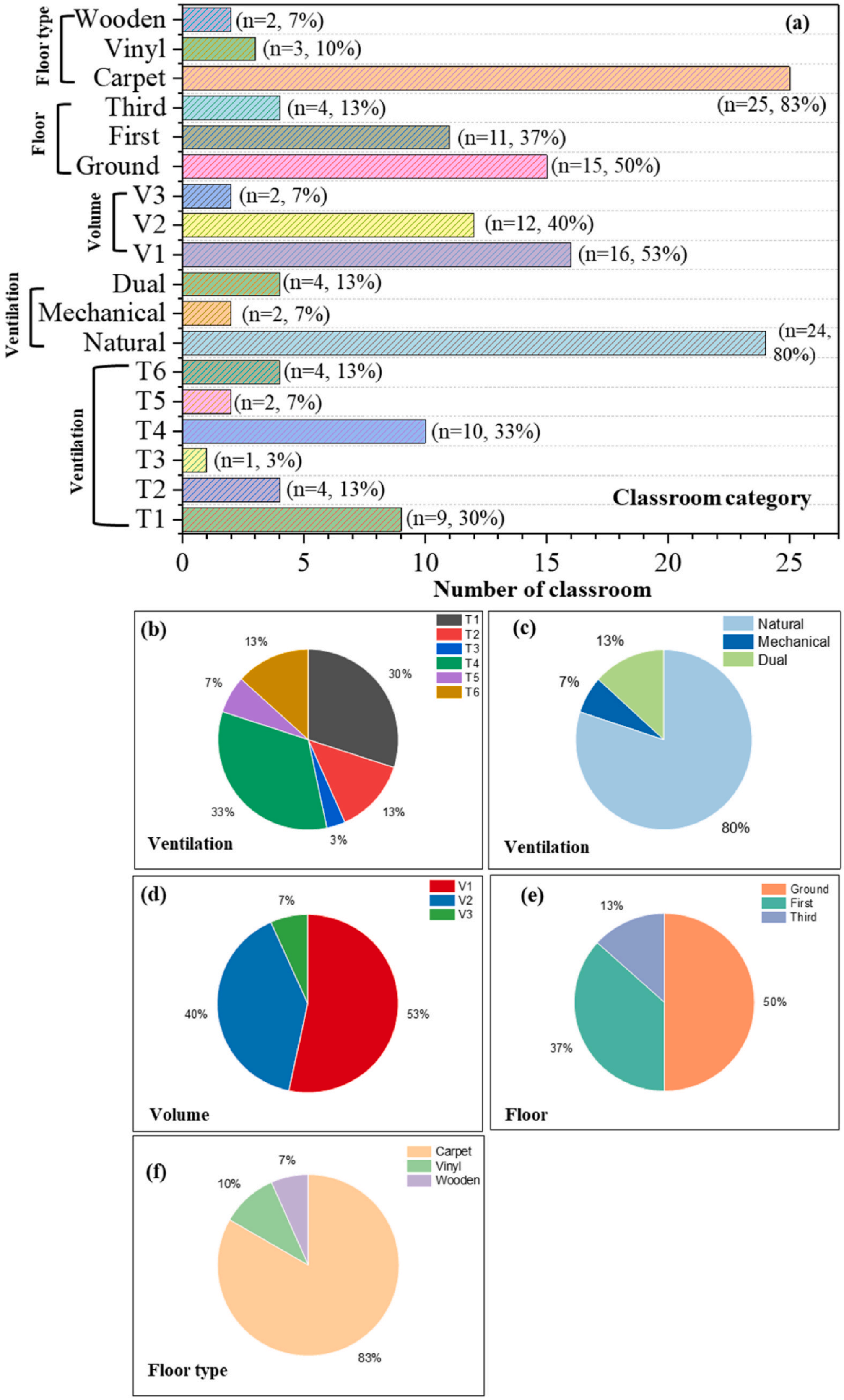

Fig. 2. (a) The proportion of different categories (floor types, floor location, volume and ventilation types) across the 30 classrooms in five schools. Pie Charts summarising the classroom characteristics according to: (b) type of ventilation (six categories); (c) ventilation type (three categories); (d) classroom volume; (e) floor location, and (f) type of floor.

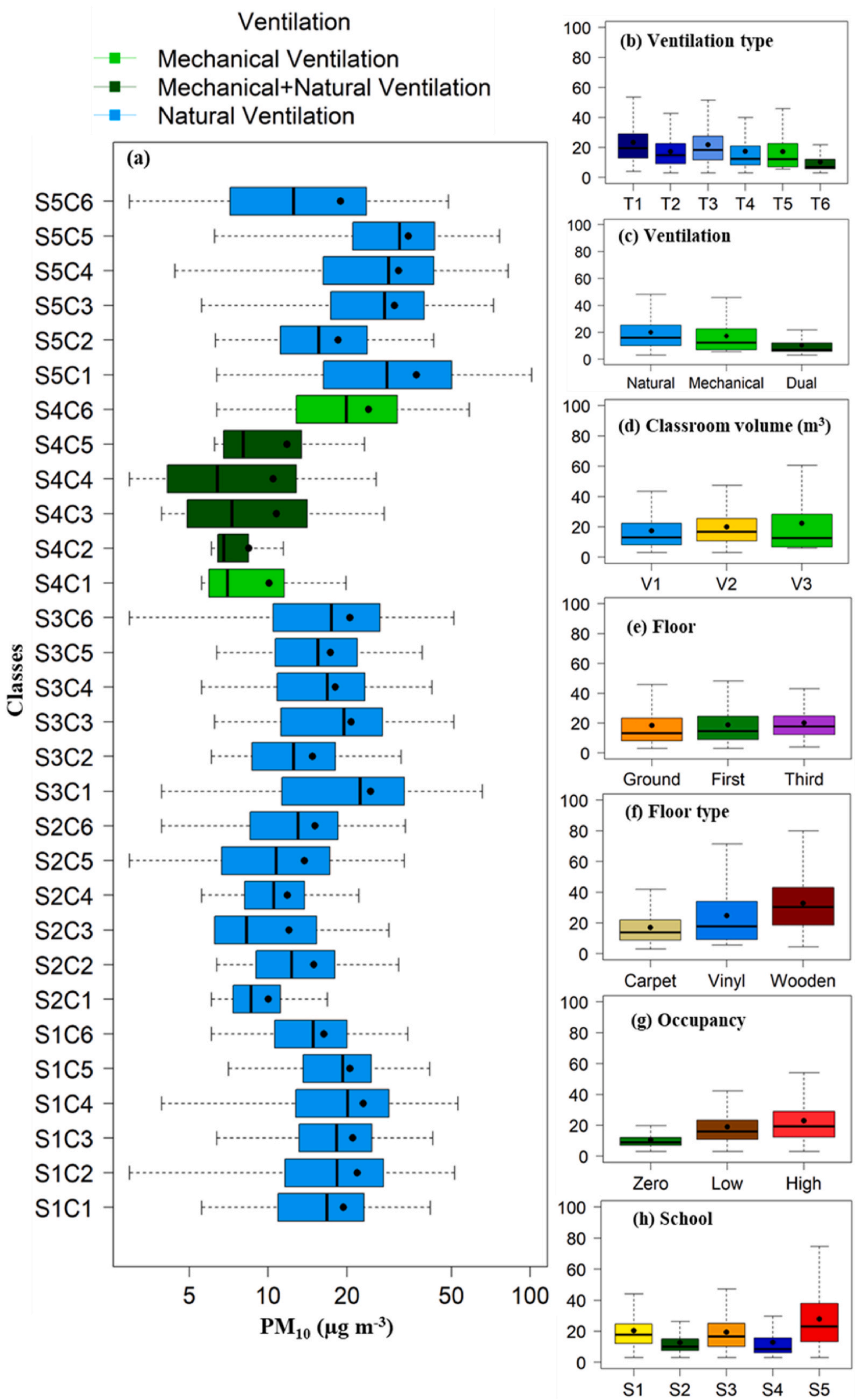

Fig. 3. (a) Box plots of PM_{10} measured in the classrooms (left panel) as denoted by classroom code. Box plots (right panel) depict mean value for: (b) type of ventilation; (c) ventilation (three types); (d) classroom volume; (e) floor location; (f) floor type; (g) classroom occupancy; and (h) school. The boxplot denotes the 25th (bottom), 75th percentiles (top) and median (middle). Plot also include the mean (shown by the dot), and minimum and maximum values (bottom and the top edge of the whiskers).

3.5-times lower than medium (∼63%), and high (∼82%), respectively for both carpet and vinyl floor types (You and Wan, 2015).

Fig. 3g depicts the average PM_{10} concentration for the various occupancy periods. The occupancy periods have been separated into three categories as we discussed in Section 3.1. The average PM_{10} concentrations were 10 ± 7, 19 ± 12 and 23 ± 15 μg m^{-3} for zero, low and high occupancy periods, respectively (Table S8). The average PM_{10} level during the high and low occupancy periods was ∼230% and 190% higher than during the unoccupied period, respectively, in line with the findings of previous studies in schools in the UK (Abhijith et al., 2022; Kumar et al., 2023) and elsewhere (Madureira et al., 2016; Sadrizadeh et al., 2022). Figures S2g and S3g show average PM_1, and $PM_{2.5}$ levels for the occupancy periods in 30 classrooms. The $PM_{2.5}$ (PM_1) levels were 8 ± 3 (5 ± 2), 10 ± 3 (5 ± 2) and 10 ± 4 (6 ± 3) μg m^{-3} for zero, low and high occupancy periods, respectively (Tables S9 and S10). The average $PM_{2.5}$ concentration during the high and low occupancy periods were identical by ∼125% and 125% higher than during the unoccupied period, respectively. The PM_1 showed no occupancy impact. Unlike PM_{10}, as expected, $PM_{2.5}$ and PM_1 levels were not substantially influenced by occupancy level due to their specific sources, such as traffic emissions and combustion as we discussed above.

Fig. 3h shows the average PM_{10} concentration for the different schools during school-opening hours. The highest average in-classroom PM_{10} concentration was found in school five (S5 = 28 ± 19), followed by S1 (20 ± 13), S3 (19 ± 12), S4 (13 ± 11), and S2 (13 ± 8 μg m^{-3}) (Table S8).

The average PM_{10} concentration in S5 (highest PM_{10} concentration) was approximately 215% higher than the S2 (lowest) during school-opening hours. This can be associated with classroom characteristics of S5 (Table 1), which caused higher PM_{10} concentration in all classrooms in the school. Also, this was possibly attributable to the combined effect of multiple factors discussed above (e.g., ventilation, floor types and occupancy). For example, all classrooms of S5 had natural ventilation (∼66% and ∼33% of classrooms had T1 and T4 ventilation types, respectively). In addition, ∼66% of classrooms in S5 had wooden and vinyl types of floor (they showed higher PM_{10} concentrations as discussed above), while ∼33% of classrooms had carpet floors which showed relatively lower PM_{10} concentrations.

Furthermore, SI Figure S4 presents the diurnal profile of CO_2 and PM_{10} concentrations in classrooms across all five schools. As anticipated, the indoor CO_2 and PM_{10} concentrations typically exhibited an increase at the start of class when students entered the classroom around 09:00 h. Subsequently, these concentrations decreased gradually after the lessons, typically around 15:30 h. This consistent pattern was observed in all classrooms, indicating a clear correlation with the occupancy level, as discussed in Section 3.2.

The above results suggest that the ventilation had the most effect on PM_{10}, PM_1 and $PM_{2.5}$ levels, and particularly the dual ventilation had a significant effect on reducing coarse particles. PM concentration is also affected by the floor type where the use of wooden and vinyl was associated with more particles. The occupancy showed a clear effect on the PM_{10} concentration during school-opening hours, but did not exhibit a clear influence on the $PM_{2.5}$ and PM_1 concentrations. Thus, it is recommended to adopt a dual ventilation strategy in schools to reduce pupils' exposure to PM.

3.3. In-classroom $PM_{2.5}/PM_{10}$ and $PM_1/PM_{2.5}$

The majority of in-classroom PMs are resuspended or produced by several activities performed by students (or teachers), including strolling, playing, cutting paper, drawing and colouring. $PM_{2.5}/PM_{10}$ was determined by the assimilating characteristics of particle sources in the classroom and other influencing variables, since fine and coarse particles often come from different sources (Fig. 4).

Fig. 4a depicts the average $PM_{2.5}/PM_{10}$ ratio for classrooms during school-opening hours. As anticipated, the coarse particles predominate ($PM_{2.5}/PM_{10} < 0.5$) in half of the monitored classrooms despite the wide variations in different categories, including ventilation, the volume of the classroom, floor location and floor type. However, the ratios for some classrooms (23%) were greater than 0.6, indicating the fine particles were dominant ($PM_{2.5}/PM_{10} > 0.5$). Interestingly, the $PM_{2.5}/PM_{10} > 0.5$ for classrooms located on the ground floor in schools two and four (S2C1–C4 and S4C1–C2), could be linked to the effect of outdoor emissions such as traffic and other activities (Kalimeri et al., 2019; Kumar et al., 2022a; Abhijith et al., 2022; Branco et al., 2019).

Fig. 4b depicts the average $PM_{2.5}/PM_{10}$ for specific ventilation types during school-opening hours. The average ratio exhibits the highest for T6 (DVmn) of 0.62, followed by T4 (NV, Low ceiling: single-sided) of 0.55, T5 (MV) of 0.54, T2 (NV, medium ceiling height and single side ventilation) of 0.48, T1 (NV, high ceilings) of 0.47 and T3 (same as T2 but with cross ventilation) of 0.46 (Fig. 4b). The average ratio exhibits the highest (0.62) for the DVmn, followed by MV of 0.54, while NV exhibits the lowest ratio ∼0.49 (Fig. 4c). Thus, it is clear that the dual ventilation contributed to the reduction of more coarse particles in classrooms. This can also confirm that classrooms are dominated by coarse-sized PM_{10}, which is resuspended or predominantly generated by pupils and teachers engaged in a variety of activities as discussed above. These findings are consistent with the previous studies (Abhijith et al., 2022; Chithra and Nagendra, 2014; Goyal and Khare, 2009) which reported a higher probability of the coarse particles resuspension in indoor spaces (Qian et al., 2014).

Fig. 4d depicts $PM_{2.5}/PM_{10}$ for various classroom volumes. The average values were 0.5, 0.5 and 0.6 for V1, V2 and V3, respectively (Fig. 4d). The average ratio showed the highest (0.6) in larger classrooms (>300 m^3). The small- (100–200 m^3) and medium-volume (200–300 m^3) classrooms showed similar values of $PM_{2.5}/PM_{10}$. This indicated that the ratio did not differ significantly with different sizes of classrooms. The above findings confirmed the significant effect of other factors (such as occupancy and ventilation) on in-classroom $PM_{2.5}/PM_{10}$ as discussed in Sections 3.2 and 3.4.

Fig. 4e depicts the $PM_{2.5}/PM_{10}$ for different floors during school-opening hours. The $PM_{2.5}/PM_{10}$ were 0.57, 0.49 and 0.50 for the ground, first and third floors, respectively. The average ratio was the highest (0.55) in ground-floor classrooms, caused by the impact of outdoor ingress on fine particles as discussed above.

Fig. 4f exhibits the $PM_{2.5}/PM_{10}$ for separate floor types in the classrooms. The average values were 0.53, 0.52 and 0.43 for carpet, vinyl and wooden, respectively. The average ratio showed the highest (0.53) for carpet, while the wooden type exhibits the lowest ratio ∼ 0.43 (Fig. 4f). This indicates that the wooden floor is dominated by coarse particulate matter as observed in Section 3.2.

Fig. 4g depicts the average $PM_{2.5}/PM_{10}$ ratio for different occupancy levels during school-opening hours. The average ratios were 0.87, 0.61 and 0.56 for zero, low and high occupancy periods, respectively. The average ratio depicts the highest (0.87) for the zero occupancy period, while the high occupancy period exhibits the lowest ratio ∼ 0.56 (Fig. 4f). Therefore, it becomes evident that higher occupancy levels increased in-classroom PM_{10} concentration. This is consistent with a previous study for schools in London where high occupancies were associated with larger increases in PM_{10} concentrations in the classroom (Abhijith et al., 2022).

Fig. 4h depicts the average $PM_{2.5}/PM_{10}$ for various schools during school-opening hours. The highest average in-classroom ratio was found in school two (S2) of 0.63, followed by S4 (0.59), S3 (0.48), S1 (0.46), and S5 (0.46). These observations indicated that some schools were more affected by outdoor air pollution such as traffic, while others were more impacted by indoor activities-related air pollution, probably due to the distance from road traffic.

Furthermore, the analysis revealed that the average $PM_1/PM_{2.5}$ ratio within classrooms during school hours remained unaffected by various factors, including ventilation type (Figures S5b and S5c), classroom volume (Figure S5d), floor level (Figure S5e), floor type (Figure S5f),

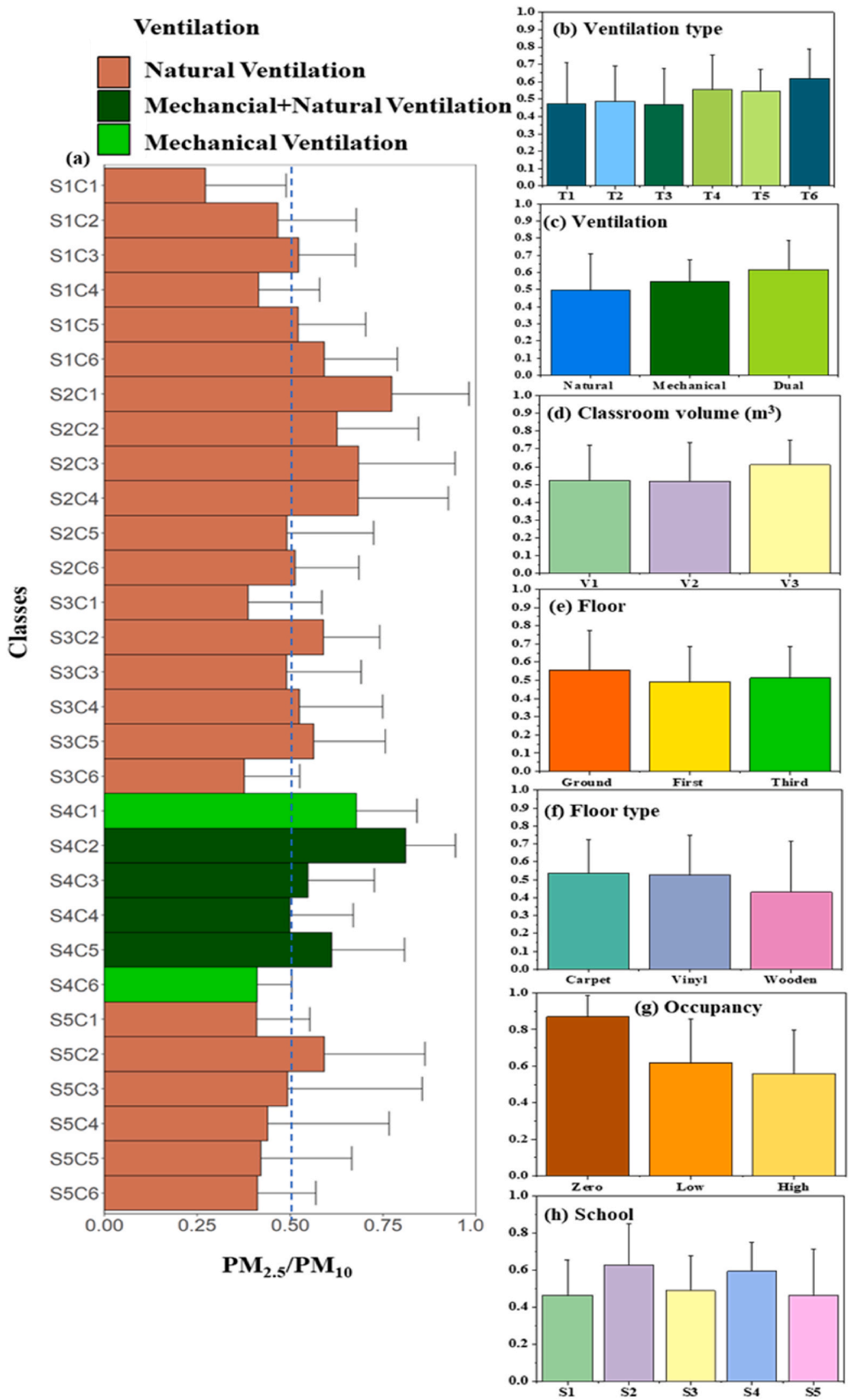

Fig. 4. Bar plots of $PM_{2.5}/PM_{10}$ for 30 classrooms (a). The average ratio for 30 classrooms is classified to: (b) type of ventilation; (c) ventilation (three types); (d) classroom volume; (e) floor location; (f) floor type; (g) classroom occupancy; and (h) school. The dashed blue line (right figure) denotes $PM_{2.5}/PM_{10}$ of 0.5.

occupancy (Figure S5g), and school (Figure S5h). Please refer to SI Section S3 for more detailed discussions on each of these factors.

According to the above findings, the ventilation and floor type both had a significant effect on the $PM_{2.5}/PM_{10}$ ratios, while the dual ventilation (DVmn) had a significant effect on reducing PM_{10} (coarse particles). Owing to the ingress of particles from the outdoor environment, the $PM_{2.5}/PM_{10}$ value was over 0.5 for classrooms at the ground floor. The $PM_{2.5}/PM_{10}$ was also affected by different occupancy periods. It showed the highest value during the zero occupancy period (~0.87), indicating that fine particles predominated during unoccupied periods in classrooms. However, these factors did not exhibit a clear influence on $PM_1/PM_{2.5}$ due to the low concentration of fine particles in the classrooms.

3.4. In-classroom CO_2 concentrations

The average CO_2 concentration in the monitored classrooms was 840 ± 306 ppm, which varied between 500 and 1500 ppm, during school-opening hours (Table S11). It is in line with a previous work in London, which found average CO_2 levels varying from 546 to 1263 ppm and 561–874 ppm between the times of pre- and post-intervention in London classrooms (Abhijith et al., 2022). The average CO_2 level in each classroom was considerably lower than the guideline value (1000 ppm) (Fig. 5a). It is consistent with a previous study in Swedish primary school classrooms, where they observed the CO_2 levels were much below the proposed guideline value. (weekly average, 520 ppm; occupied period, 690 ppm) (Cabovská et al., 2022). It was below the average level observed (1284 and 1370 ppm) in European schools (Baloch, et al., 2020; Szabados et al., 2021), in French elementary schools (1123–1329 ppm, Ramalho et al., 2013), in Southwestern (~1780 ppm) and Midwestern (~1171 ppm) US schools (Haverinen-Shaughnessy et al., 2015; Deng and Lau, 2019). There are several factors that can influence the in-classroom CO_2 concentration, including ventilation (Fig. 5b and c), classroom volume (Fig. 5d), floor level (Fig. 5e), type of floor (Fig. 5f), occupancy (Fig. 5g) and school (Fig. 5h), as discussed below.

Regarding the specific types of natural ventilation (Fig. 5b), lower CO_2 concentrations were observed in classrooms with cross-ventilation (T3; 809 ± 258) than those in single-sided ventilation (876 ± 249, 928 ± 441 and 826 ± 411 ppm for T1, T2 and T4, respectively). This finding highlights the importance of cross-ventilation, which can enhance natural ventilation and consequently, can reduce indoor CO_2 more effectively. Regarding ventilation (Fig. 5c), the classrooms that only had natural ventilation tended to experience higher CO_2 concentrations (861 ± 361 ppm) compared with MV (796 ± 235 ppm) (Table S11). Moreover, the dual ventilation seemed to result in even lower CO_2 levels (731 ± 206 ppm) than those with the MV. This finding substantiates the advantage of improved ventilation provided by windows, doors and mechanical ventilation (Jia, et al., 2021; Bain-Reguis et al., 2022).

Fig. 5d groups classrooms according to the classroom volume, with 16, 12 and 2 classrooms falling into small- (V1, 100–200 m^3), medium- (V2, 200–300 m^3) and large-volume (V3, >300 m^3) classrooms. The average CO_2 concentrations were 812 ± 356, 874 ± 315 and 890 ± 371 ppm for V1, V2 and V3, respectively. Usually, small-volume classrooms are expected to have higher CO_2 levels compared to larger volume ones but the reasons for this opposite trend observed can be explained as follows. The total number of small-volume classrooms was 16 with an average of 27 ± 3 occupants, compared with 12 medium- (26 ± 4 occupants) and 2 large-volume (43 ± 12 occupants) classrooms. This suggests that the small-volume classroom may have contributed to lower CO_2 concentrations, which is understandable because smaller rooms tend to have higher ACHs for the same air flow rate (Section 3.7). In addition, CO_2 could accumulate above ventilation openings in high-ceiling rooms (above ~225 cm) as highlighted by Kumar et al. (2023).

As regards to the floor location (Fig. 5e), classrooms on the first floor showed relatively higher average CO_2 concentration (878 ± 371 ppm) than those on the ground floor (816 ± 355 ppm) and the third floor (844 ± 183 ppm). This can imply that other factors aforementioned were more influential in affecting the in-classroom CO_2 concentration than the elevation of the classroom.

Fig. 5f shows the average CO_2 concentration for the different floor types. CO_2 concentrations showed a relatively little variation for different floor types, e.g. 828 ± 342, 912 ± 342 and 928 ± 323 ppm for carpet, vinyl and wooden, respectively (Table S12). Fig. 5g depicts the average CO_2 concentration for the different occupancy periods. The occupancy hours were separated into three categories: zero, low and high levels (Section 3.1). The occupancy was a decisive factor in affecting the in-class CO_2 concentrations. The average CO_2 level at periods of high and low occupancy was ~150% and 130% higher than during the unoccupied period, respectively. These observations concurred with the findings of earlier studies (Schibuola et al., 2016; Schibuola and Tambani, 2020). The average CO_2 levels exceeded the SAGE limits of 800 ppm during high (955 ± 365 ppm) and low occupancy periods (878 ± 336 ppm) in all classrooms. Thus, the occupancy density played a significant role in determining CO_2 levels in classrooms (Abhijith et al., 2022; Vassella et al., 2021). Moreover, the lack of adequate ventilation caused by infrequent window openings in a classroom could cause CO_2 levels to rise and therefore breaching the recommended guidelines. This result indicates that different ventilation strategies are necessary to accommodate different occupancy periods to maintain in-classroom CO_2 concentration at an acceptable range.

Fig. 5h depicts the average CO_2 level for the different schools during school-opening hours. Average CO_2 concentrations among different schools differed significantly from one to another. The highest average in-classroom CO_2 concentration was found in school S3 (S3, 990 ± 472 ppm), followed by S5 (950 ± 334 ppm), S1 (841 ± 218 ppm), S4 (752 ± 218 ppm), and S2 (674 ± 289 ppm). The average CO_2 concentration in S3 (highest CO_2 level) was ~150% higher than the S2 (lowest CO_2 level) during school-opening hours. This can be related to classroom characteristics of S3 (Table 1) which caused higher CO_2 concentration in its classrooms. Also, this was possibly attributable to the combined effect of multiple factors discussed above (e.g., ventilation, classroom volume, occupancy), rather than the differences in the background CO_2 levels at different locations.

In summary, the above findings show that high CO_2 concentrations in the classrooms are favoured by low ventilation (e.g., one-sided natural ventilation) and high occupancy while the other factors such as floor location, floor type and classroom volume did not demonstrate a significant impact. Therefore, it is of great benefit to enhance ventilation through windows, doors and mechanical ventilation to minimise in-classroom CO_2 concentration.

3.5. Thermal comfort

For students' health, well-being, and academic performance, a thermally comfortable classroom atmosphere is essential. The temperature and RH ranges between 21 and 23 °C and 40–60%, respectively, are recommended for indoor thermal comfort (ASHRAE, 2013). Table S11 summarises the informative data of RH and T. Boxplots show relative humidity (Fig. 6a) and temperature (Figure S6a) values in the monitored classrooms. During school-opening hours, the average RH for all schools was 29 ± 6% (Table S11). The average temperature across the classrooms was 24±2 °C (Table S11). Overall, the average RH in all classrooms was below 40%. On the other hand, the average air temperature stayed between 21 and 23 °C in 12 out of 30 classrooms, but was over 23 °C in the rest of the 18 classrooms. We have also investigated the average temperature and RH levels during school hours based on types of ventilation, classroom volume, floor level, floor type, occupancy and school, as detailed below.

In terms of ventilation type, average RH and air temperature in classrooms with natural, mechanical or dual ventilation were rather similar (Tables S13 and S14). Likewise, specific ventilation formats (e.g.,

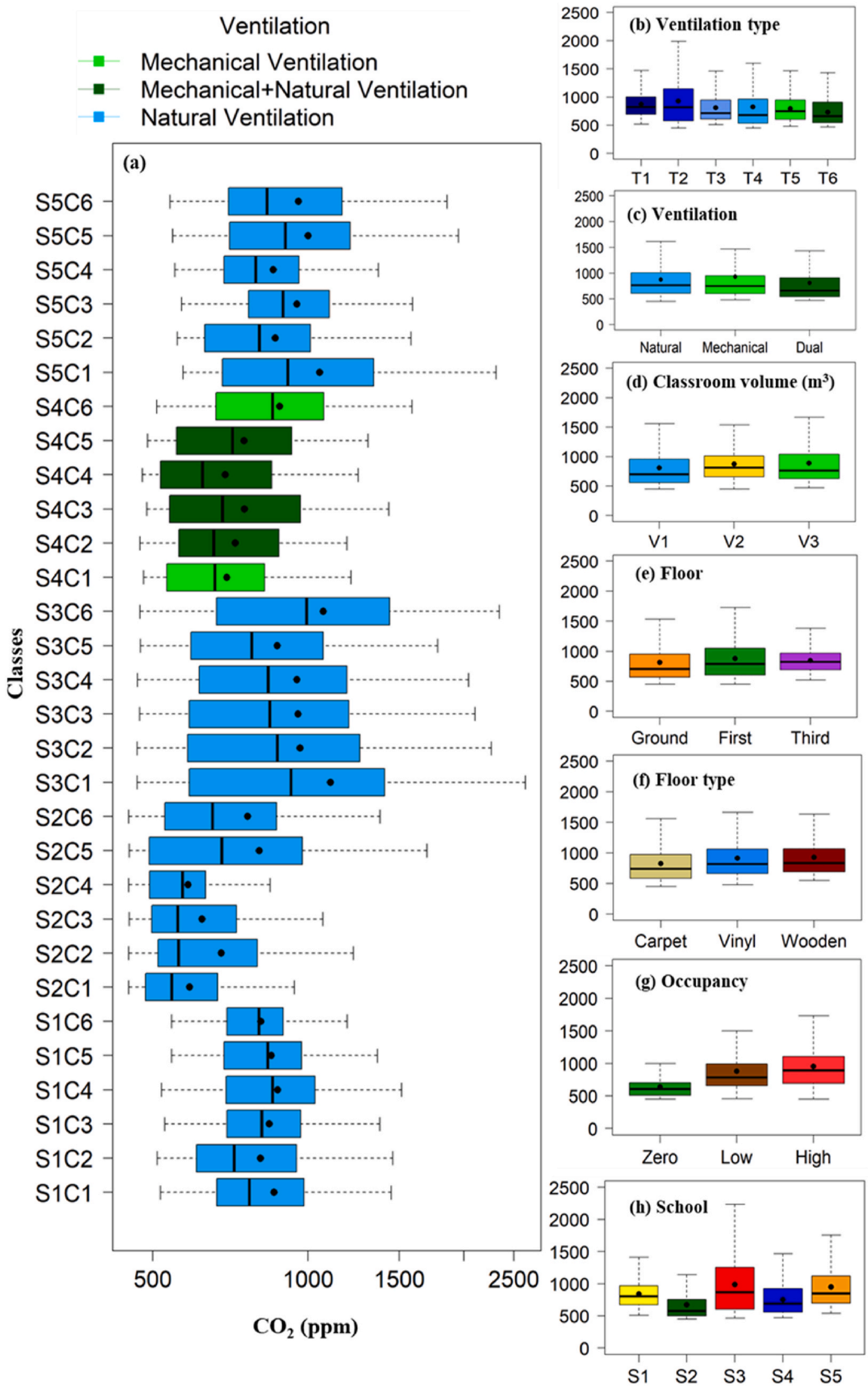

Fig. 5. (a) Box plots of CO_2 measured in the classrooms (left panel) in each school as denoted by classroom code. Box plots (right panel) depict mean value for: (b) type of ventilation; (c) ventilation (three types); (d) classroom volume; (e) floor location; (f) floor type; (g) classroom occupancy; and (h) school. The boxplot denotes the 25th (bottom), 75th percentiles (top) and median (middle). Plot also include the mean (shown by the dot), and minimum and maximum values (bottom and the top edge of the whiskers).

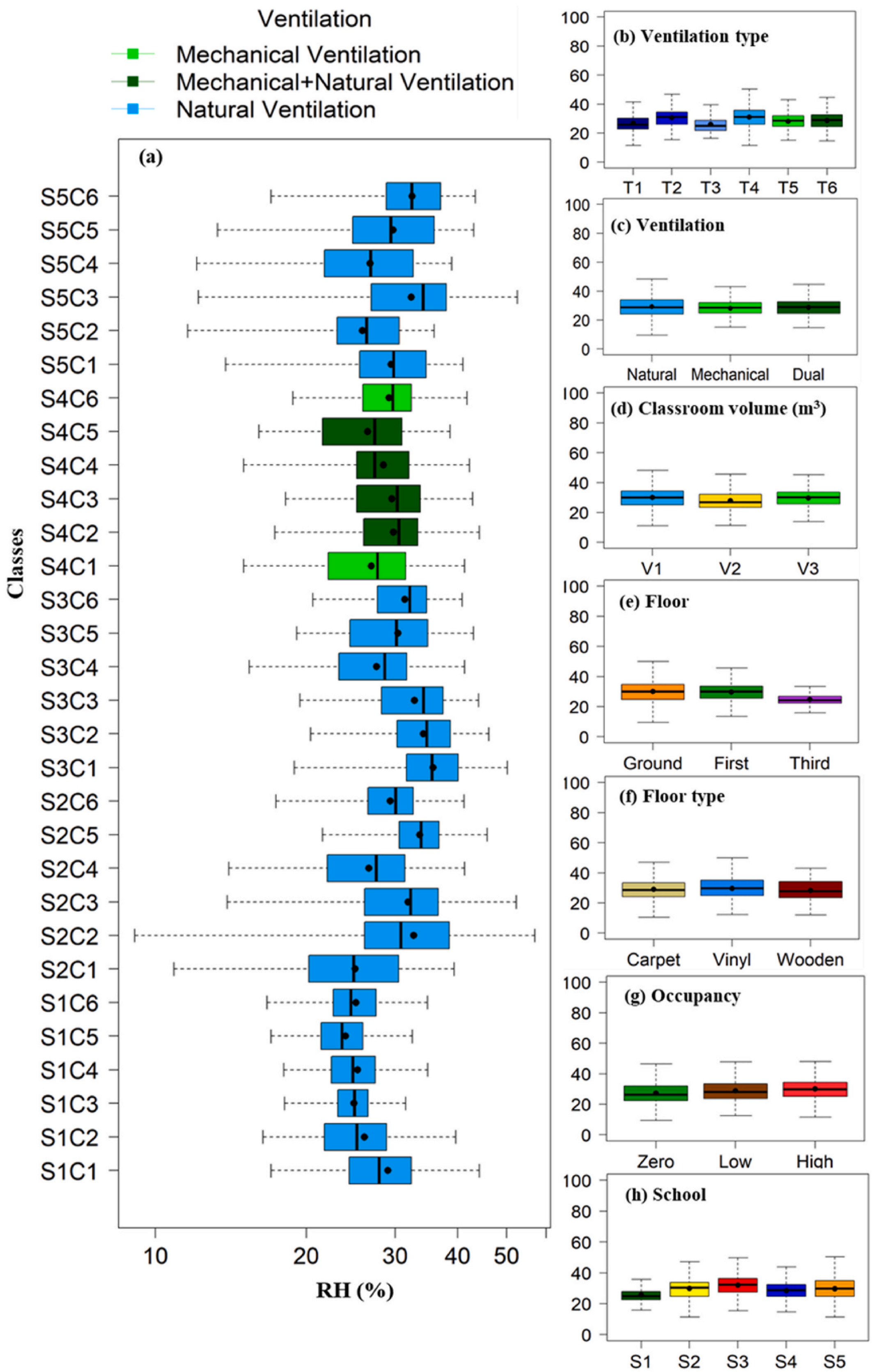

Fig. 6. (a) Box plots of relative humidity (RH) level measured in all classrooms (left panel) in each school as denoted by classroom code. Box plots (right panel) depict mean value for: (b) type of ventilation; (c) ventilation (three types); (d) classroom volume; (e) floor location; (f) floor type; (g) classroom occupancy; and (h) school. The boxplot denotes the 25th (bottom), 75th percentiles (top) and median (middle). Plot also include the mean (shown by the dot), and minimum and maximum values (bottom and the top edge of the whiskers).

one-sided or cross ventilation, high or low ceilings) did not have a substantial effect on the indoor thermal environment (average in-classroom RH and temperature ranges were 26–31% and 23–25 °C, respectively). In general, the RH was quite low (<40%), while the in-classroom air temperature was slightly higher (1–2 °C) than the maximum comfortable temperature of the ASHRAE guideline (ASHRAE, 2013), regardless of the ventilation-related conditions. This was likely attributable to the effect of the heating system which was used during the monitoring period in the schools. Generally, the ventilation type did not affect the temperature substantially in the classrooms (Figure S6b and c).

In addition, the average RH did not change substantially with the classroom volume (Fig. 6d). For example, the average in-classroom RH values were 30 ± 7%, 28 ± 6% and 30 ± 6% for small-, medium- and large-volume classrooms, respectively (Table S13). Similarly, the in-classroom temperature did not vary accordingly with the classroom volume, given that the medium-volume classrooms had a higher average temperature (25 ± 2 °C) than small (23 ± 2 °C) or large-volume (23 ± 2 °C) classrooms (Figure S6d). This might be due to the measurement taking place during cold weather when the heating was on. Figs. 6e and 7e show the average in-classroom RH and temperature for the different floor levels in all schools, respectively. The air temperature rose slightly with the increased elevation of the classrooms, given that the average air temperature on the third floor (25 ± 1 °C) was slightly higher than that on the ground (23 ± 3 °C) and the first (24 ± 2 °C) floor (Figure S6e). In contrast, the average RH was the same on the lower floors (30 ± 7% and 30 ± 6% for the ground and first floor respectively), about 5% lower than on the third floor (25 ± 4%) (Fig. 6e).

As regards to the floor type, there was a very minimal difference in both in-classroom RH and air temperature. The average in-classroom RH with vinyl floors was only 1–2% greater than that in those with carpets or wooden floors (Fig. 6f), while the carpeted classrooms had a 1 °C higher average air temperature than those with other floor types (Figure S6f). In-classroom average RH and temperature do not seem to vary significantly in relation to different types of classroom floors, showing that the previously discussed other factors may have a greater influence.

Regarding the effect of occupancy numbers, the difference in the average RH was marginal, i.e., 27 ± 7%, 29 ± 6% and 30 ± 7% for zero, low and high occupancy periods, respectively (Fig. 6g). Figure S6g shows the average in-classroom temperature for the different occupancy periods in all schools. The average temperature remained also quite the same during different occupancy periods (24 ± 2 °C for zero and low occupancy periods and 24 ± 3 °C for high occupancy). A plausible explanation is that the effect of the impacts of occupants on the indoor temperature and RH was outweighed by the radiators effectively working in the classrooms.

Lastly, we assessed thermal comfort for different schools (Figs. 6h and 7h). It was estimated that the students in most of the surveyed classrooms experienced a certain level of thermal discomfort due to the dry and slightly hot air, as the average in-classroom RH was all below 40% at all schools and the average air temperature was over 23 °C at three out of five schools. This finding was consistent with the result from another study that reported overheating issues in some UK schools when the heating was on (Korsavi et al., 2020). These observations indicate that it is beneficial for schools to adjust the operating temperature of the heating system, upgrade the thermostatic control, and even supply humidifiers in some cases where humidity levels are high.

3.6. Peak frequencies

We examined PM_{10} and CO_2 distribution via density plots in the classrooms (SI Section S1). The distribution of kernel density helps to understand CO_2 (Fig. 8a–g) with PM_{10} (Fig. 8h-n) peak frequencies based on the ventilation, classroom volume, floor location, floor type, occupancy, and school.

Fig. 7a exhibits the plot of the density of CO_2 levels for specific types of natural ventilation during school-opening hours. The density distribution curves showed comparable plots (bimodal shape) for different types of natural ventilation but peaked and narrowed at different ranges. For instance, T6 showed a narrow peak between 480 and 1200 ppm CO_2. While for T2, the peaks showed a wider range between 470 and 2000 ppm, showing a higher frequency across a larger concentration range. Also, for DVmn the peak density showed the tallest and sharpest with bimodal distribution (ranges, 480–1200 ppm), indicative of a less often occurrence at high CO_2 levels (Fig. 7b). For the MV, a wider peak was found in the 480–1500 ppm CO_2 range. For NV, the peaks were the shortest and broadest with unimodal distribution (diminishing in the range of 480–2400 ppm with slow buildup), indicating a more frequent occurrence over a wider CO_2 range (Fig. 7b).

Fig. 7c exhibits the density plot of CO_2 levels for different classroom sizes. Small-volume classrooms in the lower CO_2 range (480–1200 ppm) show a narrow density function tail, revealing a higher probability of low levels (Fig. 7c). However, large and medium classrooms exhibit a relatively lower peak with a larger CO_2 range (490–2000 ppm) and (490–2400 ppm), respectively (Fig. 7c). These results support prior observations (Section 3.2) that classrooms with higher heights or larger surface area could assist to reduce levels of CO_2 with respect to occupancy level.

Fig. 7d exhibits the density plot of CO_2 levels for different floor levels. Classrooms located on the third floor displayed a relatively higher probability (bimodal distribution) of the CO_2 level ranging between 500 and 1500 ppm, compared with those located on the first and ground floors. For the first floor, the peaks were the broadest with unimodal distribution (ranges 480–2000 ppm). For the ground floor, classrooms showed a sharp peak in wider CO_2 ranges (480–2300 ppm) with unimodal distribution (Fig. 7d). Hence, a direct correlation does not exist between CO_2 levels and different floor levels.

Fig. 7e exhibits the density plot of CO_2 levels for different types of floors in all classrooms. With all types showing unimodal distributions, carpet and wooden floors showed the highest density peak, while the vinyl floors had the lowest. They followed very similar variations for CO_2 concentration (480–2100, 480–2200 and 480–2200 ppm for carpet, vinyl and wooden, respectively). This reaffirms that the floor types did not have a significant impact on the incidence of high in-classroom CO_2 levels.

Fig. 7f exhibits the density plot of CO_2 levels for different occupancy periods in school-opening hours. Classrooms with zero occupants showed a sharper and narrower peak of CO_2 levels (480–1200 ppm) than those with low (lower and wider peak with CO_2 range, 480–1900 ppm) and high occupants (lowest and widest peak with higher CO_2 range, 480–2500 ppm). Thus, a direct relationship existed between the occurrence of high in-classroom CO_2 concentrations and the number of classroom occupants across all schools.

Furthermore, the density plot of CO_2 levels for different schools during school-opening hours were grouped by school (Fig. 7g) and presented separately (Figure S7a). The frequency variations differ between each school. The lowest most frequent CO_2 peaks were 480–1200 ppm for S2 classrooms. The highest most frequent CO_2 concentrations among the schools were ~480–2200 and 500–2300 ppm for S3 and S5 classrooms, respectively. Furthermore, the elongated tail for the density on the right side was noticeable in S3 and S4 classrooms, which had a higher probability of higher CO_2 levels. These results denote that CO_2 levels differ for each classroom and school (Section 3.4). For example, S2, S3 and S5 showed the unimodal distribution at the above CO_2 ranges, while S1 and S4 experienced the bimodal distribution and CO_2 ranges were 480–1300 and 480–1300 ppm, respectively (Fig. 7g). This consequence is in line with the previous results in section 3.4, indicating that S3 classrooms had the highest average CO_2 concentrations within 871–1100 ppm.

Furthermore, density plots illustrating the average PM_{10} concentration based on the seven factors under investigation were presented in

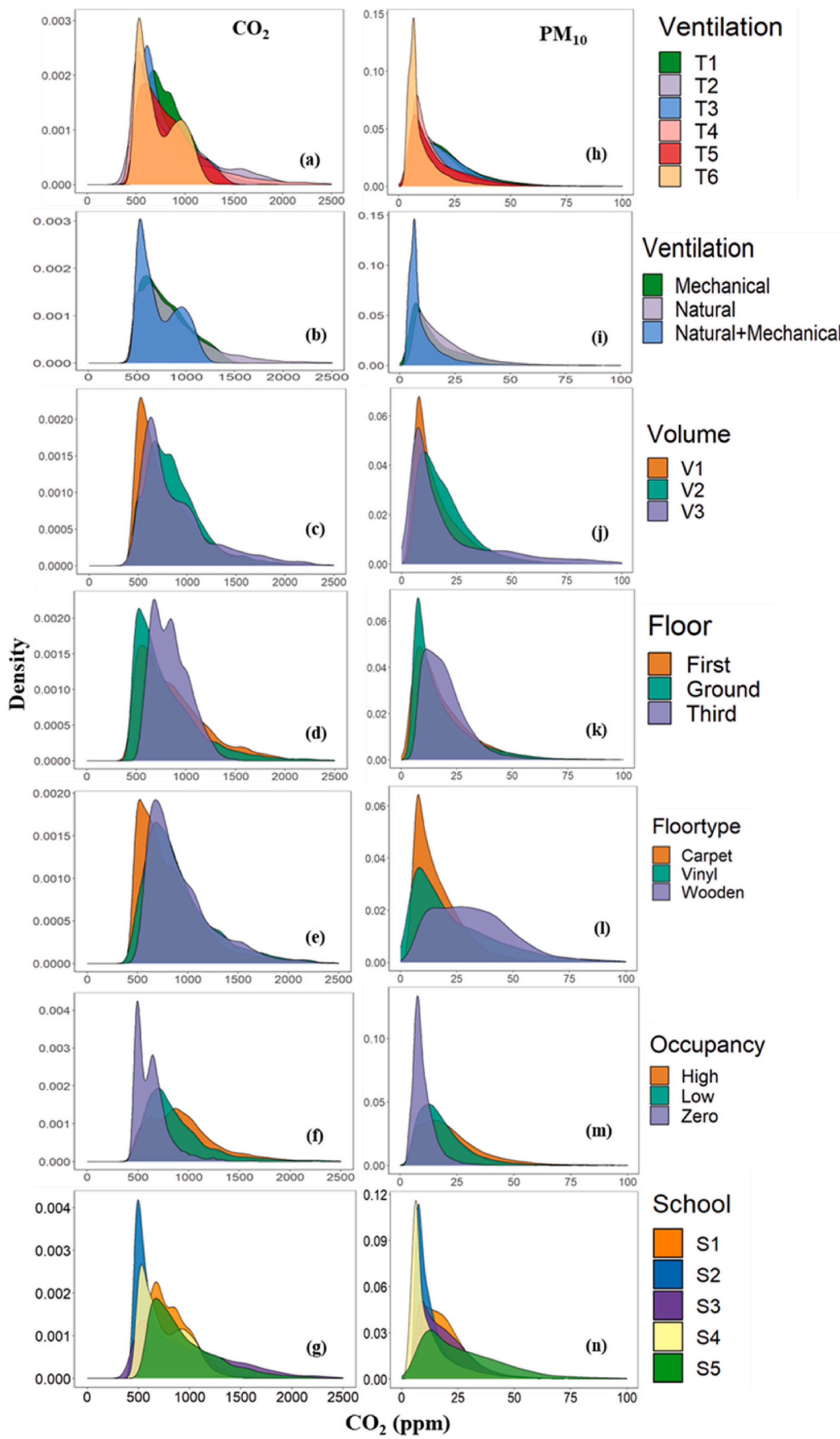

Fig. 7. Density plots of averaged CO_2 and PM_{10} concentrations in all classrooms grouped by (a) ventilation; (b) ventilation (three types); (c) classroom volume; (d) floor location; (e) floor type; (f) classroom occupancy; and (g) school.

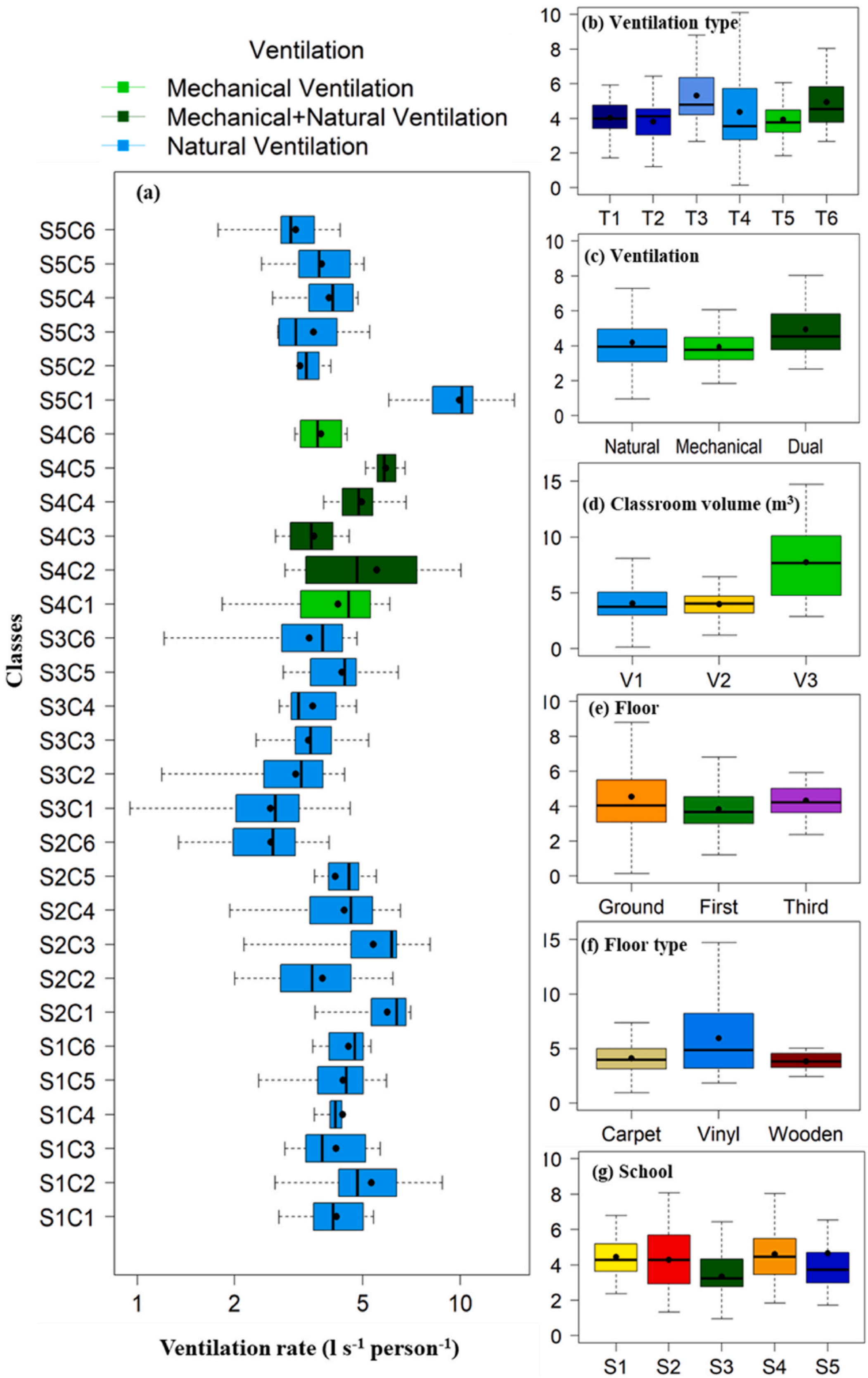

Fig. 8. (a) Box plots of ventilation rate calculated for all classrooms in each school as denoted by classroom code. Box plots (right panel) depict mean value for: (b) type of ventilation; (c) ventilation (three types); (d) classroom volume; (e) floor location; (f) floor type; and (g) school. The boxplot denotes the 25th (bottom), 75th percentiles (top) and median (middle). Plot also includes the mean (shown by the dot), and minimum and maximum values (bottom and the top edge of the whiskers).

Fig. 7h-n. These results revealed that factors such as dual ventilation (Fig. 7h), classrooms volume (Fig. 7j), floor level (Fig. 7k), occupants (Fig. 7m), and school (Fig. 7n) have an impact on the distribution of PM_{10} concentration, including peaks and frequencies. For a more comprehensive analysis of each of these factors, please refer to the detailed discussions provided in SI Section S4.

The ventilation types had a substantial effect on the PM_{10} and CO_2 concentrations, as shown in the density plots. Particularly, the dual ventilation had a significant effect on reducing CO_2 and PM_{10}. The density plot also showed that the floor type had an impact on PM_{10}, but not on CO_2 levels. The density plot also revealed that the occupancy had a clear impact on the PM_{10} and CO_2 concentrations during school-opening hours. This result is in line with the findings stated in Sections 3.2 and 3.4, showing that ventilation and occupancy are the main factors that had an impact on PM_{10} and CO_2 concentrations.

3.7. Ventilation

3.7.1. Air change rates (ACH)

The average ACH during school-opening hours, calculated using the method described in SI section S1, was 2.3 ± 0.8 h^{-1}, ranging between 4.0 ± 0.7 (S2C1) and 1.1 ± 0.3 h^{-1} (S5C1) (Table S15). Figure S8a shows the average ACH for classrooms during school-opening hours. The average ACH across all classrooms (2.3 h^{-1}) is comparable with those (2.11 h^{-1}) measured by Abhijith et al. (2022) in London schools and lower than those reported (3.41 h^{-1}) for schools in England (Korsavi et al., 2020) and 4.16 h^{-1} schools in Athens (Santamouris et al., 2008). The classrooms in the latter two studies had higher numbers of openable windows which helped to increase the ACH. We investigated several factors that can possibly influence the ACH, including ventilation (Figures S7b and c), classroom volume (Figure S8d), floor location (Figure S8e), floor type (Figure S8f) and school (Figure S8g), as discussed below.

Figure S8b shows the average ACH for the specific types of natural ventilation during school-opening hours. The average ACH shows the highest value for T3 (NV) with cross ventilation e.g. to a corridor) and T6 (DVmn) of 3 ± 1 h^{-1}, followed by other types (T1, T2, T4 and T5) which all had the same ACH of 2 ± 1 h^{-1} (Table S16). Figure S8c shows the three types of ventilation. The average ACH shows the highest value for the DVmn of 3 ± 1 h^{-1}, followed by NV and MV of 2 ± 1 h^{-1}. The above findings indicated that the variations in window opening frequency were closely related to variations in the ACH of naturally ventilated classrooms (Korsavi et al., 2020; Haddad et al., 2021).

Figure S8d shows the average ACH for different classroom sizes. The average ACH values were about 3 ± 1, 2 ± 1 and 1 ± 0.5 h^{-1} for V1, V2 and V3, respectively. The average of ACH shows the highest value of 3 ± 1 h^{-1} in small-volume classrooms (100–200 m^3), followed by the ACH of 2 ± 1 h^{-1} for medium-volume (200–300 m^3) classrooms and 1 ± 0.5 h^{-1} for larger classrooms (>300 m^3). These results highlight the dependence of classroom volumes on ACH (i.e., the larger the classroom size, the smaller the ACH).

Figure S8e shows the average ACH for different levels of the floor during school-opening hours. The average ACH were the same for the three levels (ground, first and third) of 2 ± 1 h^{-1}. Figure S8f depicts the average ACH for different floor types in the 30 classrooms. Average ACH values were also the same for the three floor types (carpet, vinyl and wooden) of 2 ± 1 h^{-1}, indicating that the floor level and types had no relation with the ACH in the classroom.

Figure S8g shows the average ACH for different schools during school-opening hours. The highest average in-classroom ACH was found in school two (S2) and school four (S4) of roughly 3 h^{-1}, and the rest schools showed the same ACH of 2 h^{-1} (Table S16). The S2 and S4 classrooms used NV and DVmn, confirming that the ventilation type had a significant impact on the ACH in the classroom.

We conclude that the ventilation types and classroom size are the significant factors influencing ACHs in the school. Lower ACH values were observed for naturally ventilated classrooms with regular opening windows and large-volume classrooms. The large-volume classrooms (>300 m^3) showed 33% less ACH compared with small-volume classrooms (100–200 m^3). Thus, it would be recommended to use both mechanical and natural ventilation to prompt air change rate in the classroom.

3.7.2. Ventilation rates (VRs)

Previous studies showed the relationships between ventilation rates and in-classroom PM and CO_2 concentrations (Kumar et al., 2022b; Wargocki et al., 2020; Korsavi et al., 2020). We derived VRs per person in all monitored classrooms, following the method explained in Section S1. The average VRs in 29 classrooms out of 30 were lower standard limits proposed by the ASHRAE Standard 62 (8 l s^{-1} $person^{-1}$, ASHRAE, 2004) and CIBSE guidelines (CIBSE, 2015, 10 l s^{-1} $person^{-1}$) (Table S15). Fig. 8a shows the average VR for classrooms during school-opening hours. In the classrooms, the VRs ranged from 2.6 to 9.9 with the average (median) ~ 4.3 (4.1) l s^{-1} $person^{-1}$ (Table S15). Similarly, our VR (4.3 l s^{-1} $person^{-1}$) were comparable with those reported as 4.5 l s^{-1} $person^{-1}$ in the UK (Abhijith et al., 2022), 4.5 l s^{-1} $person^{-1}$ (Satamoris et al., 2009) and 3.8 l s^{-1} $person^{-1}$ (Shagnessy et al., 2006). Moreover, our VR (4.3 l s^{-1} $person^{-1}$) was smaller than 6.2 l s^{-1} $person^{-1}$ stated for 29 naturally ventilated classrooms in the UK (Korsavi et al., 2020) and substantially lower than 7.2 l s^{-1} $person^{-1}$ determined in six mechanically ventilated classrooms in Finland (Canha et al., 2013). Additionally, low ACH and VR may also have contributed to the elevated PM_{10} levels owing to people's movement inside classrooms and the higher CO_2 concentrations due to pupil's respiration. Hence, increasing ACH and VR would lower PM_{10} and CO_2 levels in classrooms and assist in lowering the extent of in-classroom CO_2 build-up and particle levels, which can improve students' academic performance (Hwang et al., 2022; Wargocki et al., 2020).

We examined several factors that can possibly influence the VRs, including ventilation (Fig. 8b and c), classroom volume (Fig. 8d), floor location (Fig. 8e), floor type (Fig. 8f) and school (Fig. 8g), as discussed below.

Fig. 8b shows the average VR for the specific types of natural ventilation during school-opening hours. The average VR shows the highest value for T3 (NV with cross ventilation e.g. to a corridor) and T6 (DVmn) of 5 l s^{-1} $person^{-1}$ (Table S17), followed by other types (T1, T2, T4 and T5) which all had the same VR ~ 4 l s^{-1} $person^{-1}$. Fig. 8c shows the average VR for the three ventilation types. Average VRs value shows quite similar for the three ventilation types, which were 5, 4 and 4 l s^{-1} $person^{-1}$ for the DVmn, NV and MV, respectively. Based on the PM and CO_2 levels aforementioned (Sections 3.2 and 3.4), DVmn showed the lowest, followed by MV and NV. Hence, DVmn is strongly recommended.

Fig. 8d shows the average VR for different classroom sizes. For instance, V3 showed the highest (8 l s^{-1} $person^{-1}$), followed by V1 and V2 (4 l s^{-1} $person^{-1}$) (Table S17). The average of VRs shows the highest value of 8 l s^{-1} $person^{-1}$ in large-volume classrooms (>300 m^3), and the small- (100–200 m^3) and medium-volume (200–300 m^3) classrooms had nearly identical VR (4 l s^{-1} $person^{-1}$). As discussed in Section 3.7.1, large-volume classrooms showed the lowest ACH, followed by medium- and small-size classrooms. As expected, the large-volume classrooms showed the lowest ACH (1 h^{-1}) but the highest VR meeting the 8 l s^{-1} $person^{-1}$ requirements. However, VR were smaller than required in small and medium classroom groups and the ACH were not high either (i.e. 3 h^{-1} and 2 h^{-1}), showing the importance of having a larger classroom volume. However, other parameters will also need to be considered, other than the classroom volume, to draw comprehensive conclusions. For instance, VR also depends on the occupancy metric, thermal condition (Batterman, 2017), air-tightness of the external walls (Nantka, 2006), and particularly the window opening status which was not documented in the current study.

Fig. 8e shows the average VR for the different levels of floor during school-opening hours. Average VRs were also very close for the three levels (ground, first and third) of 5, 4 and 4 l s^{-1} $person^{-1}$. Fig. 8f depicts the average VRs for different floor types in the classrooms. Average VRs were 4, 6 and 4 l s^{-1} $person^{-1}$ for carpet, vinyl and wooden, respectively. These results showed that the floor level and types had no clear impact on the VRs in the classrooms.

Fig. 8g depicts average VRs for different schools during school-opening hours. The highest average in-classroom VRs (5 l s^{-1} $person^{-1}$) was found in S4 and S5, and the rest of the schools showed quite similar VR of ~4 l s^{-1} $person^{-1}$ (Table S17). The S4 and S5 classrooms used DVmn and NV (T1 and T4), confirming that the ventilation type had an impact on the VRs in the classroom.

It can be concluded that the VRs depend on the ventilation types in the classrooms and other parameters discussed above, especially the opening of doors and windows.

4. Conclusions, recommendations and future outlook

We investigated in-classroom CO_2 and PM concentrations in 30 classrooms across five schools during winter (January–March 2022) in London, UK. We also investigated the influence of the parameters (ventilation, volume of classroom, floor location, floor type and occupancy) on CO_2 and PM concentrations together with air temperature and relative humidity. In-classroom PM and CO_2 monitoring was carried out using a unified methodology and similar equipment to obtain a comparable dataset in all schools. The following are the main conclusions drawn from the study:

- In all classrooms, PM_1, $PM_{2.5}$ and PM_{10} levels were 5 ± 2, 10 ± 2 and 20 ± 11 μg m^{-3}, respectively during school-opening periods. The highest PM_{10} concentration range was found to be 16–41 μg m^{-3}, while the lowest was found to be 10–15 μg m^{-3}. The total reduction of PM_{10} concentration (50%) by dual ventilation was significantly higher than $PM_{2.5}$ (40%) and PM_1 (33%) when compared with natural ventilation. The average PM_{10} levels during high and low occupancy periods were ~230% and 190% higher than the unoccupied period, respectively.
- The ventilation and floor type had the largest influence on $PM_{2.5}/PM_{10}$. The dual ventilation had a significant effect on lowering PM_{10} concentration. The ratio was also influenced by different occupancy periods where the $PM_{2.5}/PM_{10}$ showed the highest (~0.87) for zero occupancy period. The $PM_{2.5}/PM_{10}$ > 0.5 for classrooms located on the ground floor owing to ingress of particles from outdoor. The studied factors did not show an obvious effect on $PM_1/PM_{2.5}$ due to low concentration of fine particles in the classrooms.
- The CO_2 concentration in the monitored classrooms mainly varied between 500 and 1500 ppm during school-opening hours. The average CO_2 levels were ~150% and 130% higher than the unoccupied period for high and low occupancy periods, respectively.
- In-classroom average RH level was below 40% at all schools and the average air temperature was over 23 °C at three out of five schools. The average air temperature was recorded between 21 and 23 °C in 12 out of 30 classrooms but was over 23 °C in the rest of the 18 classrooms.
- The density plots showed that the ventilation types had the largest influence on PM_{10} and CO_2 and concentrations, and particularly the dual ventilation had a clear impact on decreasing CO_2 and PM_{10}. The density plot also showed that the floor type had an impact on PM_{10}, but not on CO_2 levels. The density plot also confirmed that the occupancy had a positive relation with CO_2 and PM_{10} concentrations during school-opening hours.
- The ventilation types and classroom volume are the significant factors influencing ACH in the school. The large-volume classrooms (>300 m^3) decreased the ACH by 33% compared with small-volume classrooms (100–200 m^3). The average VRs were 5, 4 and 4 l s^{-1} $person^{-1}$ for DVmn, NV and MV, respectively, suggesting that other factors will have a significant impact on the VRs including the occupancy metric, thermal condition and particularly the window opening status, which was not considered in the present study.

Below are the evidence-based recommendations:

- **Use of dual ventilations (mechanical + natural) lowered average in-classroom PM_{10}, $PM_{2.5}$ and PM_1 exposure by ~50%, 40% and 33%, respectively, compared with natural ventilation (window + door).** Regardless of the classroom's features, the classrooms using dual ventilation during school-opening hours showed up to 1.5-, 1.7- and 2-times lower PM_{10}, $PM_{2.5}$, and PM_1 levels, compared with classrooms depending on the NV (window + door). This underlines the positive advantage of mounting mechanical ventilation and/or air purifiers for use during school-opening hours for reducing exposure to PM. Additionally, it is proposed that windows remain open during school-opening hours, when feasible, to improve the natural ventilation while installing a mechanical ventilation system is not feasible in the school.
- **Wooden and vinyl type of floors were generally associated with more particles during school-opening hours.** Classrooms using carpet indicated ~48% and 32% less PM_{10} concentration than wooden and vinyl floor types. It shows that carpets act as a sink for PM and can trap dust and allergens. Therefore, caution should be taken for laying wall-to-wall carpets (Bergmans et al., 2022; Becher et al., 2018; He et al., 2022).
- **Large-volume classrooms (>300 m^3) were found to be associated with ~200% higher VR compared with smaller classrooms.** The effect of classroom volume on VR was clearly obvious. Despite showing the lowest ACH (1 ± 0.5 h^{-1}), the large-volume classrooms showed the highest VR meeting the 8 l s^{-1} $person^{-1}$ requirements. The small- and medium-volume classroom groups showed both relatively higher ACH (i.e. 3 h^{-1} and 2 h^{-1}) but their VR were relatively low (4 l s^{-1} $person^{-1}$). Therefore, whenever feasible, considerations should be given to increase classroom volume via their floor area and/or ceiling height in those under refurbishment or newly built schools.
- **Real-time pollution monitoring equipment should be installed by school management. For example, CO_2 and PM monitors.** Installing indoor CO_2 observing devices in the classroom is proposed to alert teachers when CO_2 exceeds the prescribed limits. In combination, PM monitors can allow class teachers to understand the classroom dust concentrations.

We investigated a variety of classroom parameters to understand the underlying factors affecting the air quality in classrooms. The scientific data gathered in this study highlighted a number of considerations, such as the ventilation condition, the classroom size, the type of floor and the occupancy numbers, to reduce exposure to PM inside schools. This study produced a unified CO_2 and particle profile dataset of 30 classrooms in five schools within London, which can be used for developing and validating dispersion models. Similar studies are required to further develop a database under a range of conditions such as the classroom typology, seasons and ventilation conditions to determine more robust guidelines and recommendations for improving air quality inside classrooms.

Author credit

Sarkawt Hama: Formal analysis, Data Curation, Methodology, Investigation, Validation, Conceptualization, Writing - Original Draft, Writing - review & editing. **Prashant Kumar**: Conceptualization, Methodology, Funding acquisition, Resources, Supervision, Project Administration, Writing - Original Draft, Writing - review & editing. **Arvind Tiwari**: Data Curation, Investigation, Validation, Writing - review & editing. **Yan Wang:** Writing - review & editing. **Paul S. Linden**:

Funding acquisition, Writing - review & editing.

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

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