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Environmental quality in sixty primary school classrooms in London

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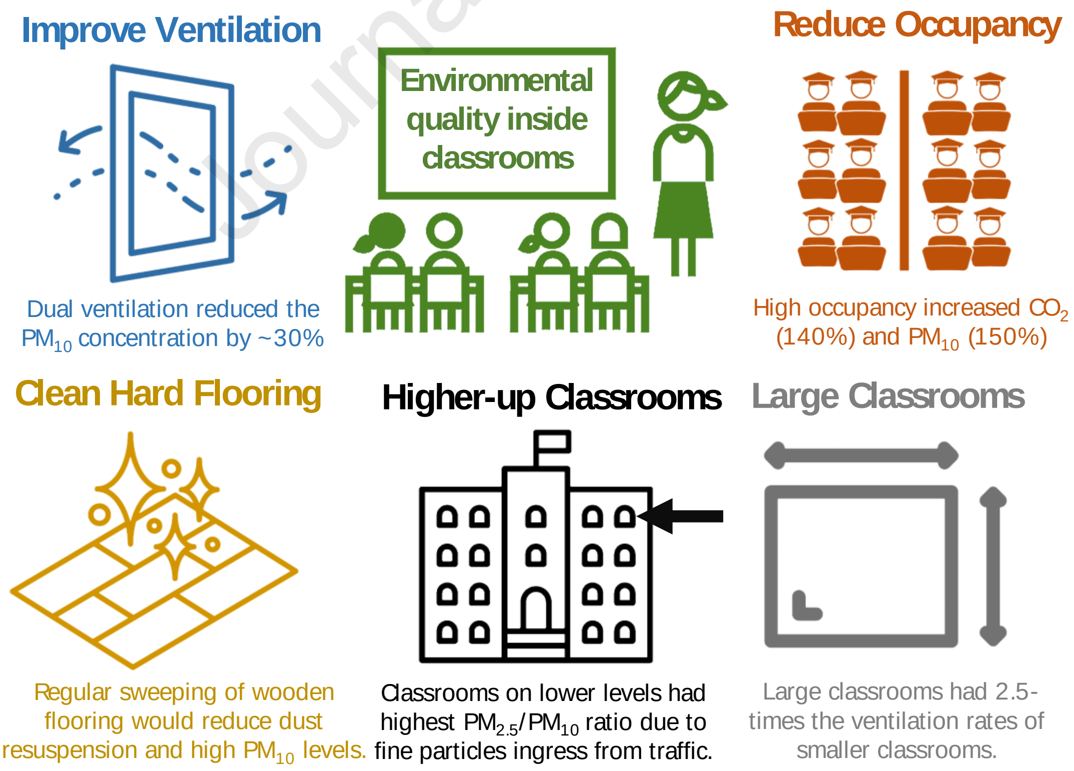
Graphical abstract



Abstract

Poor environmental quality in school classrooms can have a detrimental impact on children's health, nevertheless, the association between air pollutants and physical features of classrooms is poorly understood. We monitored particulate matter (PM), carbon dioxide (CO_2) and thermal comfort in sixty classrooms across ten London primary schools using similar equipment to produce a comparable dataset. The overall research objective was to understand the association of classroom air quality with occupancy levels, floor types, classroom locations, classroom volume, ventilation types and different year groups. Average in-classroom PM_{10} (29±20), $PM_{2.5}$ (10±2) and PM_1 (5±2 μg m-3) during occupied hours were ~150% (PM_{10}) and 110% ($PM_{2.5}$) higher compared to non-occupied hours. PM_{10} concentration was reduced by 30% for dual (mechanical+natural) compared to natural ventilation only; the corresponding reduction was slightly lower for $PM_{2.5}$ (28%) and PM_1 (20%). PM_{10} almost doubled for wooden floored classrooms compared with those having carpets. During high occupancy (>26 occupants), the average CO_2 (935±453 ppm) was ~140% higher than non-occupancy. The average CO_2 in classrooms occupied by younger children (reception and year one) was ~190% higher than those with older children (years eight and nine). 68% of classrooms exceeded the recommended levels of 40% relative humidity. Low PM_{10} concentrations coincided with low CO_2 concentrations in classrooms across all schools. These findings highlight the importance of simultaneously addressing both thermal comfort and the resuspension of PM_{10} to achieve comprehensive improvements in classroom air quality. Classroom settings where indoor environment is likely to be compromised can also be identified and addressed.

Keywords: Indoor air quality; CO_2; PM_{10}; Thermal comfort; Ventilation rates; UK schools

1. Introduction

Around 30% of a child's time is spent at school, and 70% of that time is spent inside classrooms [1]. In many countries, children are mandated to attend school for a significant portion of their day, for example, UK children aged four to sixteen must receive full-time education, which typically takes place in classrooms [2]. In 2017, 7800 English schools were situated in areas with annual average concentrations of particulate matter ≤2.5 μm ($PM_{2.5}$) surpassing the World Health Organisation (WHO) recommended standard of 5 μg m^{-3} [3, 4]. Substantial evidence has indicated that compromised indoor air quality (IAQ) and thermal discomfort negatively affects academic achievement, overall health, and well-being of both students and staff [1]. Furthermore, air pollution has been linked to adverse impacts on child lung development, increasing likelihood of respiratory infection, such as asthma [5]. Evidence suggests symptoms among asthmatic children are triggered when schools return after the summer holiday period where hospital admissions for asthma-related cases have been noted to peak in September [6] of the childhood population. In the UK, childhood asthma is more prevalent when compared with other European countries, ranging between 10.2% and 20.9% [6]. Since IAQ in classrooms has an evident impact on children's health, it is pivotal to thoroughly understand pollutant levels and thermal comfort and how they are impacted by classroom characteristics to provide a safe environment for children at schools. The WHO/European centre recently released a tool to support the protection of children's health from indoor air pollution in schools [7], following a literature review on children's health outcomes related to exposure to indoor air pollution in public settings [4].

Assessing the air quality in classrooms across the UK has become a topic of interest since the pandemic (Table S1), encouraging the UK's Department for Education to deploy CO_2 monitors in late 2021; however, monitors only display air quality parameters in rooms but do not record the data [2]. For example, Hama et al. [8] monitored particulate matter (PM), CO_2 and thermal comfort across five London schools over the winter season. Results indicated that the average PM_{10} for occupied classrooms was 230% higher than non-occupied classrooms. Another air pollution monitoring campaign was conducted inside and outside three London schools to investigate the impacts of different reduction interventions including green screens, air purifiers and traffic control [9]. They found that PM concentrations dropped by 44% owing to a green display along the fences of playgrounds. In addition, installing air purifiers in a classroom reduced PM levels by about 57%. In a separate study concerned with thermal comfort [6], the majority of eight studied classrooms experienced overheating during 40% of school hours and $PM_{2.5}$ exceeded 20 μgm^{-3} when heating was used. This was also higher than 10 μgm^{-3} during the non-heating season, both exceeding recommended health guidelines. However, existing research thus far focuses on a few parameters across a limited number of classrooms over a certain timeframe. Thus, there is a need for more wide-scale and consistent research efforts that would allow for coherent analysis and reliable recommendations to be adopted as nationwide guidelines across schools.

Existing exposure studies within classrooms in England focus on a specific parameter or a certain school. Studies are also based on short-duration campaigns and inconsistent sampling methods that limit the opportunity to draw city-scale conclusions and recommendations. An overview of earlier research in this field of study indicated a lack of adoption of a holistic approach in the investigation of in-classroom pollutant levels and thermal comfort across various schools in England (see Table S1). Hence, the study attempts to address the gap by measuring concentrations of CO_2 and particulate matter (PM_1, PM_{10} and $PM_{2.5}$), thermal comfort, air changes per hour (ACH) and ventilation rates (VRs) using a consistent methodology and an extensive set of data drawn from ten schools over eight months. The study also investigates several classroom and occupant characteristics to investigate the different aspects that impact classroom air quality. This could inform relevant and reliable recommendations to vary these surrounding conditions to improve IAQ. In order to build an understanding of factors and decisions that impact the classroom microenvironment and children's health, the objective is to study the variations in IAQ and thermal parameters against classroom characteristics. These include occupancy, the volume of classrooms, specific types of ventilation, floor type, floor level and year group. Furthermore, this study is part of the CO-TRACE project, which has fueled the nationwide Schools' Air Quality Monitoring for Health and Education (SAMHE) programme. SAMHE brings together scientists, pupils and teachers to establish a network of low-cost air quality sensors in schools across the UK, to generate a wider dataset to support researchers in better understanding IAQ schools [10, 11]. The impact of this study is reflected in both its conclusions and nationwide reach to provide a safer environment for children.

2. Methodology

2.1 Study area

A total of 10 schools (denoted using the prefix S) in England took part in this study, including 8 primary and 2 secondary schools. Six locations (denoted using the prefix L) in every school were monitored. School locations are shown in Figure S1, with S8L4 representing location 4 in school 8. All schools were in urban areas except for S10 which was located in a semi-urban area. Schools were monitored from March to November 2021, when average temperature and relative humidity were 14.1±5.3°C and 72±14%, respectively (UK, Met Office). Each school has continuous data for two weeks, including two weekends, to capture the non-occupancy periods.

2.2 Characteristics of studied classrooms

A total of 60 locations were monitored. From these, 86.7% of the classrooms (52) had natural ventilation, through skylight, window and door openings, 6.7% (4) had mechanical ventilation to circulate air and 6.7% (4) used both natural and mechanical means of ventilation (Table 1). Following previous works [8], classroom were categorised into six groups of ventilation denoted using the prefix T: T1 –Natural ventilation (NV) with over 4 metre high ceilings and adjustable windows; T2 - NV with 3 to 4 metres of medium ceilings and single side ventilation with restricted opening choices; T3 - Similar to T2 but utilising cross ventilation; T4 - NV with one side ventilation and less than 3 meters low ceilings; T5 –Mechanical ventilation (MV); T6 - Dual ventilation (DVnm; natural+mechanical). In all schools examined, classrooms adhere to a daily cleaning regimen, being cleaned either before or after school hours according to a predetermined schedule. Furthermore, the monitored classrooms' volume and surface area varied from 109 to 1396 m^3 and 33.3 to 558.4 m^2, respectively. Regarding the location of classrooms, 58.3% (a total of 35 classrooms), 33.3% (20) and 8.3% (5) were situated on ground floor, first floor, and second or higher. Basement levels were neglected, meaning that floor level gives a generalised measure of distance from the ground, ignoring differences in floor to ceiling height, sloped ground and split floor levels. 70% (42) of the classes had carpet floors, 28.3% (17) had vinyl and 3.3% (2) had wooden floors. Windows in each class ranged between 0 and 14 windows, with doors ranging from 1 to 8. In addition, 61.7% (37) of the classrooms were located near (less than 100 m) busy roads, and 40% (24) were located far from busy traffic lanes. Class occupancies ranged between 23 and 63 individuals with teachers per class ranging between 1 and 7 while the rest were children. Classes hosted children between Year 1 and Year 9. All location activities fell under academic and/or sciences while only one classroom in school 8 (S8L1)was dedicated to painting. Teaching aids used were whiteboard and screen across all classrooms.

2.3 Instrumentation, data collection and quality assurance

Six classrooms were simultaneously monitored in each school using a set-up that consisted of a Q-TRAK (model 7575; TSI Inc. for CO_2, temperature and humidity) and an OPC-N3 (different sizes of aerosol). According to the calibration sheet, the CO_2 monitors have an accuracy of ±3% or ±50 ppm, whichever is higher, and can measure CO_2 (range of 0-5000 ppm). The temperature accuracy (–10 to 60°C) and RH (–5 to 95%) were found to be within ±0.5°C and ±3%, respectively. The air change rate and ventilation condition were estimated for each location using CO_2 levels, which are considered indicators of ventilation conditions. In addition, optical aerosol monitors (OPC-N3, Alphasense) were used to measure different size of PM along with a total particle number in the size range of 0.35 to 40 µm. The instruments were either newly purchased (PM) or factory fully calibrated (for example CO_2 monitors) prior to starting the monitoring campaign. The field campaign took place between March and November 2021. During this period, there was a phased re-opening of primary and secondary schools in March 2021 following an extended COVID-19 lockdown, followed by a growing number of classes having to self-isolate due to Delta variant in June-July 2023 [12]. Despite this upheaval, a considerable dataset has been acquired, to derive coherent conclusions and recommendations to provide a safer and healthier environment for children at school. To ensure the accuracy of the collected data, co-location measurements were conducted for two days (one before starting and one another after the completion of the campaign), using a research grade aerosol spectrometer (GRIMM 11-C). During the colocation measurements, all aerosol monitors were placed together with GRIMM in controlled laboratory conditions. In this setup, a nebulizer was used as a source to produce aerosols of various sizes composed of a sodium chloride solution (1% by weight) [13, 14]. To compare the concentration values, the data was recorded every minute. Among all aerosol monitors used in the study the high Pearson correlation coefficient (*r*) was found between GRIMM and aerosol monitor indicated high correlation, which the *r* values were higher than 0.96, 0.91, and 0.88 for $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, The Pearson correlation (*r*) between GRIMM and OPC-N3 was more than 0.96, 0.91, and 0.88 for $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, indicating strong agreement across all aerosol monitors used in the study (SI Figure S2). Additionally, the correlation between $PM_{1.0}$, $PM_{2.5}$, and PM_{10} among the OPC-N3 was higher than 0.98, 0.97, and 0.96. Nevertheless, during the colocation, the average aerosol concentrations reported by all OPC-N3 monitors were lower than the average aerosol concentrations measured by GRIMM. For example, the measurement error of $PM_{2.5}$ concentrations monitored from each OPC-N3 was as much as 21% less than that of high-end GRIMM. To adjust for the errors of measurement, linear regression models were used [14]. When compared to high-end equipment, the errors by PM monitors were reduced to 3%, 4%, and 6% of measurement concentrations for $PM_{1.0}$, $PM_{2.5}$, and PM_{10}, after using these models (SI Figure S3). Since factory-calibrated CO_2 monitors were used during monitoring, corrections were not required for CO_2 data. To reduce the measurement error of the CO_2 monitors of ±50 ppm, the monitored data for each school was changed to reflect the offsets of the detected CO_2 levels by each monitor from the averaged value of CO_2 in the midnight (01- 02:00am) [14].

2.4 Air exchange rates and ventilation rates

The build-up method and the decay method were used to calculate ACH and VR values for all classrooms for each monitored school day during the first lesson/registration and after the last lesson, respectively. These methods (detailed in Canha et al. [15]) are based on a fully mixed mass balance model that uses CO_2 as a tracer gas in the indoor microenvironment. The number of students and teachers present during each analysed build-up event was recorded through the teachers' log sheets. The teachers were requested to fill these log sheets so that the classroom occupancy levels, as well as the open/closed status of the windows and doors, could be captured. These data were recorded for each teaching period including registration, breaks and lunchtimes during the monitored period. In the build-up method, ACH was estimated using Eq. (1), which uses a midpoint CO_2 concentration (C_m) between C_0 and C_1 [15], and Eq. (2), respectively.

$$C_S = \left(\frac{C_m^2 - C_0 \times C_1}{2 \times C_m - C_0 - C_1}\right) \qquad (1)$$

$$A_B = \frac{1}{\Delta t \ln\left\{\frac{(C_S - C_0)}{(C_S - C_1)}\right\}} \qquad (2)$$

A_B is the build-up ACH, Δt = time (hr) between C_0 and C_1 (ppm; CO_2 concentrations measured at the start and end of the observation time window, respectively), and C_s = estimated steady-state CO_2 concentration for each monitored classroom. For the decay method, A_D (air changes per hour calculated using the decay method) was estimated using equation (3) using the monitored CO_2 data after classroom hours, once the students had left the classroom until the CO_2 concentration (C_B) had reached background levels of around 400 ppm.

$$A_D = \frac{1}{\Delta t \ln\left\{\frac{(C_1 - C_B)}{(C_0 - C_B)}\right\}} \qquad (3)$$

where C_B represents the CO_2 in the replacing ambient. Furthermore, the VRs were calculated by dividing the classroom's volume by the total number of occupants and then multiplying the result by the calculated ACH. For data analysis, our study assumed constant ACH and VRs throughout the day based on the average morning and evening data.

3 Results and Discussion

3.1 Characteristics of the classrooms

The sixty classrooms monitored data were divided into different categories: ventilation conditions, floor level and type, classroom volume, occupancy and year group. 21.3%, 19.7%, 9.8%, 34.4%, 8.2% and 6.6% of the classrooms belonged to specific types of ventilation T1, T2, T3, T4 (NV), T5 (MV) and T6 (DVmn), respectively (Figure 1). The volume averaged 209 m^3, with a median of 69 m^3) where 67.2% of the classroom belonged to V1 group (100-200), 27.9% for V2 (200-300) and 4.9% for V3 (>300) m^3 (Figure 1). Most classrooms (57.4%) were located at the ground level while, in terms of internal layout and activities 68.9% of the classrooms had carpet flooring (Figure 1). The average occupancy was 31 persons per classroom. For better understanding, classroom occupancy has been divided into three groups: zero occupancy, low (up to four occupants), and high occupancy (26–63 occupants). The study examined these classroom characteristics to explore their influence on the fluctuations in the PM (Section 3.2), $PM_{2.5}/PM_{10}$ ratio (3.3), CO_2 levels (Section 3.4), relative humidity and temperature (Section 3.5) and ventilation (Section 3.6).

3.2 PM concentrations

During classroom hours, average $PM_{1.0}$ and $PM_{2.5}$ with PM_{10} concentrations were 5.0±1, 10.0±3 and 24±6 $\mu g/m^3$ (Table S2), respectively. As anticipated, PM_{10} exhibited the highest (24±6 $\mu g/m^3$) owing to resuspension of particles caused by the movement of students and teachers as well as certain classroom activities such as crafts [14]. The highest PM_{10} range of 24-46 $\mu g\ m^{-3}$ was found in S8, while S2 experienced the lowest (13-25) (Figure 2a). The PM_{10} result (averaging

~25 μg m^{-3}) are relatively higher than for previous school studies in England [9]. The smaller particle (PM_1 and $PM_{2.5}$) concentrations were lower than PM_{10} during classroom hours, being linked to external sources like emissions from vehicles and combustion processes [16, 17, 18].

The highest PM_{10} was found in classrooms with medium ceiling height and cross ventilation (T3, PM_{10} ~34), followed by the high ceiling (T1, 24 μg m^{-3}), single-sided ventilation types (T4, 23 μg m^{-3}) and medium ceiling height and single side ventilation (T2, 20 μg m^{-3}). In reference to the broad ventilation categories (Figure 2c), the PM_{10} concentrations varied as follows: NV (23) >MV (20) >DV_{mn} (16 μg m^{-3}). $PM_{2.5}$ concentration exhibited the same profile as the PM_{10} where NV showed the highest, and DV_{mn} showed the lowest (Figures S4c and S5c). In addition, the overall decrease in PM_{10} achieved through dual ventilation (30%) surpassed the reductions observed for the $PM_{2.5}$ (28%) and $PM_{1.0}$ (20%) compared to NV.

With regards to classroom volumes, the average PM_{10} concentrations were 22±18 (V1), 24±19 (V2) and 18±13 (V3) μgm^{-3} (Figure 2d), where large-volume classrooms (>300 m^3) were associated with lower PM_{10}, but low variations across different classroom sizes were observed for PM_1 and $PM_{2.5}$ (Figures S4d and 5d). PM_{10} concentrations were 22±17 (ground), 21±17 (first), 36±28 (second) and 24±18 (third floor) μgm^{-3} (Figure 2e and Table S3). $PM_{2.5}$ exhibited a similar profile as PM_{10} (Figures S4e and S5e), where the second floor showed the highest average $PM_{2.5}$ and PM_1 of 12 and 10 μg m^{-3} (Tables S4 and S5). Owing to the effect of other factors, for instance, the low number and volume of classrooms located on the second floor (Table 1) show that the PM vertical profile could be independent of the height of the building. However, due to site differences such as slope profile and design differences such as split levels and differing floor to ceiling heights, floor location is likely to be defined differently from school to school.

In regards to the floor type (Figures 2f, S4f and S5f), average PM_{10} experienced the highest (43±30 17 μg/m^3) for wood, while the lowest (22±18 and 22±17) for carpet and vinyl. $PM_{2.5}$ ($PM_{1.0}$) concentrations were 10±3 (5±2), 10±3(5±2) and 11±3 (5±1) μg m^{-3} for carpet, vinyl and wooden (Table S4 and S5), respectively. Classroom PM concentrations were highest in classrooms with wooden flooring (hard floors), while those with carpeted floors (soft floors) had the lowest PM concentrations. This may be connected to the elevated resuspension of particles from hard floors [8, 19, 20]. According to earlier research, wood and carpeted floors had a PM_{10} resuspension rate that was around ~2.5 times greater than $PM_{2.5}$ [21]. Additionally, You and Wan (2015) stated that for both carpet and vinyl floor types, the PM_{10} resuspension rate was 3- and 3.5-times lower at low humidity levels (RH = 41%) than it was under medium (63%) and high (82%) RH levels.

Compared to periods of zero occupancy, the average PM_{10} was around 152% higher for high occupancy (Figure 2g and Table S3). These results were consistent with earlier research conducted in UK schools [8, 9, 14] and elsewhere [21, 22]. The $PM_{2.5}$ and PM_1 concentrations showed quite low during different occupancy levels (5-10 μg m^{-3}) (Figures S4g and S5g), indicating an almost negligible impact of occupancy. Unlike PM_{10}, $PM_{2.5}$ and PM_1 primarily occur from traffic emissions and combustion and hence were not significantly affected by occupancy level.

Figure 2i depicts the average PM_{10} concentration for all year groups. The highest PM_{10} was found in year four (29±23 μg m^{-3}), followed by year six (28±23) and year one (26±16), while years eight and seven showed the lowest (15±10 and 16±14 μg m^{-3}, respectively) (Table S3). While there is a general decline from younger to older age groups, the largest drop appears to occur between years 6 and 7 resulting in two separate groupings of high PM_{10} for years 0-6 and lower PM_{10} for years 7-9. While factors such as ventilation may have played a role, these results could be linked to occupants' movements and activities as younger children are more active and hence could lead to more resuspension of particles from the floor surfaces [14]. The highest average $PM_{2.5}$ concentration (11±2 μg m^{-3}) was found in the reception group (shows "0" in Figure S4i), while the lowest was in year nine (7±2 μg m^{-3}). The average PM_1 concentrations ranged between 4-6 μg m^{-3} for all year groups. Since these fine particles are the product of combustion, further investigations are needed to explain the higher concentrations for younger age groups.

According to the above findings, ventilation type appeared to have the greatest impact on PM concentrations, where dual ventilation in particular had a substantial impact on lowering coarse particles. During classroom hours, PM_{10} concentration was obviously impacted by the occupancy level, but there was no such clear trend for $PM_{2.5}$ and PM_1. The type of flooring also has an impact on PM concentrations; both wooden and vinyl floors were linked to higher particle levels across the classroom.

3.3 In-classroom $PM_{2.5}/PM_{10}$ ratio

The majority of coarse PM observed in classrooms are resuspended or generated by a variety of student (or teacher)-led activities including walking and playing, Finer fractions of PM could be ingress from outside and the activities such as sketching, and colouring. We examined the $PM_{2.5}/PM_{10}$ ratio (Figure 3) to understand the characteristics of fine and coarse particle sources inside classrooms and other influencing variables.

Despite the large variances in the different classroom categories and features, the coarse particles dominated (PM ratio <0.5) in 58% of the observed classes (Figure 3a). However, the rest of the classrooms had ratios higher than 0.6, suggesting a predominance of fine particles (PM ratio >0.5). In line with previous findings [8, 9], the ground-floor classrooms (S1, S7 and S9) had $PM_{2.5}/PM_{10}$

ratios exceeding 0.6, possibly due to the ingress of outside emissions from activities like traffic and other sources.

Ventilation conditions: T6 (DV_{mn}) was associated with the highest average $PM_{2.5}/PM_{10}$ (0.7), while T3 had the lowest (0.5) (NV, medium ceiling height with cross ventilation). Ventilation conditions: T1, T2 and T4 were all associated with the same ratio of 0.6. DV_{mn} showed the highest ratio (0.7), followed by MV (0.61), while NV showed the lowest (0.58) (Figure 3c) proving that dual ventilation is effective in classrooms owing to reducing coarse particles. This can also show that coarse-sized PM_{10}, produced by students and teacher activities as stated above, predominates in most classrooms, which is in line with earlier research for indoor conditions [9, 14].

Figure 3d shows $PM_{2.5}/PM_{10}$ for different classroom sizes where larger classrooms (>300 m^3) showed the highest ratio (0.7), while the small and medium classrooms experienced similar ratios (0.6). This demonstrates that the ratio is not considerably affected by the size of the classroom, which is in line with the other research [8].

Figure 3e shows the ratio for the floor locations. The ground- and first-floor classrooms showed the highest average ratio (0.58 and 0.62) versus second/third floors (0.5), owing to the effects of outside ingress on fine particles as previously mentioned.

The carpet experienced the highest (0.6), while the wooden flooring showed the lowest (0.38) (Figure 3f). This suggests that the coarse PM, as discussed in Section 3.2, dominates hard floors, which is in line with other earlier studies in London (carpet had the highest ratio of 0.53) [8].

Figure 3g illustrates $PM_{2.5}/PM_{10}$ for the different levels of occupancy. For zero occupancy, the ratio was the highest (0.67), while high occupancy showed the lowest (0.47) (Figure 3g). This proves that increased occupancy led to higher PM_{10} concentrations, which is aligned with studies conducted previously for schools in London [8, 9] and other works in Portugal [22, 23] and in Spain [24].

Years eight and nine showed the highest ratio (0.7 and 0.69, respectively), while the lowest were found in years four and six (0.51 and 0.52, respectively) (Figure 3i). This may be related to the movement and activities of children in classrooms, indicating that small children are more active and generate more dust from the floor surfaces, as we discussed in Section 3.2.

The ventilation specific type and types of floors both significantly impacted the PM ratio, whereas the DV_{mn} significantly lowered PM_{10} (coarse particles). The ratio was also impacted by various occupancy levels, whereas the highest ratio (0.67) for zero occupancy demonstrates that fine particles dominated classrooms with no students and teachers.

3.4 CO_2 concentrations

The systematic review of studies examining the relationship between CO_2 and health effects confirmed that the existing guideline concentrations - ≤1000 ppm, 1000–1500 ppm and >1500 ppm - represent good, moderate and poor indoor air quality, respectively, is appropriate [25]. The review also highlighted the need for studies in schools to measure/report confounding variables such as temperature, relative humidity, and ventilation, in order to improve future investigations linking CO_2 and health. During classroom hours, the in-classroom CO_2 concentrations ranged from 464 to 2115 ppm (Table S6), with an average of 809±283 ppm where each classroom across all schools (Figure 4a) was considerably lower than the recommended threshold (1000 ppm). This is consistent with earlier studies performed in London, where average CO_2 ranges were 546-1263 ppm [9], and 500-1500 ppm [8], as well as in Swedish primary school classrooms (520 ppm) [26]. However, levels observed in this study (809 ppm) averaged less than averages observed in European schools (1284 ppm in Baloch, et al. [27] and 1370 ppm in Szabados, et al. [28]), in Midwesterens (~1171 ppm in Haverien-Shahnessy et al. [29]), and Southwestern (~1780 ppm in Deng and Lau, [30]) US schools, and in France (~1229 ppm in Ramho, et al. [31]). In-classroom CO_2 can be influenced by ventilation (Figures 4b), classroom size (Figure 4d), floor location and types of floors (Figure 4e and Figure 4f), occupancy periods (Figure 4g) and year group (Figure 4i), as discussed below.

Figure 4b depicts the average in-classroom CO_2 levels for all six types of ventilation. T3 (NV) showed the highest CO_2 level (909±383 ppm), while T5 (MV) and T6 (dual, DVmn) showed the lowest (637 and 676 ppm, respectively). Generally (Figure 4c), NV showed the highest CO_2 concentration (801±414 ppm), while MV and dual (DV_{mn}) showed lower levels (637±164 and 676±229 ppm, respectively) (Table S7). This finding confirms the advantages of employing mechanical ventilation and opening windows and doors to improve ventilation [14].

Average CO_2 concentrations were 764±380, 836±454 and 812±300 ppm for V1, V2 and V3, respectively (Figure 4d). Although it is typical for smaller classrooms to have greater CO_2 levels, the reasons for this opposing trend may be caused by the relatively low number of 25 medium- (26±2) and 5 large-volume classrooms (31±12 occupants), making the comparison inconsistent. As smaller rooms often have greater ACH for the same air flow rate, this implies that the small (100-200 m^3) classrooms can have led to lower CO_2 levels. Additionally, Kumar et al. [14] indicated that CO_2 could build up above ventilation vents in the high ceiling rooms (>225 cm). This finding is consistent with a prior London research that found that there were around 16 small-sized and 2 large-sized classrooms [8].

In regard to the impact of floor levels and types (Figures 4e and 4f), the floor level seemed to have less effect on CO_2 as concentration values range at similar levels. Carpeted classrooms (soft floors) CO_2 concentrations were the lowest and hardwood floors (hard surfaces) were the highest (see also Section 3.2 for PM_{10}).

During zero occupancy periods, low and high level, CO_2 average levels were 654±293 ppm, 806±443 ppm, and 935±453 ppm, respectively (Figure 4g and Table S7). As anticipated, the density of occupancy had a notable effect on CO_2 concentrations inside the classroom. The average CO_2 during high occupancy was 140% higher than the vacant time, aligning with past investigations [32]. The average CO_2 levels in all classrooms during high (935±453 ppm) and low (806±443 ppm) occupancy periods are above the SAGE value of 800 ppm. Additionally, insufficient ventilation brought on by infrequent openings of a classroom window may result in CO_2 rising and, thus, breaching standards. Hence, to keep CO_2 in classrooms below acceptable limits, various ventilation systems should be used to accommodate various occupancy periods.

Reception classrooms ("zero" in Figure 4i) and year one showed the highest CO_2 levels (998±295, and 998±675 ppm, respectively), while years eight and nine showed the lowest (530±92, 686±240 ppm, respectively) (Table S7). This may be related to the movements and activities of children in classrooms, where small children are typically more active and generate more CO_2 (see also Section 3.2 for PM_{10}).

It can be concluded that the mechanical and dual ventilation caused a significant reduction in CO_2 levels compared with the natural ventilation. Other variables, including floor type and floor level, showed no discernible effects. The CO_2 concentrations were significantly impacted by occupancy, in comparison to the unoccupied period, the average CO2 levels during high occupancy were around 140% higher. Different year groups show high variation of CO_2 levels, owing to activity and movement of smaller children, where average CO_2 levels for smaller children (reception and year one) was ~190% higher than older children (year eight and nine). To reduce the concentration of CO_2 in the classroom, it is therefore beneficial to improve ventilation through windows, doors, and mechanical ventilation.

3.5 Thermal comfort

A thermally comfortable classroom environment is crucial for students' health, well-being, and performance. Table S6 summarises the statistical results for the relative humidity (RH) and temperature levels across the study period. Relative humidity and temperature levels in the monitored classrooms are displayed in boxplots (Figures 5a and S6a, respectively). During classroom hours, the RH was 44±6% and temperature levels ~23±1 ^{o}C, ranging from 28 to 61%, and 19 to 26 ^{o}C, respectively (Table S6), while recommended RH levels are between 40 and 60% and temperatures between 21 and 23 ^{o}C [33]. Overall, the average RH was more than 40% in 68% of the classes, whereas it was below 40% in 19 (32%) of the classrooms. Overall, the average in-classroom temperature ranged between 20 to 23 °C in 34 out of 60 (57%) classrooms but was over 23℃ in the other 26 classrooms (43%).

The impact of various parameters on thermal comfort levels, i.e. classroom volume, floor type, floor level, ventilation types, occupancy, and year group, are investigated. Figure 5b depicts the average in-classroom RH level for specific types of ventilation. T3 (NV) showed the highest RH level (58±6 %), followed by T6 (dual, DV_{mn}) of 51±6 %, while T1 (NV) showed the lowest (38±13 %) (Table S8). For the three different types of ventilation (Figure 5c), DV_{mn} showed the highest RH level (51±6%), followed by the MV (48±7%) and NV (43±12%) (Table S8), showing that ventilation types did not have a substantial effect on RH levels [8]. Observed changes in RH could be related to the different times of the monitoring period for each school (Table 1). The average temperature ranges were 22-24℃ for all six ventilation types (Figure S6b). DV_{mn} showed a similar temperature level for MV and NV which were 22, 22 and 23℃, respectively (Table S9 and Figure S6c). This confirms that other parameters might influence temperature than just ventilation.

S6 showed the highest RH level (58±6%), followed by S8 (53±7%) and S7 (51±8%), while S2 showed the lowest (24±6 %), followed by S1 (33±5 %) (Figure S6h). The temperatures ranged from 21±1 (S8) to 27±2 ℃ (S4) (Figure 5h). The average in-classroom RH and temperature levels exceeded 40% and 23℃ at seven out of ten schools, respectively, which indicates some thermal discomfort levels among the children. This finding was consistent with a previous study carried out in London over the winter season [8], and also with another study that found that several UK schools experienced overheating problems while the heater was on [34].

Reception year classrooms showed the highest RH levels, averaging 54±5 %, while year five showed the lowest with an average of 34±13 % (Table S8, Figure S6i). All year groups had RH levels over 40%, except year five. The temperatures ranged from 21±1 (reception) to 25±3 ℃ (year five). The average in-classroom temperature level was over 23℃ at five out of ten schools (Figure S6i).

The above observations allow to conclude that the occupancy had a significant impact on RH levels; average RH during high occupancy was ~114% higher than during the unoccupied period. Other variables, including volume, floor type and location, did not show any obvious correlations. These results imply that it is beneficial for schools to upgrade their heating systems and adjust the thermostats, and, in some situations like high humidity levels, provide humidifiers to achieve a thermally comfortable environment in the classroom.

3.6 Ventilation

3.6.1 ACH

The average ACH values were calculated during classroom hours using the approach described in Section 2.4. The ACH values for classrooms during study hours are presented in Figure 6a. The ACH ranged between 9.6±1.9 (S4L1) and 1.0±0.4 h^{-1} (S8L3) (Table S10), with an average of 3.5±1 h^{-1}, which is similar to those (3.4 h^{-1}) determined by Kosavi et al. [34] in England; higher than those reported (2.1 and 2.3 h^{-1}) for schools in London([8, 9]; and lower (4.2 h^{-1}) than those reported in Athens schools [35]. Additionally, we examined several variables that could have an impact on the ACH such as ventilation specific types (Figures 6b and c), classroom volume (Figure 6d), type of floor level (Figures 6e and 6f), schools (Figure 6g) and year group (Figure 6h), as elaborated further below.

T6 (DV_{mn}) showed the highest value (5±2 h^{-1}) (Figure 6b, Table S10), followed by T5 and T2, which both had the same value of 4±1 h^{-1}. DV_{mn} showed the highest value (5±2), followed by MV (4±1) and NV (3±2 h^{-1}) (Figure S6c). This indicates that changes in the frequency of window openings were directly associated with variations in the naturally ventilated classrooms' air exchange rate [8, 36].

Figure 6d depicts ACH values for various volumes of classrooms, which were 4±2 for V1, 3±2 (V2) and 2±1 h^{-1} for V3. We found the highest ACH value ~ 4±2 h^{-1} in small-sized, followed by medium-sized (3±2 h^{-1}) and large-sized classrooms (2±1 h^{-1}). These findings demonstrate the correlation between ACH and classroom volumes; whereas classroom size increases, ACH decreases.

Figure 6e depicts ACH values for various floor levels. The carpet showed the highest ACH (4±1 h^{-1}), followed by vinyl (3±0 h^{-1}) and wooden (2±1 h^{-1}). A previous study also indicated that the ACH in the classroom was unaffected by factors such as floor level and floor type [8]. Hence, these differences could be related to other parameters such as occupancy and volume of classrooms.

It can be concluded that ventilation conditions and the volume of classrooms are the primary variables affecting ACH values in classrooms. In comparison to smaller classrooms, those with a larger volume (>300 m^3) exhibited a 50% reduction in ACH values. Therefore, it would be advised to employ dual ventilation (mechanical+natural) to increase a classroom's ACH. While the other variables (floor type, floor level and year group) do not affect the ACH.

3.6.2 Ventilation rates

The correlations between the VRs, CO_2 and PM levels have been demonstrated in earlier studies [8, 37]. Following the method outlined in Section 2.4, we calculated VRs (litre per second per person) in the studied classrooms (Figure 7a). Out of 60 classrooms, 51 (85%) had average VRs that were lower than the standard limits recommended by the ASHRAE (8 l/s/person, [38]) and the CIBSE (10 l/s/person, [39]). The average VR varied from 2.1 to 16.7 l/s/person across all classrooms, with an average of 5.9 l/s/person (Figure 7a), which was less than the VR value (6.2) reported for naturally ventilated classrooms in the UK [34] and noticeably lower than the VR (7.2 classrooms with) found mechanically ventilated classrooms in Finland [15]. However, the average VR value in this study (5.9 l/s/person) was higher than those reported elsewhere ~3.8, 4.5 and 4.4 l/s/person [9, 35, 40], respectively. Moreover, because of the movement of people in the classroom and the greater CO_2 owing to children's respiration, low VR and ACH values may have also contributed to the heightened PM_{10} concentrations [8]. Particle and CO_2 levels in classrooms would therefore decrease with an increase in VRs and ACH and help reduce the buildup of CO_2, which would provide healthier conditions for students to perform [8, 41, 42].

We looked at several variables that could affect the VRs, such as specific types of ventilation (Figures 7b and c), the volume of classrooms (Figure 7d), types and locations of floors (Figures 8e and 7f), schools (Figure 7g) and year group (Figure 7h), as will be discussed in more detail below.

The VR value showed the highest (8 l/s/person, Table S11) for the T5 (MV) followed by T6 (dual) of 7 l/s/person, while T3 (NV, cross ventilation) showed the lowest VR (4 l/s/person) (Figure 7b). Figure 7c exhibits the average VR for the NV, MV and DV_{mn} ventilation types. MV showed the highest average VR, followed by the DV_{mn} and NV, which were 8, 7 and 6 l/s/person, respectively. The lowest CO_2 and PM concentrations were found in DV_{mn}, followed by MV and NV (Sections 3.2 and 3.4). DV_{mn} and MV are therefore highly advised.

V3 (>300 m^3) experienced the highest VR (16 l/s/person, Table S11), followed by V1 and V2 (6 and 5) (Figure 7d). We found the highest VR value (16) in large classrooms. The small- and medium-sized classrooms had nearly the same VR (5 and 6 l/s/person). As anticipated, large classrooms had the lowest ACH (2 h^{-1}, Section 3.6.1) but the highest VR (8 l/s/person), which shows that larger classrooms have better ventilation (low CO_2 and PM levels) [8]. However, in medium and small classrooms, VR was less than recommended, highlighting the importance of having a bigger volume of classrooms. To draw thorough findings, though, additional factors, in addition to the classroom volume, will also need to be considered. For example, VR is also influenced by occupancy [8], thermal comfort parameters [43], airtightness of the outside walls

[44], and remarkably the degree of opening the windows/doors, which were not recorded in this study.

The four levels (ground, first, second and third) showed almost the same value of VR of 5, 6, 6 and 6 l/s/person, respectively (Figure 7e). The findings indicated that the floor levels did not have an evident impact on the ventilation rates (VRs). Figure 7f illustrates the average ventilation rate (VR) values for the various floor types. The vinyl and carpet showed the highest (7 and 6 l/s/person, respectively), while the wooden ones showed the lowest (3 l/s/person). According to a prior study, the type of floor did not affect the VRs, and other factors, such as occupancy and volume, could be related to obtaining different VR values for different floor types [8].

The classrooms of reception (“zero years” in Figure 7h) showed the highest VR (17±4 l/s/person), followed by year eight (15±4 l/s/person), while year one, four and six classrooms showed the lowest (4±2 l/s/person, Table S11). The classrooms of different year groups showed different VR values and there is no clear correlation between the year group and VR. As we found the same result in the ACH section, indicating that other factors discussed above have a significant effect on the VR rather than the year groups of children.

In summary, the VR depends on the ventilation types, the status of opening of doors and windows and the size of classrooms. Other parameters, such as floor type, floor levels and year group, had no impact on the VR. The large-sized classrooms (>300 m^3) showed almost three times higher than the small-sized classrooms (100-200 m^3).

3.7 Interdependence of parameters

Figure 8 shows the correlation of different sizes of PM and CO_2 levels during classroom hours for the different levels of occupancy. Interestingly, PM_{10} levels substantially increased in all the classrooms with increasing occupancy levels (green line in Figure 8). This confirms the above findings (Section 3.2), where PM_{10} showed a positive relationship with occupancy level. However, at all levels of occupancy for studied classes, the PM_1 and $PM_{2.5}$ concentrations showed no considerable change, and their trend was comparable (yellow and red lines in Figure 8). This demonstrates that the majority of the actions that children and instructors perform in the classroom create or resuspend coarse particulate matter (PM_{10}), supporting the findings of Section 3.2. This reveals that diverse activities performed by pupils and teachers are the main sources of coarse particulate matter (PM_{10}) generation or resuspension in the classroom. This result is consistent with previous studies carried out in London [8, 9. 22, 23]. Notably, given that increases in CO_2 are caused by the respiration of occupants, CO_2 levels increased with the level of occupancy in all classrooms (blue line in Figure 8). This confirms the above findings (Section 3.4) that showed a positive relationship between CO_2 and occupancy level. When compared to unoccupied time in classrooms, a relatively high level of occupancy led to CO_2 rises of roughly 31% to 83% [9]. Therefore, a major factor influencing CO_2 concentrations in indoor spaces is the level of occupancy [45].

The in-classroom CO_2 concentrations are grouped based on a set of thresholds: low<800ppm; 800ppm>medium<1200ppm; 1200>high<1500ppm; 1500ppm>very high<2000ppm; and extreme>2000ppm. Events are the instances when the CO_2 concentration is within the above thresholds for a given number of minutes. Figure 9 depicts the duration of 'events' in minutes per classroom per day and the histogram of CO_2 'events' per classroom, which are grouped based on the length of an event i.e. 15, 30, and 45 minute. Figure S7 shows the total duration of 'events' in minutes per classroom. Events having CO_2 concentrations less than 800 ppm, "low" are not included in Figures 9, S7 and S8. Classrooms, S3L5, S3L6, S6L3, S6L4, S8L1, S8L3, S8L4, S8L5, S10L4 and S10L5, show the highest number of ‘events’ where CO_2 levels were greater than 2000 ppm (Extreme, blue colour) and between 1500-2000 ppm (red colour). However, S1L2, S4L6, S5L3, S7L1 S5L6, S10L1, and S10L6 show the lowest number of ‘events’ where CO_2 levels were between 800-1200 ppm (green colour). This is related to other features of the classroom (Table 1). For example, S3L6, S6L4, S8L3 and S8L4 classrooms showed the highest number of ‘events’ (extreme, blue colour) due to the physical features of those classrooms; using natural ventilation (T4) and located on the ground floor (Table 1). Those classrooms also showed relatively higher PM_{10} and CO_2 levels compared with other classrooms (Figures 2 and 4). On the other hand, S5L3, S5L6, S10L1 and S10L6 classrooms showed the lowest number of “events" and had mechanical ventilation (Table 1). Also, those classrooms showed relatively lower PM_{10} and CO_2 levels compared with other classrooms (Figures 2 and 4). Favourable classroom physical characteristics and conditions have positively influenced the indoor environment by reducing the frequency and duration of events of CO_2 with high concentration levels and vice versa.

Figure S7 shows a histogram of the number of “events” in each threshold category for a classroom j day and they are grouped based on the length of an event i.e. 15, 30, 45 minutes and so on. Figure S9 shows the total duration of ‘events’ in minutes per school. It can be noted that most of the events were below the medium thresholds. Similar to observations to those reported in UK schools with natural ventilation [2], short CO_2 events occurred more frequently than long-duration events (Figure S8a). This indicated that CO_2 concentration raised above the threshold categories and subsided quickly (less than 30 min).

Figures 10a-e show the duration of PM_{10} ‘events’ in minutes per school per day for various CO_2 levels. Figure 10f shows the percentage of CO_2 events with different levels across all schools. Figure 10g shows the percentage of PM_{10} events under each CO_2 event. Figures 10a-e show the interrelationship between CO_2 events and PM_{10} events. PM_{10} event duration per classroom- day under event duration were classified based on different CO_2 events. It can be seen that most of the low PM_{10} events happened during low CO_2 events. Medium, high and extreme PM_{10} events increase with higher concentration CO_2 events. Thus, indicating high concentration levels of PM_{10} and CO_2 happened in the classroom simultaneously. In addition, when CO_2 events with concentrations below 800 ppm, extreme and high PM_{10} were negligible (Figure 10a).

Figure 10f provides further evidence on the relationship between CO_2 and PM_{10} events. The low CO_2 events occurred 64% of the time (Figure 10f) and almost 60% of low PM events happened during this time (Figure 10g). Moreover, extreme CO_2 events consisted of nearly ~ 50% of extreme PM_{10} events and ~ 20% of high PM_{10} events (Figure 10g). Notably, extreme and low PM_{10} events are directly related to extreme and low CO_2 events respectively. For instance, the red bar went up when the grey bar went down and vice versa (Figure 10g). These observations confirmed the relationship between PM_{10} and CO_2 in Sections 3.2 and 3.4. The positive relationship between CO_2 and PM_{10} can be associated with the occupancy level and ventilation conditions in the classroom (Section 3.4). This result is also consistent with previous studies carried out in London where PM_{10} and CO_2 levels were highest during high occupancy levels [8, 9. 22, 23].

4. Conclusions and future work

We studied the impact of various classroom parameters (occupancy, volume of classrooms, specific types of ventilation, types of floor, floor level and year group) on the indoor air quality, ventilation and thermal comfort across 60 classrooms. Here are the key conclusions derived from this work:

- The average concentration of $PM_{1.0}$, and $PM_{2.5}$, PM_{10} was 5±2, and 10±3, 24±6 μg m^{-3}, during the classroom hours. Average PM_{10} levels were around 130% and 150% higher during high and low occupancy times compared to the unoccupied period. When compared to natural ventilation, dual ventilation considerably reduced the levels of PM_{10} and $PM_{2.5}$ (30% and 28% respectively) and less for PM_1 (20%).

- The $PM_{2.5}/PM_{10}$ was impacted by various occupancy levels, with zero occupancy periods having the most significant ratio (~0.67). Owing to the impact of outside PM, the ratio for the classrooms situated on the ground and first floor was >0.6.
- During classroom hours, CO_2 levels in examined classrooms mostly ranged between 464 and 2115 ppm. The average CO_2 levels for smaller children (reception and year one) was ~190% higher than older children (year eight and nine). The average CO_2 during the high occupancy period was ~140% higher than the unoccupied period.
- The average relative humidity for all sixty classrooms was 44±6%, falling within the 40–60% thermal comfort range. The RH level in most classrooms (68%) is higher than the recommended 40%. 43% of classrooms experienced temperatures higher than 23°C.
- When compared to small classrooms (100-200 m^3), the large classrooms (>300 m^3) displayed 50% less ACH. Large-sized classrooms showed almost three times higher than the small-sized classrooms (100-200 m^3). The varying floor types and floor levels did not significantly affect the ACH, and ventilation rate (VRs).
- CO_2 and PM_{10} levels increased with occupancy levels in all investigated classrooms. The extreme CO_2 events conincided with nearly ~ 50% of extreme PM_{10} events and ~ 20% of high PM_{10} events. Also, extreme and low PM_{10} events are directly associated with extreme and low CO_2 events respectively.

The presented measurements and analysis support the formation of recommendations that aim to improve indoor air quality at schools and reduce children's exposure to air pollutants in school environments; our recommendations include:

- **Supporting natural classroom ventilation with mechanical ventilation where needed,** using dual ventilation reduces exposure of children in classrooms to PM_{10} and $PM_{2.5}$ by on average 30% and 25%, respectively as opposed to using natural ventilation only. Dual ventilation also reduced classroom CO_2 levels by on average 16% compared to using natural ventilation only.
- **Daily sweeping of wooden flooring is favourable to avoid dust resuspension,** as it has been associated with almost double the PM_{10} levels observed in carpet flooring.
- **Students in large classrooms (>300 m^3) generally experience improved air quality conditions where ACH is reduced by around 50% compared to small classrooms (100-200 m^3).** Large-volume classrooms also exhibited the highest ventilation rates, which was more than 2.5-times that experienced in small classrooms (100-200 m^3).
- **When schools are located near busy roads, classrooms with more vulnerable children should be located at higher floor levels (or away from the roads) where children would be less exposed to the ingress of fine particles from traffic sources,** since the classrooms on the ground- and first-floor exhibited the highest average ratio of $PM_{2.5}/PM_{10}$ (0.58 and 0.62).
- **When reducing the number of students in classrooms is not feasible, improving the ventilation in high occupancy classrooms can provide better conditions for the children** since PM_{10} and CO_2 levels were around 230% and 140% higher during high occupancy times compared to the unoccupied period, respectively.

This study builds an understanding of the factors that influence air quality in classrooms in order to inform the efficient implementation of interventions that aim to improve children's exposure to air pollutants in classrooms. In order to provide holistic suggestions for enhancing the air quality within classrooms, similar research is necessary to further construct a database for gaseous and VOC pollutants.

CRediT author statement

Prashant Kumar: Conceptualization, Funding acquisition, Resources, Supervision, Project Administration, Writing – review & editing. **Sarkawt Hama**: Formal analysis, Data Curation, Methodology, Investigation, Validation, Conceptualization, Writing – Original Draft, Writing – review & editing. **Rana Alaa Abbas:** Writing – Original Draft, Writing – review & editing. **K.V. Abhijith**: Formal analysis, Writing – review & editing. **Arvind Tiwari**: Data Curation, Investigation, Validation, Writing – review & editing. **Duncan Grassie**: Writing – review & editing. **Christina Mitsakou**: Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

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Data availability

Data will be made available on request.

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List of Tables

Table 1. Characteristics of classrooms. Location shapes are either regular: rectangular or irregular: any other shape. Classrooms were categorised into six ventilation groups (Section 2.2). Floor types are W: wooden; C: carpet; V: vinyl. Floor level; G: ground, 1st: first, etc. Monitoring was conducted between March and November 2021 for all schools, i.e., S1 (school one, 08-31 March); S2 (19 April- 07 May); S3 (12-27 May); S4 (04- 22 June); S5 (23 June- 7 July); S6 (8-21 July); S7 (06-30 September); S8 (30 September-15 October); S9 (15-22 October) and S10 (11 October-16 November).

Location ID	**Room shape (volume; m^3)**	**Floor area; m^2 (ceiling height; m)**	**Ventilation type**	**No. of windows**	**No. of doors**	**Max. occupancy (children)**	**School year**	**Floor level**	**Floor type**	**Proximity to traffic**
S1L1	Regular (181)	51.7 (3.5)	T2	3	1	31 (30)	Year 1	1st	C	Near
S1L2	Regular (181)	51.7 (3.5)	T2	3	1	31 (30)	Year 1	1st	C	Near
S1L3	Regular (716)	204.6 (3.5)	T1	12	2	64	Common Hall	1st	C	Near
S1L4	Regular (176)	50.3 (3.5)	T2	3	1	31 (30)	Art room	1st	C	Near
S1L5	Regular (184)	52.6 (3.5)	T2	3	1	32 (30)	Year 2	1st	C	Near
S1L6	Regular (158)	45.1 (3.5)	T2	6	1	31	Corridor	1st	C	Near
S2L1	Irregular (144)	48 (3)	T4	2	1	31	Corridor	G	V	Near
S2L2	Irregular (140)	33.3 (4.2)	T1	2	1	31	Library	G	V	Near
S2L3	Irregular (243)	55.3 (4.4)	T1	2	1	31 (30)	Year 2	G	V	Near
S2L4	Irregular (233)	51.8 (4.5)	T1	2	1	31 (30)	Year 3	G	V	Near

S2L5	Irregular (217)	48.2 (4.5)	T1	2	1	31 (30)	Year 4	G	V	Near
S2L6	Irregular (189)	42 (4.5)	T1	2	1	31 (30)	Year 5	G	V	Near
S3L1	Irregular (169)	65 (2.6)	T4	3	4	33 (30)	Reception	G	V	Away
S3L2	Irregular (140)	53.8 (2.6)	T4	2	2	31 (30)	Year 2	G	V	Away
S3L3	Irregular (138)	53.1 (2.6)	T4	2	2	31 (30)	Year 3	G	V	Away
S3L4	Irregular (109)	41.9 (2.6)	T4	2	2	31 (30)	Year 4	G	V	Away
S3L5	Irregular (117)	45 (2.6)	T4	4	4	31 (30)	Year 5	G	V	Away
S3L6	Irregular (182)	70 (2.6)	T4	4	3	31 (30)	Year 6	G	V	Away
S4L1	Regular (146)	44.2 (3.3)	T2	5	2	31 (30)	Year 2	G	C	Near
S4L2	Regular (146)	44.2 (3.3)	T2	3	1	29 (28)	Year 2	G	C	Near
S4L3	Regular (236)	56.2 (4.2)	T1	3	1	30 (29)	Year 3	1st	C	Near
S4L4	Regular (236)	56.2 (4.2)	T1	3	1	30 (29)	Year 3	1st	C	Near
S4L5	Regular (210)	55.3 (3.8)	T2	3	1	30 (29)	Year 3	G	C	Near
S4L6	Irregular (275)	59.8 (4.6)	T1	3	1	30 (29)	Year 5	2nd	C	Near
S5L1	Regular (556)	88.3 (6.3)	T5	0	1	30 (29)	Year 8	G	V	Near
S5L2	Regular (150)	55.6 (2.7)	T6	2	1	31 (30)	Year 7	G	C	Near
S5L3	Regular (150)	55.6 (2.7)	T6	2	1	30 (29)	Year 7	G	C	Near
S5L4	Regular (150)	55.6 (2.7)	T6	2	1	31 (30)	Year 9	1st	C	Near
S5L5	Regular (150)	55.6 (2.7)	T6	2	1	29 (28)	Year 9	1st	C	Near
S5L6	Regular (137)	50.7 (2.7)	T5	0	1	29 (28)	Year 9	1st	C	Near

S6L1	Irregular (145)	45.3 (3.2)	T3	2	4	31 (30)	Year 3	G	C	Away
S6L2	Irregular (145)	45.3 (3.2)	T3	2	4	31 (30)	Year 3	G	C	Away
S6L3	Irregular (115)	35.9 (3.2)	T3	2	4	31 (30)	Year 4	G	C	Away
S6L4	Irregular (141)	44.1 (3.2)	T3	2	5	31 (30)	Year 4	G	C	Away
S6L5	Irregular (142)	44.4 (3.2)	T3	2	3	31 (30)	Year 6	G	C	Away
S6L6	Irregular (145)	45.3 (3.2)	T3	2	5	31 (30)	Year 6	G	C	Away
S7L1	Regular (151)	58.1 (2.6)	T4	2	2	30 (29)	Year 7	G	C	Near
S7L2	Regular (137)	51.7 (2.65)	T4	1	2	31 (30)	Year 9	G	C	Near
S7L3	Regular (175)	66 (2.65)	T4	3	2	31 (30)	Year 8	G	C	Near
S7L4	Regular (143)	54 (2.65)	T4	3	2	31 (30)	Year 9	G	C	Near
S7L5	Irregular (200)	48.9 (4.09)	T2	4	3	31 (30)	Year 9	1st	C	Near
S7L6	Regular (144)	53.3 (2.7)	T4	4	2	31 (30)	Year 9	1st	C	Near
S8L1	Irregular (1396)	558.4 (2.5)	T4	14	8	63 (56)	Year 0	G	V	Away
S8L2	Irregular (202)	49.3 (4.1)	T1	3	1	31 (30)	Year 4	1st	C	Away
S8L3	Regular (223)	54.4 (4.1)	T1	4	1	31 (30)	Year 1	G	V	Away
S8L4	Regular (200)	45.5 (4.4)	T1	3	1	31 (30)	Year 2	G	W	Away
S8L5	Irregular (196)	45.6 (4.3)	T1	4	1	31 (30)	Year 4	1st	W	Away
S8L6	Regular (153)	58.8 (2.6)	T4	2	2	31 (30)	Year 6	1st	C	Away
S9L1	Regular (175)	64.8 (2.7)	T4	5	2	31 (30)	Year 6	G	C	Away
S9L2	Regular (172)	63.7 (2.7)	T4	5	2	31 (30)	Year 1	G	C	Away
S9L3	Regular (175)	64.8 (2.7)	T4	5	2	31 (30)	Year 1	G	C	Away

S9L4	Irregular (208)	65 (3.2)	T2	4	1	31 (30)	Year 2	1st	C	Away
S9L5	Irregular (214)	66.9 (3.2)	T2	4	1	31 (30)	Year 4	1st	C	Away
S9L6	Irregular (211)	65.9 (3.2)	T2	4	1	31 (30)	Year 4	1st	C	Away
S10L1	Regular (128)	42.7 (3)	T5	0	1	25 (24)	Year 2	3rd	C	Near
S10L2	Regular (137)	45.7 (3)	T4	4	1	27 (26)	Year 3	G	C	Near
S10L3	Regular (268)	89.3 (3)	T4	6	1	26 (25)	Year 2	1st	V	Near
S10L4	Regular (144)	48 (3)	T4	6	1	26 (25)	Year 1	2nd	C	Near
S10L5	Irregular (240)	80 (3)	T4	6	1	24 (23)	Year 3	2nd	C	Near
S10L6	Regular (154)	51.3 (3)	T5	0	1	26 (25)	Year 4	3rd	C	Near

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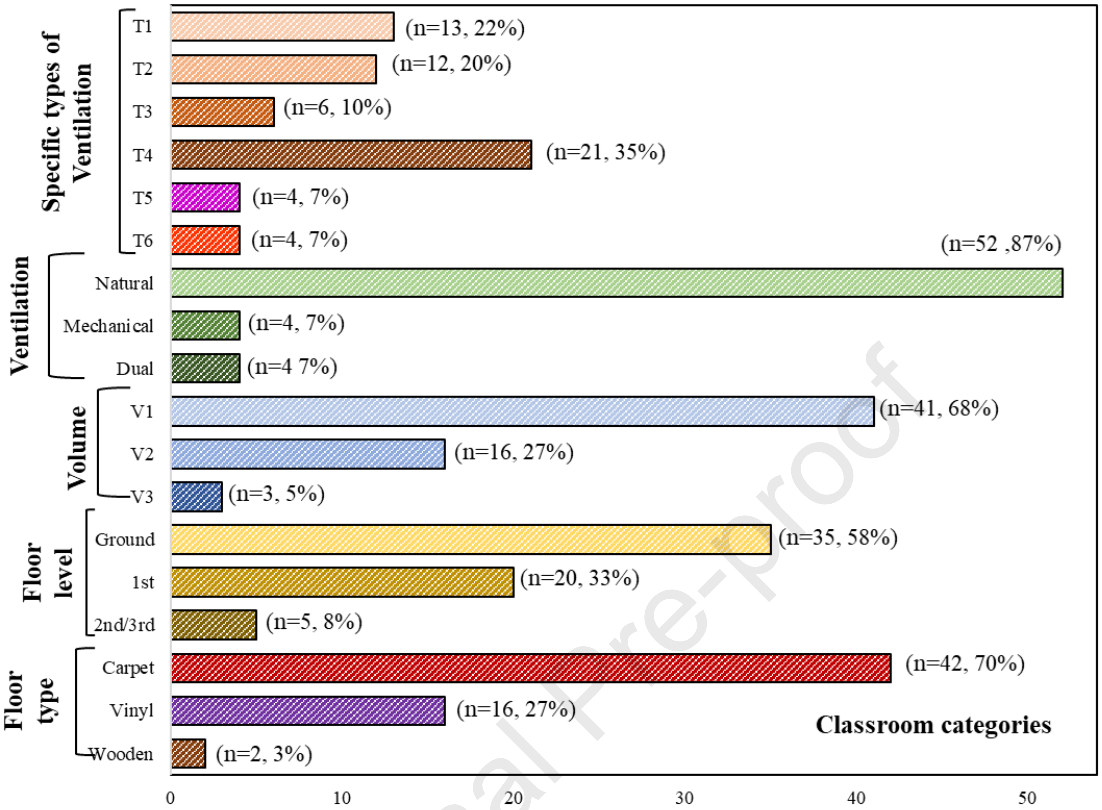


Figure 1. (a) The percentages of the various classroom parameter groups; types of floor, floor level, types of ventilation and volume of classrooms in ten schools. Classrooms were categorised into six groups of ventilation: T1 – NV(Natural ventilation) with over 4 meters high ceilings and adjustable windows; T2 - NV with 3 to 4 meters of medium ceilings and single side ventilation with restricted opening choices; T3 - Similar to T2 but it had the cross ventilation type; T4 - NV with one side ventilation and less than 3 meters low ceilings; T5 – MV (Mechanical ventilation); T6 - dual ventilation (natural+mechanical). Volume categories are now as follows: V1 group (100-200 m^3), V2 (200-300 m^3) and V3 (>300 m^3).

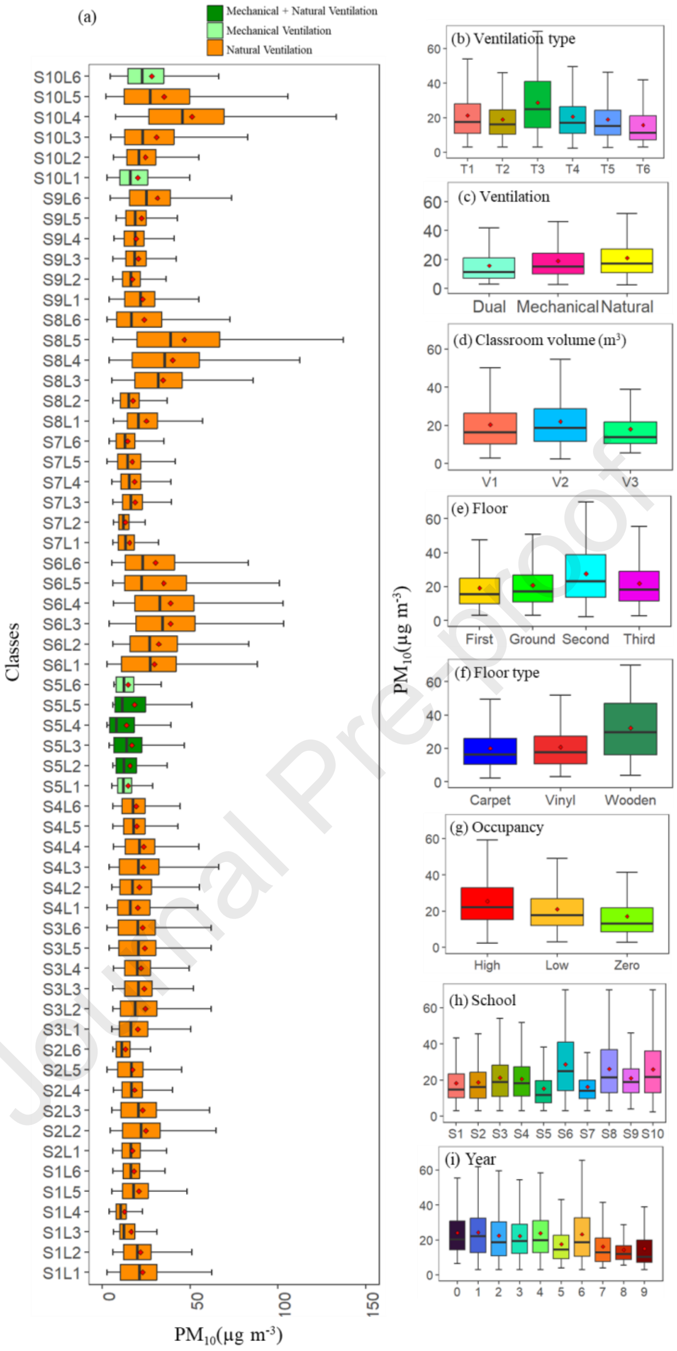


Figure 2. (a) PM$_{10}$ concentration for all classrooms represented in box plots (left panel) indicated by classroom code. On the right, box plots represent the PM$_{10}$ average values in reference to classroom characteristics: (b) specific types of ventilation; (c) ventilation mode; (d) volume of classrooms; (e) floor levels; (f) types of floor; (g) the level of occupancy; (h) schools, and (i) year group. Each box has top, middle, and bottom lines representing the 75, median, and 25 percentiles. The whiskers' bottom and top edges indicate the minimum and maximum values, while the mean is displayed as a dot.

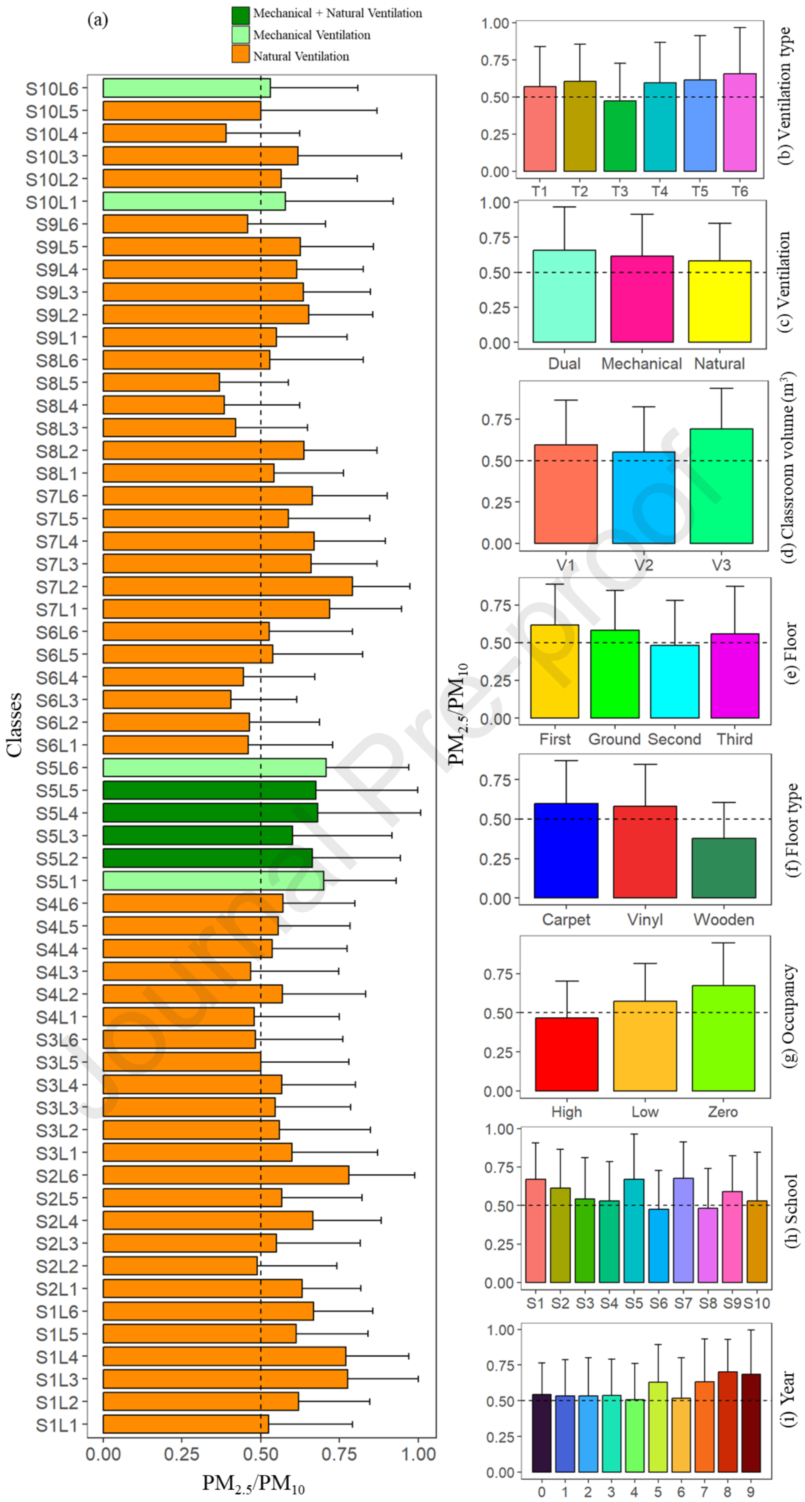


Figure 3. (a) Bar plots of PM ratio for the sixty classrooms. The ratio of 0.5 is shown by the dashed line. The average PM ratio in each classroom for the whole monitoring period is categorised based on (b) specific types of ventilation; (c) ventilation mode; (d) volume of classrooms; (e) floor level; (f) types of floor; (g) the level of occupancy; (h) schools and (i) year group.

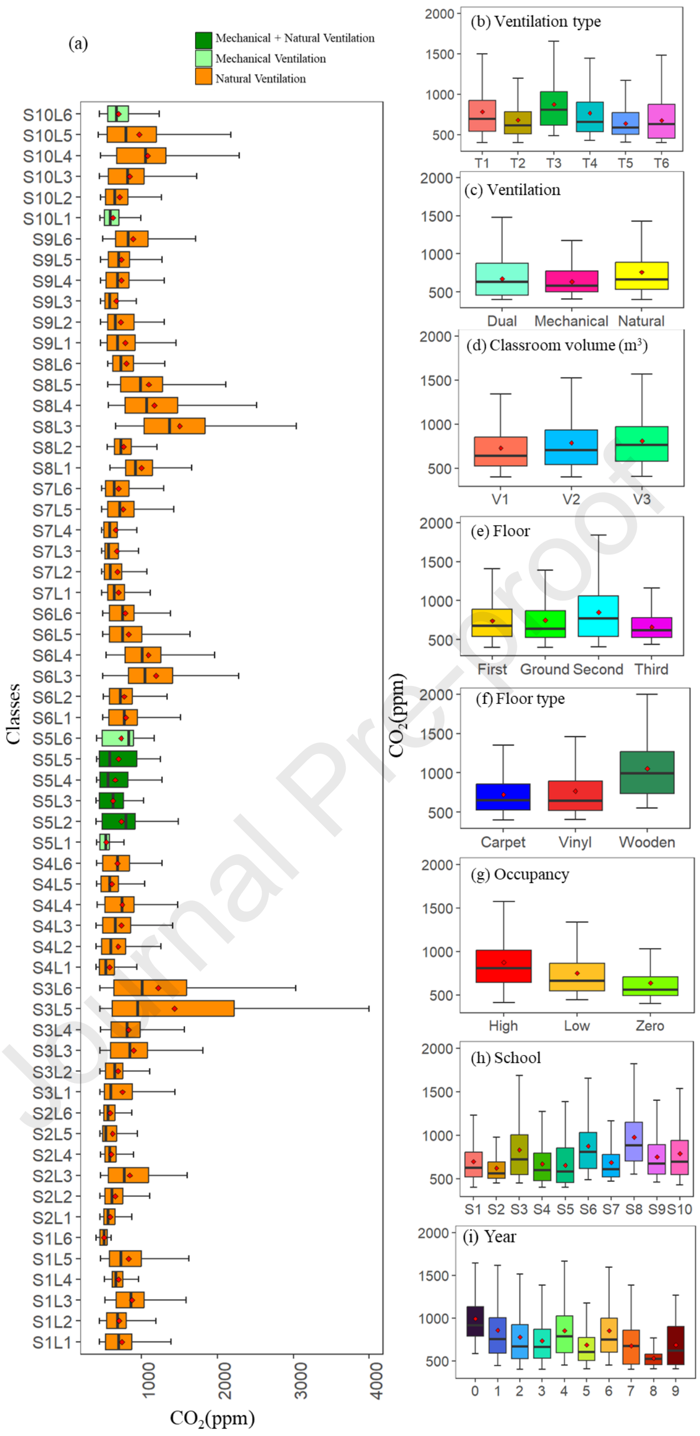


Figure 4. (a) CO$_2$ concentration for all classrooms represented in box plots (left panel) indicated by classroom code. On the right, box plots represent the CO$_2$ average values in reference to classroom characteristics: (b) specific types of ventilation; (c) ventilation mode; (d) volume of classrooms; (e) floor levels; (f) types of floor; (g) the level of occupancy; (h) schools, and (i) year group. Each box has top, middle, and bottom lines representing the 75, median, and 25 percentiles. The whiskers' bottom and top edges indicate the minimum and maximum values, while the mean is displayed as a dot.

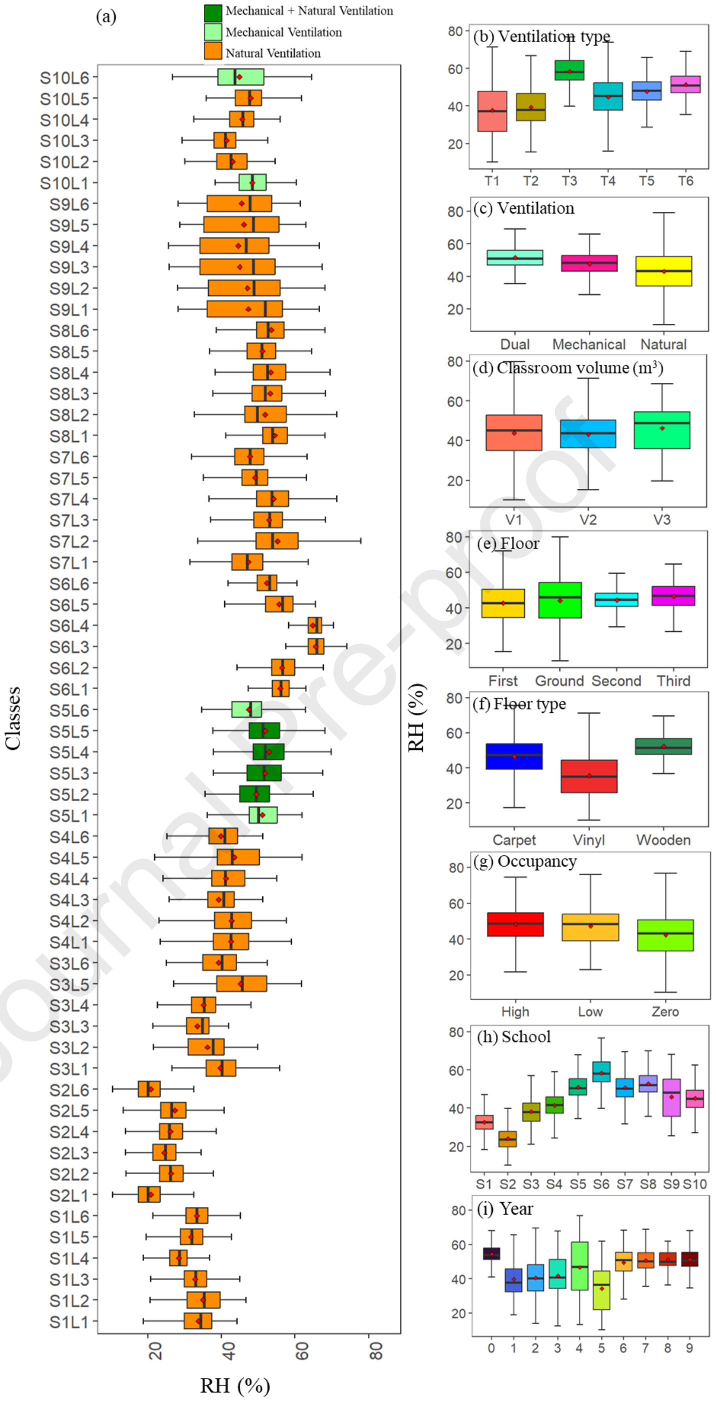


Figure 5. (a) RH level for all classrooms represented in box plots (left panel) indicated by classroom code. On the right, box plots represent the average value in reference to classroom characteristics: ((b) specific types of ventilation; (c) ventilation mode; (d) volume of classrooms; (e) floor levels; (f) types of floor; (g) the level of occupancy; (h) schools, and (i) year group. Each box has top, middle, and bottom lines representing the 75, median, and 25 percentiles. The whiskers' bottom and top edges indicate the minimum and maximum values, while the mean is displayed as a dot.

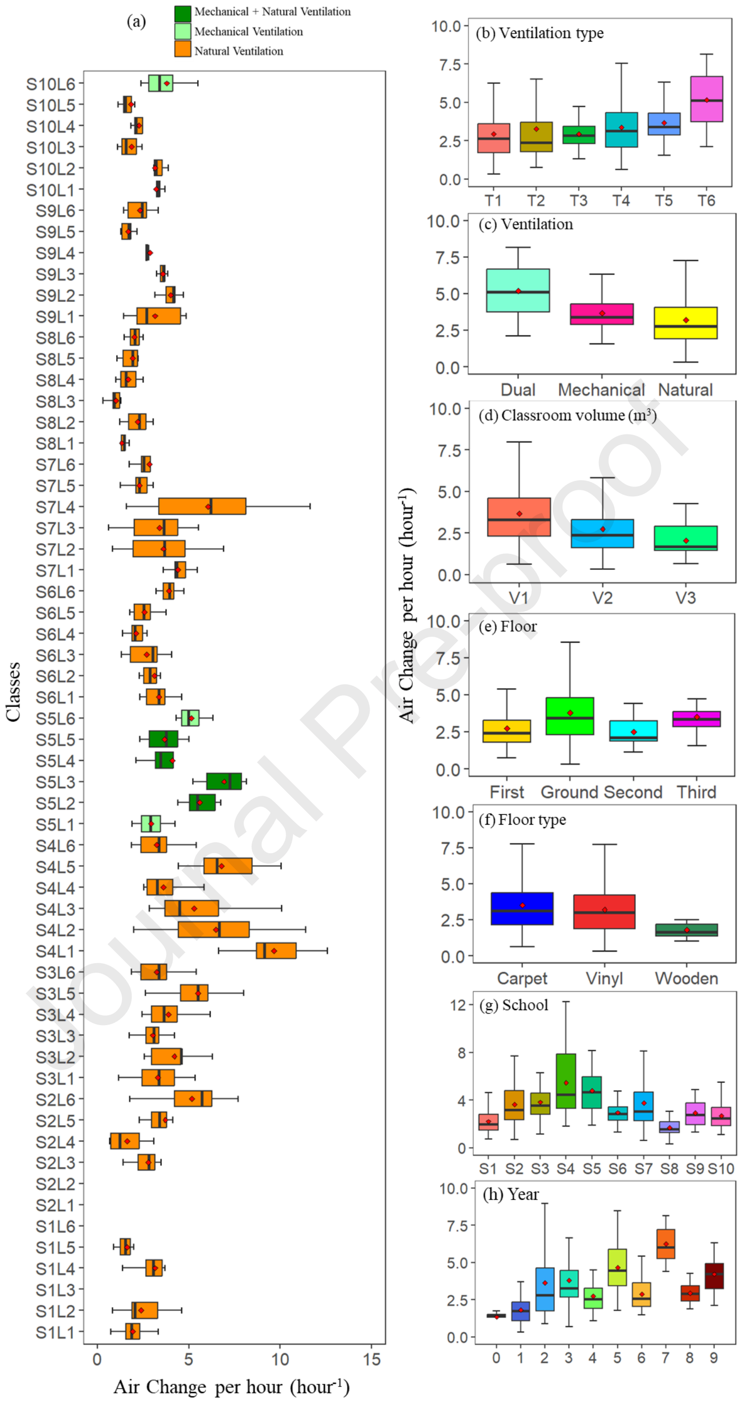


Figure 6. (a) ACH calculated for all classrooms represented in box plots (left panel) indicated by classroom code. On the right, box plots represent the average value in reference to classroom characteristics: (b) specific types of ventilation; (c) ventilation mode; (d) volume of classrooms; (e) floor levels; (f) types of floor; (g) schools, and (h) year group. Each box has top, middle, and

bottom lines representing the 75, median, and 25 percentiles. The whiskers' bottom and top edges indicate the minimum and maximum values, while the mean is displayed as a dot.

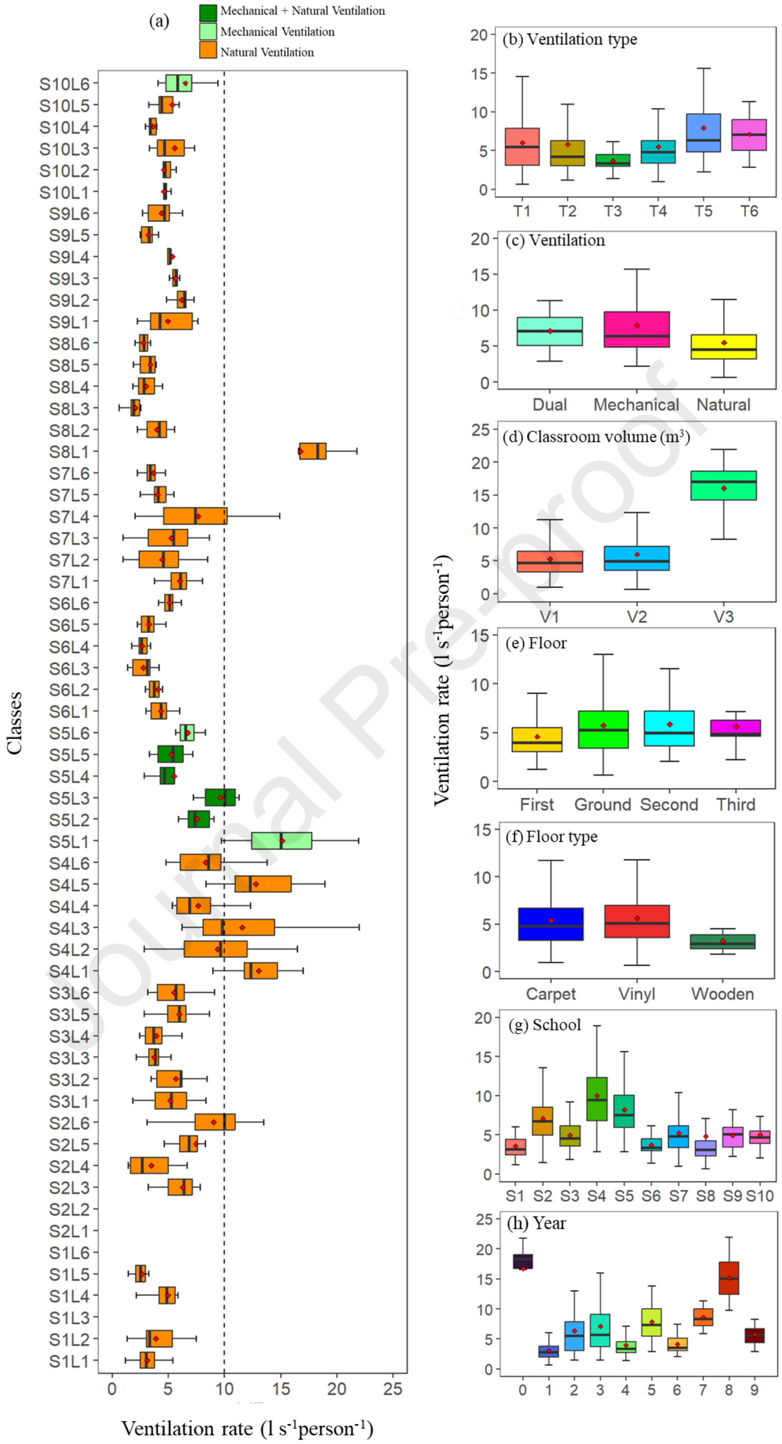
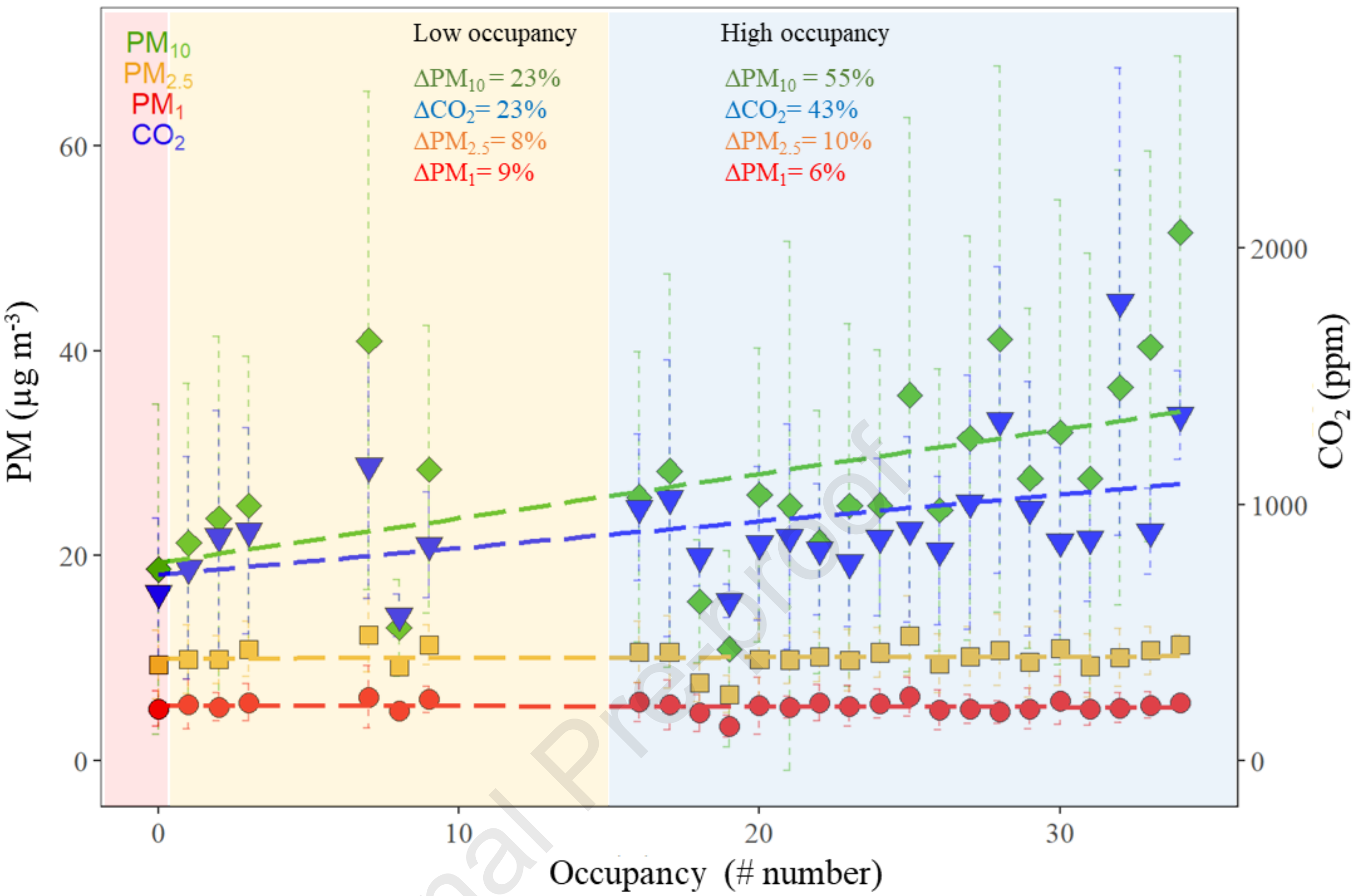


Figure 7. (a) Ventilation rate calculated for all classrooms represented in box plots (left panel) indicated by classroom code. On the right, box plots represent the average value in reference to classroom characteristics: (b) specific types of ventilation; (c) ventilation mode; (d) volume of classrooms; (e) floor levels; (f) types of floor; (g) schools, and (h) year group. Each box has top,

middle, and bottom lines representing the 75, median, and 25 percentiles. The whiskers' bottom and top edges indicate the minimum and maximum values, while the mean is displayed as a dot.


PM$_{10}$
PM$_{2.5}$
PM$_1$
CO$_2$
Low occupancy
ΔPM$_{10}$ = 23%
ΔCO$_2$= 23%
ΔPM$_{2.5}$= 8%
ΔPM$_1$= 9%
High occupancy
ΔPM$_{10}$ = 55%
ΔCO$_2$= 43%
ΔPM$_{2.5}$= 10%
ΔPM$_1$= 6%
PM (µg m^{-3})
0
20
40
60
CO$_2$ (ppm)
0
1000
2000
0
10
20
30
Occupancy (# number)

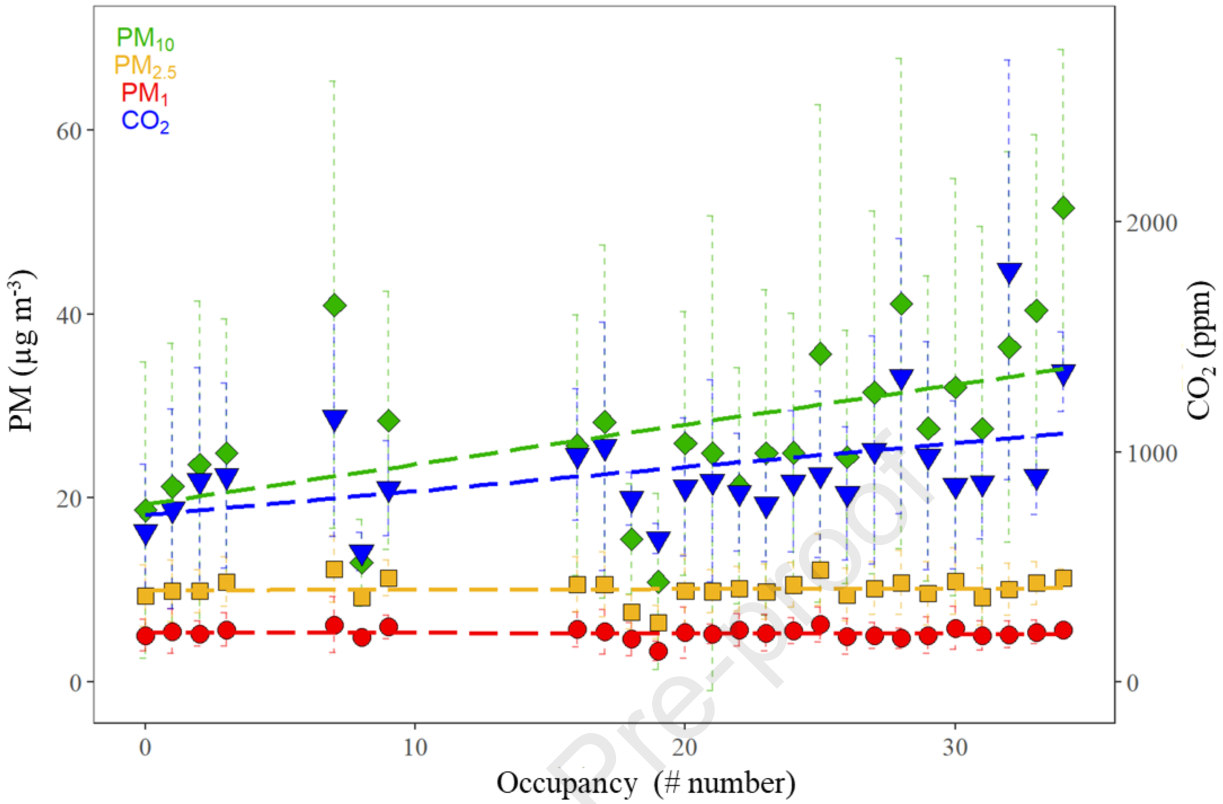


Figure 8. Correlation of average PM_{10}, $PM_{2.5}$, PM_1 and CO_2 concentrations for different occupancy levels in all classrooms across ten schools. PM_{10} correlation is shown in green, $PM_{2.5}$ is in yellow, PM_1 is in red and CO_2 is in blue. Red, yellow and red shaded area denotes zero occupancy (representing vacant classroom), low occupancy (up to four occupants), and high occupancy (full classroom with the majority of the students and teachers (>26 occupants). The percentage difference in PM_{10}, $PM_{2.5}$, PM_1 and CO_2 concentrations during low and high occupancies are calculated by comparing their concentrations at zero occupancy period during school working hours.

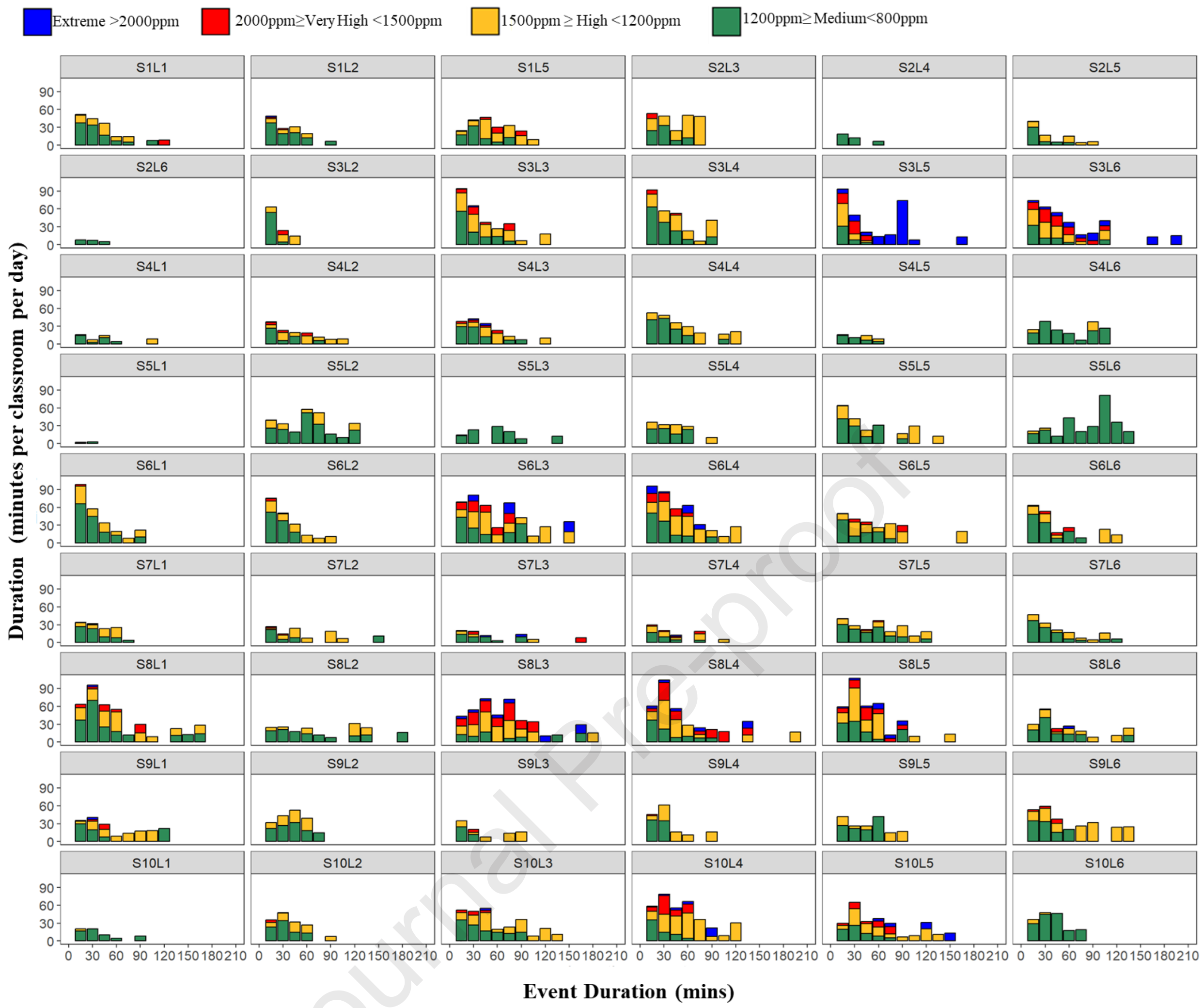


Figure 9. The duration of ‘events’ in minutes per classroom per day. In-classroom CO_2 concentrations are grouped based on a set of thresholds: low<800ppm; 800ppm>medium<1200ppm; 1200>high<1500ppm; 1500ppm>very high<2000ppm; and extreme>2000ppm.

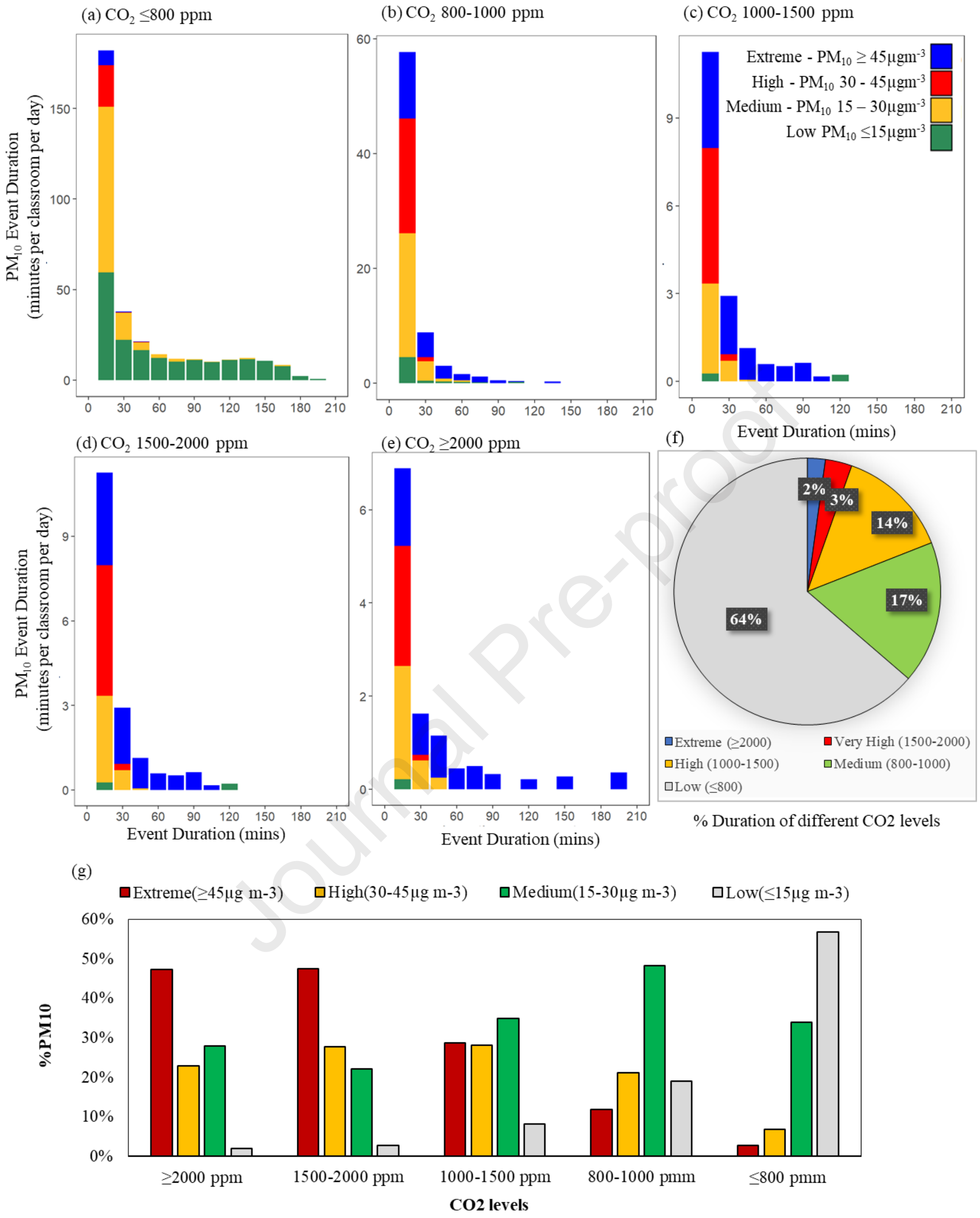


Figure 10. The duration of PM_{10} 'events' in minutes per school per day for various CO_2 levels (a-e); (f) shows the percentage of CO_2 events with different levels across all schools; and (g) shows the percentage of PM_{10} events under each CO_2 event.

Research highlights

- Particulate matter, CO_2 and thermal comfort were monitored in 60 classrooms.
- High occupancy classrooms showed an increase in PM_{10} of 150% and in CO_2 of 140%.
- Dual ventilation lowered PM_{10} concentration by 30% compared to natural ventilation.
- Hardwood had double the PM_{10} concentration compared to carpeted floored classrooms.
- Low PM_{10} events coincided with low CO_2 events in classrooms across studied schools.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: