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Indoor Air Quality (IAQ) in Naturally-ventilated Primary Schools in the UK: Occupant-Related Factors

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Abstract:

Indoor Air Quality (IAQ) is affected by *Context, Occupant and Building* (COB) related factors. This paper evaluates IAQ as a function of occupant-related factors including occupants' Adaptive Behaviours (ABs), occupancy patterns, occupant's CO_2 generation rates and occupancy density. This study observed occupant-related factors of 805 children in 29 naturally-ventilated (NV) classrooms in UK primary schools during Non-Heating and Heating seasons.

Occupant-related factors affecting IAQ include occupants' adaptive behaviours, occupancy patterns, occupants' CO_2 generation rate and occupancy densities. Results of this study suggest that a classroom with high potentials for natural ventilation does not necessarily provide adequate IAQ, however, occupants' good practice of ABs is also required. Average occupancy densities to have CO_2 levels of 1000±50 ppm are suggested to be $2.3\pm0.05 m^2/p$ and $7.6\pm0.25\ m^3/p$. These values correspond to classroom area of $62.1\pm1.35\ m^2$ and volume of $205.2\pm6.75\ m^3$ with a height of 3.3 m. Mean CO_2 level is maintained below 900 ppm when all occupant-related factors are in the favour of IAQ, however, it exceeds 1300 ppm when none of the occupant-related factors are in favour of IAQ. (none of the occupant-related factors)

It is shown that 17% of CO_2 variations are explained by open area (m^2), 14% by occupants' generation rates (cm^3/s) and 11% by occupancy density (m^3/p). IAQ is mostly affected by occupants' adaptive behaviours than other occupant-related factors in naturally-ventilated classrooms.

Keywords: Indoor Air Quality (IAQ), CO_2 levels, Occupants, Adaptive Behaviours, Occupancy Density (OD), Primary Schools

Highlights:

- Occupancy patterns in classrooms are dynamic and varied.
- 17% of CO_2 variations are explained by occupancy density (m^2/p).
- To have average CO_2 levels of 1000 ppm, class area=$62.1m^2$ and volume=$205.2m^3$.
- When all occupant-related factors are in favour of air quality, $CO_{2(mean)}$<1000ppm.
- Occupants' adaptive behaviours have the most significant impact on air quality.

1. Introduction:

Children spend almost 12% of their life inside classrooms, that is more time than in any other building except their home [1,2]. School and government authorities should ensure that appropriate indoor air quality (IAQ) is maintained for children [3]. IAQ in schools is recognized as one of the most important factors affecting students' health [4–9] and academic performance [10–13]. IAQ in classrooms is mainly assessed by CO_2 levels [14–18], especially in buildings where people, exhaled air or bio-effluents are the main pollution sources [19]. Authors have previously suggested [20] that the main

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factors influencing IAQ in buildings fall into three categories of *Context, Occupant and Building* (COB). 1) *Contextual* factors on the macro level such as climatic conditions [21] and season [22–24], or the micro level such as regional temperature [25] and draughts from windows [26], 2) *Building-related* factors such as airtightness [27,28], schools' location, classrooms and windows' design [21], type of ventilation, ventilation rate [27], CO_2 exhalation rate and room volume [29], 3) Occupant-related factors such as occupants' behaviour [26,27], maintenance and operation of systems, operating schedule [27], number of occupants [28,30], activity levels, amount of time spent in the room, previous room's occupancy [23], occupants' age and diet [9,25], and individual's thermal comfort [5].

It is important to focus on occupant-related factors affecting IAQ in primary schools for four main reasons; **1)** Children have physical and physiological differences with adults [31–35], which makes them more vulnerable and less resistant than adults to health risks from environmental hazards [36–41]. Physically, children have a smaller body surface area [42], have narrower airways [43,44], their organs, tissues and immune system are not fully developed [45] and their body's defence against infection is limited [44]. Children breathe in more air (approximately 50% more) into their developing lungs relative to their body weight [46,47]. Physiologically, children have higher metabolic and respiration rates [48], which results in children producing heat at a rate of 85% of that for adults [49,50]. **2)** Due to above-mentioned differences and also teachers' role in controlling classrooms [51,52], children's environmental adaptive behaviours are more limited than that for adults [53–55]. The impact of poor IAQ on children is exacerbated because they usually do not complain about it [55,56]. **3)** Classrooms are more crowded than other workplaces [45,57] and occupancy density of classrooms is about four times higher than that of office buildings [58]. Therefore, CO_2 exhalation rate can be higher in schools. **4)** Children's perception of IAQ can negatively be affected by external factors, such as type of their work [45,55] and their stress level [59]. Children's work in schools is almost always new to them, while adults frequently perform routine tasks [55]. Thus, the effect of environmental conditions on schoolwork performance by children is larger than that on office-work performance by adults [60].

Healthy IAQ is vital for the health of children as they are more sensitive towards indoor air pollutants. Hence, the effect of occupant-related factors on IAQ is remarkable in the context of primary school buildings, especially considering potential unpredictability of those factors. This paper aims to provide a detailed analysis of IAQ as a function of occupant-related factors during heating and non-heating seasons with the aim of delivering healthier classrooms for the next generation of children.

2. METHODOLOGY

This paper is focused on how occupant-related factors affect IAQ in UK primary schools. (remove). The main steps carried out (in this methodology) are 1. Sampling climate, buildings, windows and occupants, 2. Acquiring data on adaptive behaviours, occupancy patterns, and environmental measurements. 3. Calculating occupants' CO_2 emission rate 4. Reviewing Standards, 5. Overviewing recorded data.

2.1. Sample Selection:

In this study, Samples were selected with specific attention to the climate in which buildings were located, buildings and their neighbourhood, windows within the buildings and buildings' occupants.

2.1.1. Climate:

The study was carried out in Coventry, West Midland, with the mild climate according to Koppen classification [61] from mid-July 2017 until the end of May 2018 to represent all climatic conditions. Schools were selected in the *mild* climate of the UK because mild or temperate climates can provide opportunities for buildings' natural ventilation [62–65] and can reduce the biased impact of extreme climates on window operation in NV buildings.

2.1.2. Buildings:

To study the effect of occupant-related factors, especially adaptive behaviours on IAQ, selected schools met five criteria. 1) Selected schools in this study are naturally ventilated since the main source of ventilation in most UK schools is windows. Furthermore, variations in temperature, humidity and pollutants from mechanical ventilation and air-conditioning systems [66] can limit our understating about IAQ in buildings and its relation with occupants. 2) Buildings were selected in quiet areas to not restrict window operation due to high background noise level, as supported in [67,68]. 3) Buildings were selected in low-polluted areas to not restrict window operation due to high pollution level, as supported in [15,16,68]. 4) Buildings were selected with different architectural features as different buildings provide different potentials for practising adaptive behaviours (ABs), Table 1. 5) Schools were selected among both renovated and existing buildings because they should comply with different IAQ standard [69]. Schools 1, 2 and 6 (13 classrooms) are among renovated schools and the rest (16 classrooms) are among existing buildings. In total, 29 naturally ventilated classrooms in eight primary schools were selected and studied during non-heating (NH) and heating (H) seasons, Table 1. Further details on the selection of the school buildings can be found in an earlier study by authors [52].

2.1.3. Windows:

To study how window design affects occupants' **A**daptive **B**ehaviour (AB), classrooms are classified into two groups that provide high or low potentials for the practice of ABs based on a comprehensive literature review on window design.

Window's design: High and low-level openings by reducing draughts in the occupied zone and directing the airflow above the occupied head height zone can reduce CO_2 concentrations without discomforting occupants [15]. It is shown that large openings can be used for still summer days and small high-level openings can be used for winter days to avoid overheating [50,70]. Windows at different levels (high and low-level openings) and sizes (small and large) can provide IAQ [15,20,50,70–72] during both heating and non-heating seasons. Therefore, classrooms with windows at different levels and sizes can potentially increase occupants' practice of ABs. Columns 5-9 in Table 1 (under window design section) show windows' area, number of windows, windows' type, ventilation type and a minimum height of operable windows, respectively.

Window's operation: Windows' operation method affects occupants' practice of ABs; it is shown that manual operation of windows helps to improve IAQ significantly [20,30,40,73,74] and makes people feel more comfortable in manually-controlled buildings [20]. Based on children's physiology, safe windows designed at lower heights are more accessible for children's window operation [20,52]. Therefore, classrooms that provide windows at accessible heights with manual and easy operation for children can potentially increase occupants' practice of ABs. Windows operated with a remote control or a handle suggest lower potentials for practice of ABs. Column 10 in Table 1 shows windows' type of operation. Classrooms that provide both of above criteria are classified as classrooms with high potentials for practice of ABs. The last column in Table 1 shows that 13 classrooms provide high potentials for practice of ABs and 16 classrooms provide low potentials for practice of ABs.

Table 1. An overview of the architectural features of schools and classrooms

General		**Classroom**		**Window Design**					**W Operation**	**NO[5]**	**Density[6]**		**AB [7]**
Mode	**No.**	**Area**	**Vo[1]**	**WA[2]**	**NW[3]**	**W Type**	**Ventilation**	**MW[4]**			**M^2/p**	**M^3/p**	
Non-heating	**1.1**	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level+ louvre opening	1	Manually	25	2.4	7.7	H
	1.2	60		8	8			1	Manually	25	2.4	7.7	H
	1.3	60		8	8			1	Manually	25	2.4	7.7	H
	1.4	60		8	8			1	Manually	28	2.1	6.9	H
	2.6	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level +louvre openings	1	Manually	29	2.1	6.6	H
	2.7	60		8	8			1	Manually	26	2.3	7.4	H
	2.8	60		8	8			1	Manually	30	2.0	6.4	H
	2.9	60		8	8			1	Manually	28	2.1	6.9	H
Heating	**3.10**	65	227	2	5	Top-hung outward	Single-sided	1.7	Manually	25	2.6	9.1	L
	3.11	70	245	2.2	6		Double-sided	1.6	Manually	28	2.5	8.8	L
	3.12	60	192	2.5	5		Single-sided	2.6	With handle	25	2.4	7.7	L
	4.13	50	130	0.5	2	Top-hung outward	Single-sided	1.8	Manually	27	1.9	4.8	L
	4.14	60	156	0.5	2			1.8	Manually	26	2.3	6.0	L
	4.15	50	175	0	0	-	No opening	-	No window	29	1.7	6.0	L
	5.16	55	137	5.7	8			0.5	Manually	30	1.8	4.6	H

	5.18	55		5.7	8	Top-hung openings at 2 levels	Single-sided at two levels	0.5	Manually	27	2.0	5.1	H
	5.20	55		5.7	8			0.5	Manually	32	1.7	4.3	H
	6.21	60	168	1.8	4	Top-hung outward opening	Single-sided windows + Louvre openings	2.3	Remote-control	29	2.1	5.8	L
	6.22	60		1.8	4			2.3		28	2.1	6.0	L
	6.23	60		1.8	4			2.3		30	2.0	5.6	L
	6.24	60		1.8	4			2.3		29	2.1	5.8	L
	6.25	60		1.8	4			2.3		30	2.0	5.6	L
Non-heating	**7.26**	70	252	3.9	6	Top-hung outward opening	Double-sided	2.7	With handle	29	2.4	8.7	L
	7.27	55	137	3.3	3		Single-sided	1.65	Manually	27	2.0	5.1	H
	7.28	55	137	5.4	6		Double-sided	1.6	Manually	30	1.8	4.6	H
	8.29	60	150	2.2	4	Top-hung outward opening	Single-sided	1.4	Manually	28	2.1	5.4	L
	8.30	60	150	2.2	4			1.4	Manually	29	2.1	5.2	L
	8.31	55	137	2.2	4			1.4	Manually	24	2.3	5.7	L
	8.32	55	137	2.2	4			1.4	Manually	26	2.1	5.3	L
1=Volume(m^3)- 2=Window Area (m^2)- 3= Number of Windows- 4=Minimum Height of window sill (m)- 5=Number of Occupants- 6= Occupant Density (m^2/number of students and m^3/number of students)- 7=Potentials for practice of AB													

Fig 1 shows a classroom with single-sided double openings at two different sizes and levels that are operated manually alongside the length of the classrooms (school 5). Fig 2 shows a classroom with 2 small windows at the height of 1.8m located at the end of the classroom (school 4).

Fig 1. Classroom providing high potentials for practice of ABs (indoor and outdoor view). Fig 2. Classroom providing low potentials for practice of ABs (indoor and outdoor view)

2.1.4. Occupants:

Among primary school students, children in their late middle childhood (9-11 YO) compared to their peers in early middle childhood (6-9 YO) were selected as the main respondents of this study. Children in late middle childhood compared to their peers have a better understanding of their environment [52] and have higher heights according to UK-World Health Organisation growth charts [42] which let them be more engaged in environmental adaptive behaviours. Furthermore, older children are allowed to move around during classroom breaks and operate controls, whereas younger children are kept under stricter supervision inside the classrooms [75].

2.2. Data Acquisition

The overview of behavioural studies shows that they mostly use transverse method to collect data [76–84], therefore, the study applies the transverse method. Hence, data acquisition and observations were carried out in 29 different classrooms on 29 distinct days throughout one year. To increase the validity of the study and reduce bias, the number of studied classrooms is similar during both seasons, 15 classrooms during non-heating and 14 classrooms during heating seasons. Table 1 shows the number of studied classrooms, the season at which each classroom was studied and the number of observed children in each classroom.

An observation form that was developed and validated in an earlier study by authors [85] is used to obtain information on architectural features, occupancy patterns and controls' operation, Table 2. Observations were conducted to have an in-depth understanding of factors affecting IAQ, as applied in another study [86]. Occupancy patterns and window operations are observed at 10-min intervals.

Table 2. Questions on architectural features, occupancy patterns and adaptive behaviours taken from questionnaires developed by authors [85]

Variables	Questions and Responses

Observation at 10-min interval	**Occupancy Patterns**	No. Students in the classroom?	Type of subject? (☐math, ☐English, ☐art, …)	
		Type of activity? ☐Seated, Reading and writing, ☐Standing and tidying, singing, ☐dancing or performing		
		Occupancy pattern in the classroom? ☐Occupied, ☐not occupied, ☐Left for break, ☐left for PE, ☐left for lunch, ☐left for assembly, ☐left for home		
	Windows operation	Total open area (m^2)? …	Total number of window adjustments? …	
Classrooms' architectural features		Classroom area (m^2)? …	Total area of operable windows (m^2)? …	
		Type of window operation? … (☐manual, ☐manual with a handle, ☐automatic, ☐ remotely controlled)		
		Type of window opening? … (☐Top hung, ☐side hung, ☐horizontal slider, ☐hopper, ☐awning, ☐casement)		
		Depth to Height Ratio? …	Openings area to classroom area? …	Min Height of operable windows? …
		Type and number of doors? (☐connecting door between classes, ☐internal door, ☐external door)		

Schools' occupied period is divided into three categories, teaching, non-teaching and total period. In this study, teaching period accounts for 75.4% of the times and non-teaching period, consisting of lunch breaks (11.3%), assembly (6.9%), short breaks (5.4%) and Physical Education (PE) (1%), accounts for the rest 24.6% of the times. The total period of occupancy (09:00-15:30) consists of both teaching and non-teaching period.

2.2.1. Environmental Measurements:

Environmental variables affecting occupants and their adaptive behaviours were recorded at 5-minute intervals by multi-functional SWEMA equipment [87], standalone data loggers [88] and CO_2 meter (TGE-0011, accuracy:±50+2% of the reading) [89] at a height of 1.1 m as recommended by ISO 7726 [90]. Specifications of the measuring equipment are shown in Table 3.

Table 3. Specifications of the measuring equipment shown in an earlier study by authors [85]

Probe	Variables	Meas. Range	Resolution
SWEMA [87]	Humidity and air temperature	0 to 100 %RH, -40 to +60 °C	0.1% RH 0.1 °C
	Air velocity and, Air temperature	0.05 to 3.0 m/s at 15 to 30°C, +10 to +40°C	0.01 m/s 0.1 °C
	Radiant temperature (Ø globe: approx.150 mm)	0 to +50°C	0.1 °C
Data Logger [88]	Temperature	-35 to +80°C	0.1 °C
	Humidity	0 to 100 %RH	0.5% RH
TGE-0011 [89]	CO_2	0 to 5000ppm	1 ppm

The instruments were usually set up in the classrooms before children's arrival in the morning and continued recording until the end of the school day (08:50-15:30). Time-lapse cameras were installed inside the classrooms to record occupants' adaptive behaviours on blinds and doors at 5-minute intervals.

2.3. Carbon Dioxide (CO_2) Generation (G)

CO_2 generation (G) is calculated based on children's age, metabolic rate, body surface area and room temperature. CO_2 generation for an average child is given in Equation (1) [26]:

$$G = \frac{-0.94(A-5)+52.3}{40}k \quad \text{Equation (1)}$$

Where

$$k = 0.148\alpha m\frac{273+tr}{273} \quad \text{Equation (2)}$$

G (kg/s) is CO_2 generation
A (years) is children's age
m (W/m^2) is the metabolic rate
α (m^2) is body surface area and
t_r(°C) is room temperature

Body surface area is calculated from Dubois equation (3) [26] when w = weight (kg) and h = height (m), are known [26].

$$a = 0.202w^{0.425}h^{0.725} \quad \text{Equation (3)}$$

Children's height and weight were derived from UK-World Health Organisation growth charts (average weight=32Kg and average height=1.38 m) [42]. Average body surface area of 9-11 years old children was found 1.1 m^2 [42].

Metabolic Equivalent of Task (MET) is the ratio of the working metabolic rate to the metabolic rate at resting condition [41]. MET equals the energy produced per unit surface area of an average person (1.8 m^2) seated at rest [58], where 1 MET=58.2 $W \cdot m^{-2}$ for seated relaxed activities [58,90]. MET expresses physical activity of humans and varies with type of activity [90]. The ASHRAE 55 (2013) defines the metabolic rate as the level of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism [91]. Metabolic rate of children can be modified by considering 0.85 value to metabolic rate of adults [92,93] because children produce heat at a rate of 85% of that for adults [15,49,50]. Metabolic rate of 1.2 corresponds to CO_2 concentration of approximately 900 ppm, assuming outdoor CO_2 concentration of 400 ppm [94,95]. The study by Havenith (2007) has estimated metabolic rate ($W.m^{-2}$) of 9-11 years old primary school children for different school activities (language=52, writing=53, art=59, drawing=62 and calculus=64 $W.m^{-2}$) [32]. Metabolic rate of children [32] and adults [92] for different activities is shown in Table 4.

Table 4. Metabolic rate of children and adults for different activities

Children [32]			**Adult** [92]		
Type of activities for children	**W/m²**	**MET**	**Type of activities for adults**	**W/m²**	**MET**
Seated activities (working individually, listening, writing and following)	58	1	Seated activities (Office, dwelling, school, laboratory)	70	1.2
Standing (walking through classroom to get material and light manual work)	79	1.3	Standing (shopping, laboratory, light industry)	93	1.6
Standing, medium activity (signing and adjusting clothing for PE)	99	1.7	Standing, medium activity (shop assistant, domestic and machine work)	116	2

Calculated CO_2 generation rate per child according to *equation 1* ranges from 3.34-5.89 cm^3/s with a median of 3.41 cm^3/s and mean of 3.64 cm^3/s. Several other studies have reported similar CO_2 generations per child; 4.4-5.15 cm^3/s in [28,29], 3.8-4 cm^3/s in [26], 3.75-4.57 in [96], and 4.4 cm^3/s in [27].

2.4. IAQ Standards

The European standard of EN 13779:2007 [97] recommends IAQ values in four different building categories in Table 5. I) high level of expectation for spaces occupied by sensitive people, II) normal level of expectation for new buildings and renovations, III) moderate level of expectation for existing buildings and IV) low level of expectation only acceptable for a short period. The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) standard 62 recommends CO_2 level of 1000 ppm [98].

Table 5. Recommended CO_2 values by EN 13779:2007 [97]

Categories	**IAQ standard**	**Typical Range**	**Total CO_2 values Based on outdoor CO_2 of 400 ppm**
Category I	High	<400	<800
Category II	Medium	400-600	800-1000
Category III	Moderate	600-1000	1000-1400
Category IV	Low	>1000	>1400

2.5. Statistical Analysis:

To decide on the most appropriate statistical test, the dependent variable and its type should be identified. To check the normality of CO_2 levels in this study, the histogram is used, as supported in [99]. Fig 3 shows that CO_2 measurements are not normally distributed, therefore, none-parametric tests are used, as supported in [100,101].

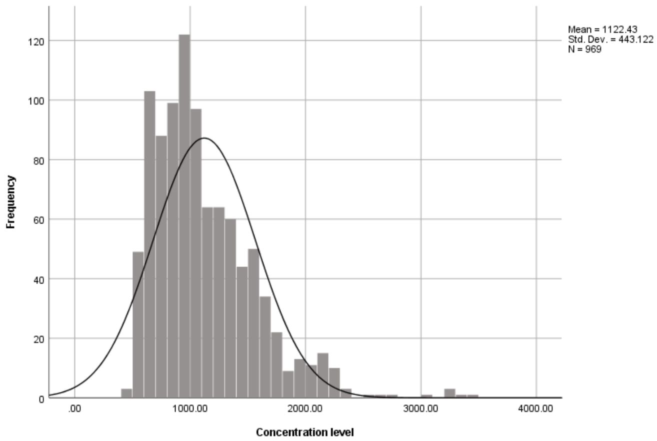


Fig 3. Histogram and distribution of CO_2 measurements in classrooms

Statistical analysis in this study are categorized into four main groups: 1) Descriptive, 2) Correlational, 3) predictive and 4) Group differences (cause and effect). Table 6 shows a summary of tests done in this study based on the type of dependent and independent variables.

Descriptive statistics: For continuous normally distributed data, mean and standard deviations are used [102] and for skewed data with influential outliers, median and interquartile range are more appropriate [102,103]. Therefore, in this study, alongside descriptive statistics (minimum, maximum, mean and standard deviation) [102], median and interquartile range are also used for describing CO_2 levels.

Correlational: Correlation indicates both the strength and direction of the relationship between a pair of variables [100,101]. Cohen has proposed classifications for the strength of correlations using *r* values; 0.10 to 0.30 is taken as a weak correlation, 0.30 to 0.50 as a moderate correlation and more than 0.50 as a strong correlation [104]. It is assumed that higher absolute values and smaller associated *P* values imply a stronger correlation [105]. Spearman's correlation is a non-parametric statistical measure for the strength of the relationship between paired data, used for ordinal/interval and skewed data [99–102]. Unlike Pearson's r, Spearman's rho can be used in a wide variety of contexts since they make fewer assumptions about variables [100,101].

Predictive (Regression): Regression is concerned with making predictions [100,101] and it predicts dependent variable (y) given the independent variable (x) [102]. Regression explains how variables are related to produces a line of best fit ($y=a+ bx+e$, $R^2=n$), where y is dependent and x is the independent variable [102]. The R^2 value shows the proportion of the variation in the dependent variable which is explained by the model [100–102], or is the measure of how much of the variability in the outcome is accounted for the predictors [106].

In this study, correlations and regressions are used to show how CO_2 levels are related to open area (m^2), G (cm^3/s) and OD (m^2/p, m^3/p), Table 6.

Group differences: These tests compare the medians of groups, such as Mann-Whitney test [99–103] or Kruskal-Wallis [99–101] to determine whether the groups are the same or not. In this study, Mann-Whitney and Kruskal-Wallis tests are used to show how mean and median CO_2 levels change in different categories, Table 6.

The data were analysed using the Statistical Package for Social Science (SPSS) [107].

Table 6. Summary of all tests in this study

Variables		**Corresponding Test**	**Variables in this Study**	
Independent (IV)	**Dependent (DV)**		**Dependent**	**Independent**
1 interval IV	ordinal or interval (Skewed Data)	Spearman correlation test [99–101]	CO_2 levels	Open area (m^2)
				G (cm^3/s)
				OD (m^2/p, m^3/p)
1 IV with 2 levels	ordinal or interval (Skewed Data)	Mann-Whitney test [99–103]	CO_2 levels	Two Seasons
				Occupied groups (teaching and break)
1 IV with 2 or more groups	ordinal or interval (Skewed Data)	Non-parametric Kruskal-Wallis test [99–102]	CO_2 levels	Categories for ABs (potential and practice)
				Categories of occupant-related factors

2.6. Overview of the Recorded Data:

Descriptive statistics of CO_2 levels during teaching and total occupied period (teaching + non-teaching) are presented for non-heating and heating seasons in Table 7. The study on a total of 969 CO_2 measurements in 29 classrooms shows that mean and median concentrations are 1155 and 1063 ppm during teaching period, and 1122 ppm and 1021 ppm during total occupied period, Table 7.

Table 7. Descriptive Statistics of CO_2 levels for teaching and total period

Mode	Period	N	Minimum	Maximum	Mean	Median	S.D.
Non-heating (NH)	Teaching	359	475	3360	1087	1002	440
	Total	526	475	3430	1050	953	444
Heating (H)	Teaching	358	555	2269	1224	1125	422
	Total	443	555	2659	1208	1084	427
Whole Year (WY)	Teaching	717	475	3360	1155	1063	436
	Total	969	475	3430	1122	1021	443

Fig 4 shows median CO_2 levels for teaching and total occupied period during both seasons. Median values for teaching and total occupied period are 1002 and 953 ppm during non-heating seasons and 1125 ppm and 1084 ppm during heating seasons.

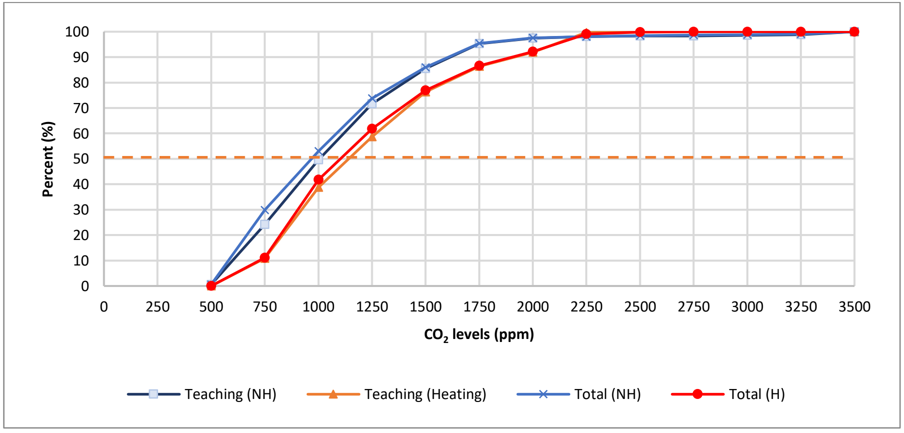
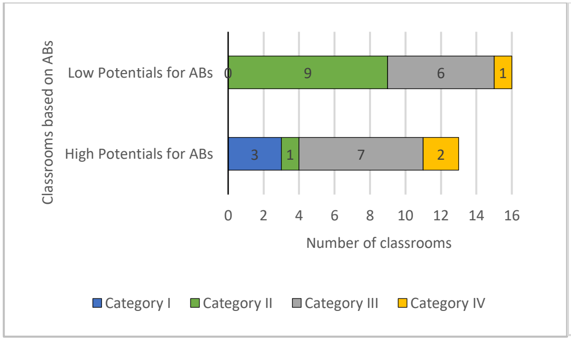


Fig 4. Cumulative frequency (%) of CO_2 measurements

Fig 5 shows the number of classrooms with high and low potentials for ABs in each category of IAQ. Fig 5 suggests that 23% of classrooms with high potentials for ABs and 56% classrooms with low potentials for ABs provide CO_2 levels lower than 1000 ppm. Figure 6 shows the number of renovated and existing classrooms in each category of IAQ. Fig 6 suggests that 46% renovated classrooms and 44% of existing classrooms provide CO_2 levels lower than 1000 ppm.



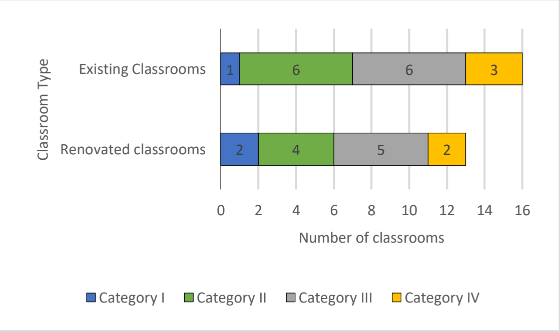


Fig 5. Number of classrooms with high and low potentials for ABs in each category of IAQ. Fig 6. Number of renovated and existing classrooms in each category of IAQ.

3. Results and Analysis:

3.1. CO_2 Concentration: This section provides an overview of CO_2 measurements and their comparison with those in other studies.

Distribution of CO_2 level: Frequency (%) of CO_2 measurements falling in four categories of EN 13779:2007 [97] is shown in Fig 7. During non-heating seasons, 29.1% of CO_2 measurements fall in category I ($CO_2<800$ ppm), 20.1% in category II ($800<CO_2<1000$ ppm), 27.5% in category III ($1000<CO_2<1400$ ppm) and 23.2% in category IV ($CO_2>1400$ ppm), Fig 7. During heating seasons, 13% of CO_2 measurements fall in category I, 27% in category II, 30.6% in category III and 29.4% in category IV, Fig 7. Category I has the highest frequency (29.1%) of CO_2 measurements during non-heating seasons and category III has the highest frequency (30.6%) during heating seasons.

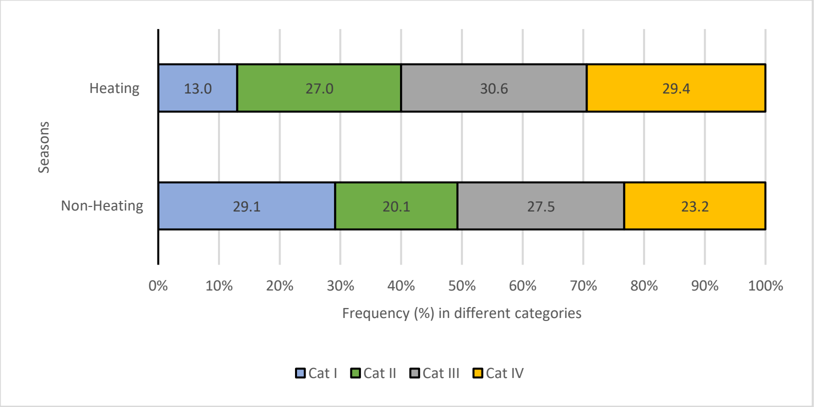


Fig 7. Frequency (%) of CO_2 measurements falling in four categories of IAQ

Overall, 45% of CO_2 measurements in this study are below 1000 ppm and 55% of all CO_2 measurements are above 1000 ppm. In a similar study, 53% of CO_2 measurements exceed concentration value of 1000 ppm due to classrooms' insufficient ventilation. Results of another study show that 17% of the measurements exceeded CO_2 level of 1,150 ppm, only 22.5% exceeded ASHRAE's upper limit of 1,000ppm, and 34% exceeded CO_2 level of 850 ppm [59], because windows and doors were usually kept open during most of occupancy hours [59].

Mean and Median CO_2 levels: In this study, mean CO_2 concentrations during teaching periods [1087(NH), 1224(H) and 1155 (T)] are above 1000 ppm which is recommended by ASHRAE standard 62 [98] and several other studies [3]. Average CO_2 level in this study is higher than average of 1070 ppm in [25] due to frequent window openings [25] and it is lower than average of 1957ppm in [26] due to not frequent window opening [26]. In this study, mean CO_2 concentration for total occupied period (T) is slightly lower than that for teaching period because total period includes non-teaching period with low occupancy density. This finding is supported in [30] with lower CO_2 levels during non-teaching period (1055 ppm) than teaching period (1482 ppm) [30]. In this study, daily mean concentrations exceed 1000 ppm in 55% of the classes, exceed 1500 ppm in 10% of the cases and exceed 2000 in 3% of cases. In a similar study [25], daily mean concentrations exceed 1000 ppm in 52% of NV classes, exceed 1500 ppm in 29% of cases and exceed 2000 ppm in 10% of classes [25]. In another study, median CO_2 level during school day exceeds 1000 ppm in only 28% of classrooms due to use of mechanical ventilation systems in [96].

3.2. CO_2 levels and Occupant-related Factors

Occupant-related factors that affect IAQ including occupants' adaptive behaviours, occupancy patterns, occupants' CO_2 generation rate and occupancy density are presented in Fig 8.

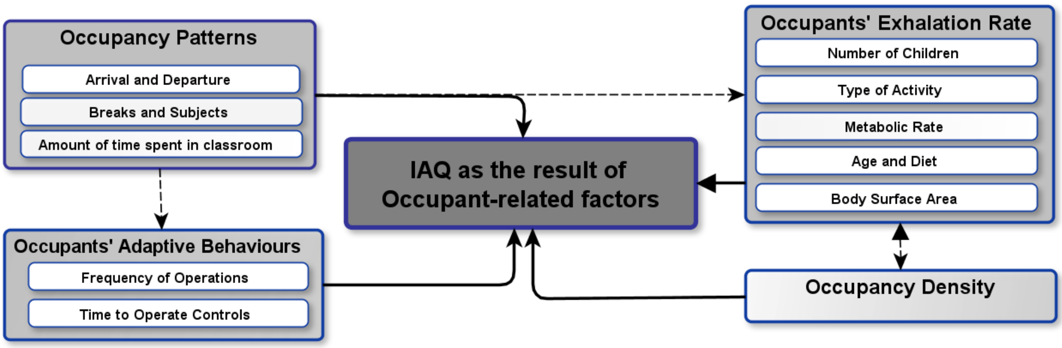


Fig 8. A summary of occupant-related factors affecting IAQ

3.2.1. Occupants' Adaptive Behaviours (ABs)

Due to the significant effect of adaptive behaviours on IAQ [26,59,108,109], this study focuses on window operation as the main environmental practice.

Window Operations; Potentials and Practices: In this study, 45% of classrooms provide high potentials for practising ABs, however, it is also important to consider school occupant's practice of environmental ABs. This study introduces two terms of 'good practice' and 'poor practice' for occupants' environmental ABs. Good practice suggests occupants' adequate operation of windows to erase accumulated CO_2 concentrations (average open area more than 50% in each classroom) and poor practice suggests occupants' inadequate window operation to provide IAQ (average open area less than 50% in each classroom).

The study has defined four groups of ABs based on potentials and practices; 1) High potentials and good practice, 2) High potentials and poor practice, 3) Low potentials and poor practice, 4) Low potentials and good practice. Results of the Kruskal-Wallis test show that there is a significant difference in median CO_2 levels [X^2 (3) =24.3, p=0.001] between these defined groups, Fig 9. To test categorical independent (such as groups of ABs) with interval dependent (such as CO_2 levels), analysis of covariance is used. Mean CO_2 levels in defined categories are 896, 1459, 1380 and 1007 ppm, respectively. Mean CO_2 level is lowest in group **1** (high potentials and good practice) and then in group **4** (low potentials and good practice), Fig 9. Classrooms with good practice (mean= 896 and 1007) compared to classrooms with poor practice (mean= 1459 and 1380) can provide lower CO_2 levels disrespectful of their potentials for ABs. Results show that to maintain mean and median CO_2 levels lower than 1000 ppm, classrooms with both high potentials and good practice are required, however, occupants' practice is more important than classrooms' potentials. This suggests that classrooms with high potentials do not necessarily lower CO_2 levels and good practice of ABs is also required.

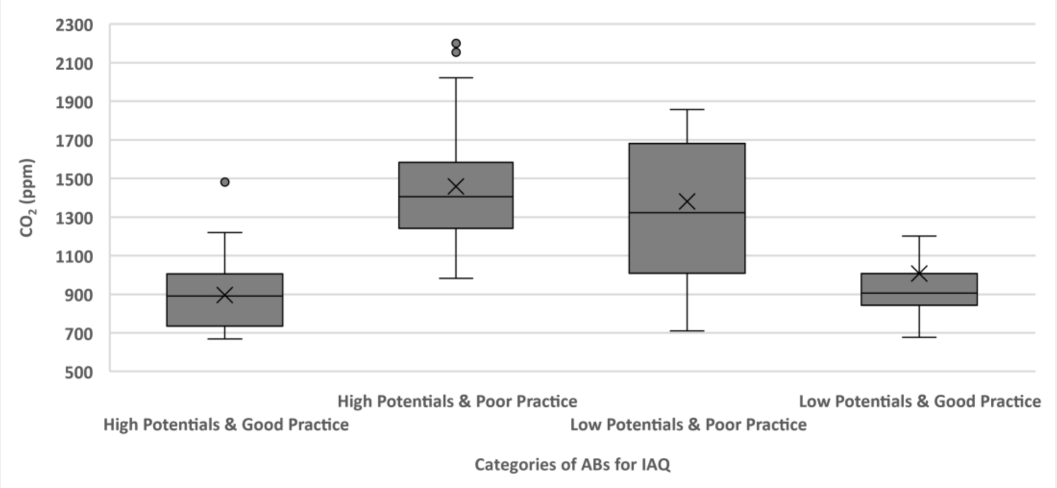


Fig 9. CO_2 levels based on classrooms' potentials for natural ventilation and practice of ABs

It is shown that ‘high performance’ buildings do not determine CO_2 levels [27]; IAQ is mostly affected by maintenance, operation practices, operating schedule and teacher behaviour [27]. Another study indicates that classrooms should be designed capable of supplying enough fresh air, however, occupants should avail themselves of this capability [26]. This study suggests that good practice of ABs at the right time can prevent CO_2 build-up and increase IAQ, as supported in [15,26,27,59,108,109]. A review of published studies spanning 1983–2013 suggests that behavioural changes have the potential to reduce indoor air pollution by 20%–98% in laboratory settings and 31%–94% in field settings [110].

Window Operation and Environmental Variables: In studied classrooms, teachers are mainly in charge of window operations, as supported in previous studies [40,111,112], and only 16% of operations are carried out by children. To discover how window openings are affected by environmental variables, CO_2 levels and operative temperatures (T_{op}) at which windows are opened and average CO_2 levels in corresponding classrooms are plotted in Fig 10. Results of this study show that CO_2 levels at which windows are opened and average CO_2 levels in corresponding classrooms are strongly correlated (Spearman Correlation coefficient=0.60, $P<0.001$). According to Cohen’s classification [104], high correlation coefficient and small *P* values suggest a strong correlation.
Results show that 52% and 16% of window openings occur when CO_2 levels are higher than 1000 and 1500 ppm, respectively. Around half (52%) of window openings in this study occur when CO_2 levels>1000 ppm which can be attributed to following reasons: 1. Window operation can be affected by inappropriate design of windows and controls, as supported in [20,52]. Furthermore, some openings are not designed based on children’s ergonomics [51,52]. In this study, 55% of classrooms provide low potentials for practice of ABs. 2. Window operation is more limited and less frequent among children than their teachers as they are mainly in charge of controlling classroom condition [40,52,56,111]. Authors highlight that only 16% of environmental ABs are done by children in this study due to the above reasons. 3. Window operation can also be affected by operative temperature. Teachers who are mainly in charge of the classrooms have higher comfort temperature than children [52,111,113]. According to an earlier study by authors [52], the upper limit of thermal comfort band for studied children is around 23 °C in this study, while for their teacher the upper limit is higher. Fig 10 shows that among cases that window opening occurs at CO_2 levels higher than 1000 ppm, 20% of them have T_{op}<23 °C. This suggests that despite high concentrations (CO_2>1000 ppm), windows were kept closed by teachers to avoid their thermal discomfort in 20% of the cases.

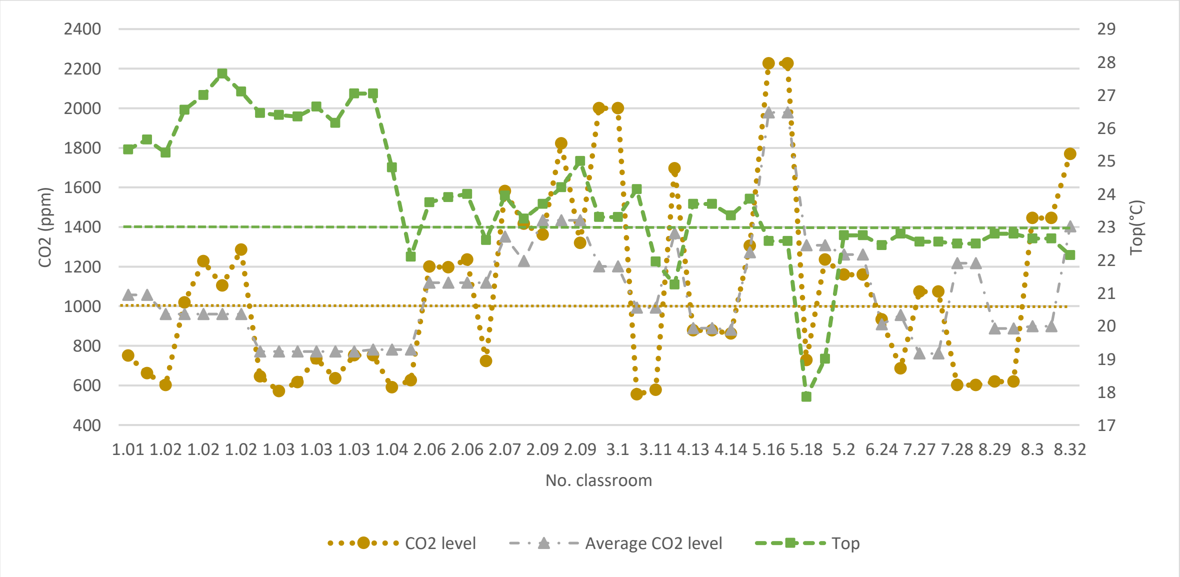


Fig 10. CO_2 levels and T_{op} at which windows are opened and average CO_2 levels in classrooms

Windows’ Open Area and IAQ: Occupants’ environmental adaptive behaviours by changing total open areas (open windows and external doors) affect IAQ. Results show that CO_2 levels and total open areas are significantly correlated during non-heating (Spearman Correlation coefficient=-0.32, P<0.001) and heating seasons (Spearman Correlation coefficient=-0.45, P<0.001). Results suggest negative moderate correlations between CO_2 levels and total open areas for non-heating (-0.32) and heating seasons (-0.45). To investigate how changes in CO_2 levels are explained by total open areas (m^2), open areas and CO_2 measurements at 10-min intervals are plotted in Fig 11. R^2 values in Fig 11 suggest that 13% and 31% of CO_2 variations are explained by open areas during non-heating and heating seasons, respectively. Combining data from heating and non-heating seasons suggest that 17% of CO_2 variations are explained by open areas.

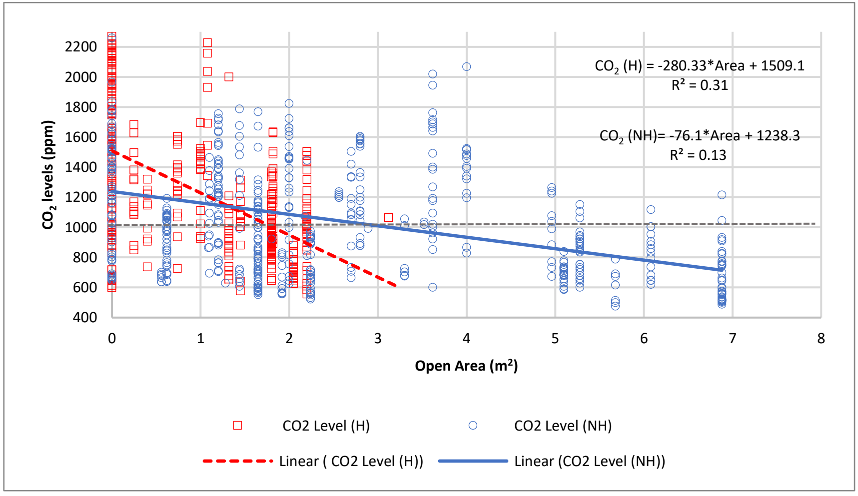
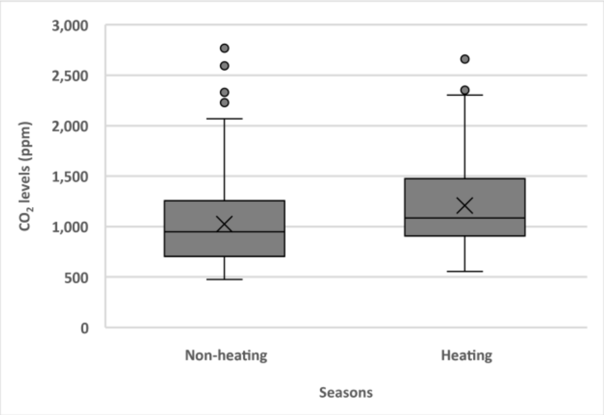


Fig 11. The relationship between 'window area' and 'CO_2 levels' in classrooms

Correlations and R^2 values between CO_2 levels and open areas are higher during heating seasons than non-heating seasons. It is mainly because open areas during non-heating seasons are more correlated to T_{op} (Correlation coefficient=0.53, P<0.001) than CO_2 levels (Correlation coefficient=-0.32, P<0.001). However, open area during heating seasons is more related to CO_2 levels (Correlation coefficient=-0.45, P<0.001) than T_{op} (Correlation coefficient=0.29, P<0.001). Previous studies suggest that windows and doors are operated more when temperature is high [114,115] rather than when IAQ is poor [116], mainly because poor IAQ is not perceived due to gradual sensory fatigue or adaptation [15,117].

Window operation and Seasonal Changes: There is evidence that seasonal variations affect CO_2 concentrations indirectly by changing occupants' ABs [118]. Figs 12 and 13 show changes in CO_2 levels and open areas during non-heating and heating seasons. Results of Mann-Whitney test in this study confirm that median CO_2 levels are significantly different during heating and non-heating seasons (U = 88399, p = 0.000). These Figures show that mean and median CO_2 levels are 137ppm and 123ppm higher during heating seasons than non-heating seasons due to lower average open areas during heating seasons (0.8m^2) than non-heating seasons (2.4m^2). Window operation is less frequent during heating seasons due to cold or draught [22,24,75,119] and energy consumption [116], which results in lower average open areas. It is shown that meeting IAQ requirements without comprising thermal comfort is difficult during heating season [119].



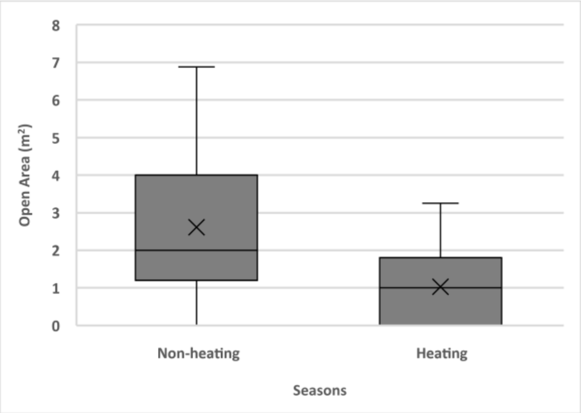


Fig 12. CO_2 levels during non-heating and heating seasons. Fig 13. Open areas (m^2) during non-heating and heating seasons.

Results of a similar study show that median CO_2 values during heating seasons ($1400<\text{Median}_{CO2}<3000$ ppm) are higher than those during non-heating seasons ($\text{Median}_{CO2}<1000$ ppm), which is due to higher open windows during non-heating seasons [5]. Average CO_2 concentrations are 1.2-3.5 times higher during heating seasons compared to non-heating seasons due to open windows during non-heating seasons [5]. Another study shows that average CO_2 concentration reaches to almost 2500 ppm in one of the schools due to limitations in window opening during the winter [38]. In another study, mean CO_2 concentrations remain below 1000 ppm in all schools during the summer [38].

Due to the effect of occupant behaviour on IAQ [109,110], motivating and training school occupants for appropriate adaptive behaviours help to improve IAQ [21]. Several studies have shown that CO_2 warning devices by reminding occupants of the time at which windows should be operated can decrease CO_2 levels [55,63,109,120,121].

3.2.2. Occupancy Patterns:

There is evidence that occupancy patterns affect CO_2 levels generated in indoor environment [23,25,28,41,75,86,108,122,123]. An overview of the results in this study shows that occupancy patterns and CO_2 levels in studied schools are dynamic and varied, as suggested in similar studies [118]. Fig 14 shows mean and median CO_2 values from all 29 classrooms against time of day. As can be seen in Fig 14, mean and median lines are similar which suggests data's symmetrical distribution. Similar studies support that small difference between mean and median shows symmetrical distribution [102].

The observation and trend suggest that teachers usually arrive before children at 8:00 and they possibly operate windows based on the classroom's temperature and IAQ. Children get into the classroom around 8:40-08:50 to start teaching session at around 9:00. Children often remain in the classroom for two hours before they leave for a short break (10:50-11:10 a.m). According to Fig 14, mean CO_2 concentration goes up to 1350 ppm until the first break and reduces to 1190 ppm during the first break (12% reduction). Breaks are not long enough to decrease CO_2 levels significantly, however, longer breaks for assembly or Physical Education (PE) can decrease CO_2 levels more noticeably. After the first break, children remain in the classroom until lunch break (12:10-13:10). Longer lunch breaks can lower mean CO_2 levels from 1250 ppm to around 800 ppm (36% reduction). After lunch break, mean and median CO_2 levels usually increase until the end of afternoon session (15:20). It is shown that periodical absence of students during recess times is one of the main reasons behind periodical drop and rise of CO_2 concentrations in classrooms [41]. This trend for rising and fall of CO_2 levels in studied schools is suggested in several other studies [96,108].

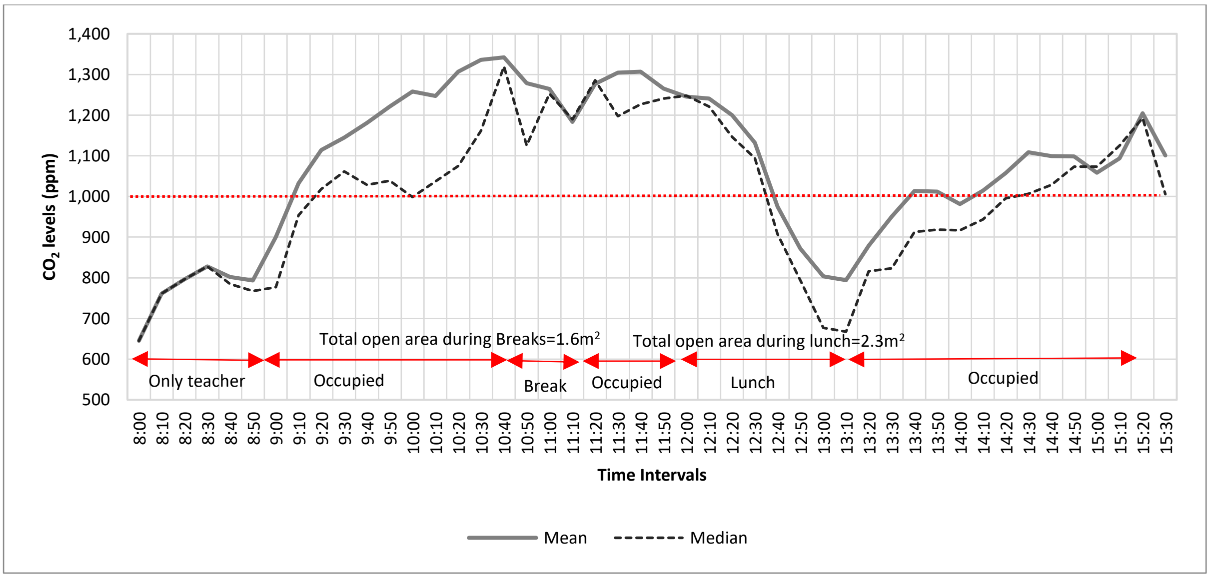
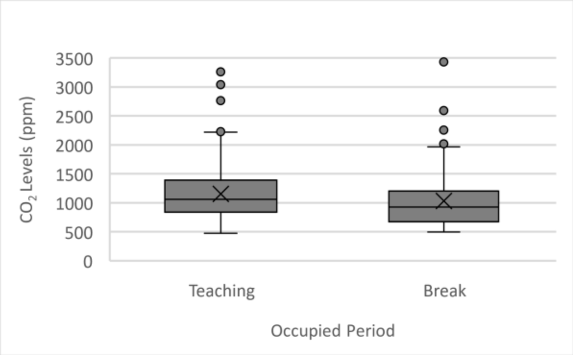


Fig 14. The trend for rising and fall of CO_2 levels during school occupancy based on 29 classrooms

Fig 14 shows that mean and median CO_2 levels are higher at the end of morning sessions (approximately 12:20 pm) compared to afternoon sessions (approximately 3:30 pm) due to longer morning sessions and accordingly more CO_2 built-up. Furthermore, longer lunch breaks (causing 36% reduction in CO_2 levels) compared to short breaks (causing 12% reduction in CO_2 levels) can clear accumulated CO_2 levels more significantly, as supported in [59]. Results of another study show the effect of scheduled breaks on maintaining CO_2 levels in different building types; 35% reduction for renovated schools, 25% reduction for new schools and 5% reduction for old schools [75]. The reduction of 160 ppm during the first break which is usually around 20 min shows a decrease of 8 ppm/min among studied classrooms. Similarly, reduction of 450 ppm during lunch break the which is usually around 50 min shows a decrease of 9 ppm/min. Speed of clearance 'ppm/min' is slightly higher during lunchtime than that during break which can be explained by larger open areas (2.3m^2 v.s. 1.6m^2) during lunchtime. Another study by taking into account all school breaks from different buildings expects a reduction of 19.4 ppm/min [75], which gives a reduction of 250 ppm for a 13-minute break [75]. Results of this study, as already supported in [75], suggest that although the effect of school breaks on decreasing pollutant concentration is significant, it is still insufficient to lower accumulated CO_2 levels within standards, Fig 14. That is where the effect of adaptive behaviours consistent with occupancy patterns becomes more important.

Figs 15 and 16 show changes in CO_2 levels and open area in box plots. Results of Mann-Whitney test in this study confirm that median CO_2 levels are significantly different during teaching and break period ($U = 71293$, $p = 0.000$). These figures show that higher CO_2 levels during teaching period (1156 ppm) compared to breaks (1032 ppm) which can be explained by higher mean open area during breaks (2.1 m^2) compared to teaching period (1.8 m^2). It is suggested that windows are closed during teaching period due to low exterior temperatures [75] or outdoor noise [109]. Therefore, this study recommends that by leaving windows open during breaks, accumulated CO_2 levels can be cleared without comprising children's overall comfort, as supported in [41,75,109]. It is shown that IAQ during breaks can be 1-4 times higher than that during teaching period [25].



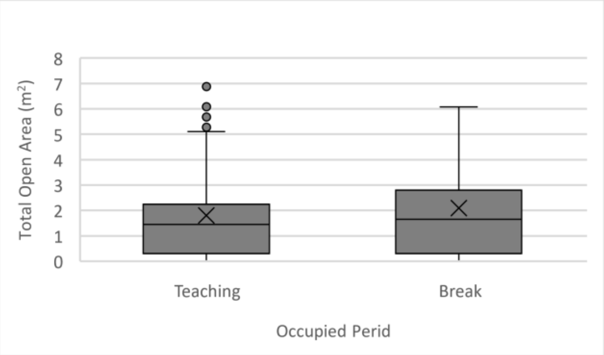


Fig 15. Changes in CO_2 levels during occupied period. Fig 16. Changes in open area during occupied period

3.2.3. Occupants' CO_2 Generation (G) rates:

Total CO_2 generation rate (G) from building occupants considers number of children, their age, metabolic rate, activity level, body surface area and room temperature [26]. In this study, children's generation rates are calculated at 10-min intervals due to varied occupancy patterns. Generation rates per child (3.34-5.89 cm^3/s) are multiplied by the number of children for calculating children's generation rates at 10-min intervals. Generation rate of teachers (11 cm^3/s) is added to this amount for total G. Fig 17 shows box plots of total G for sedentary and non-sedentary activities. Mean G for sedentary activities (Reading and writing) equals to 97 cm^3/s and for non-sedentary activities (Standing and walking) equals to 132cm^3/s, Fig 17. Similar studies support that students' activity intensity contribute to classrooms' CO_2 concentrations [86,122]. Effect of 'activity type' on CO_2 levels is more noticeable when two classrooms join for some activities or when children get back from play and bring a different heat load to classrooms [28].

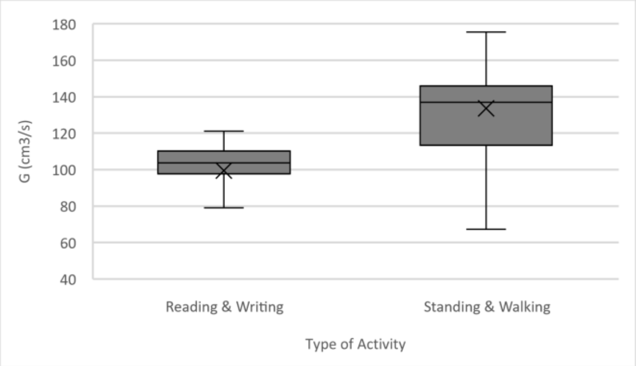


Fig 17. Total G for different activities.

Mean generation rates for sedentary activities in each classroom are plotted against mean CO_2 levels in Fig 18. Results show that mean CO_2 levels and total generation rates are correlated (Spearman Correlation coefficient=0.17, $P<0.001$). R^2 value suggests that 14% of CO_2 variations are explained by average G, Fig 18.

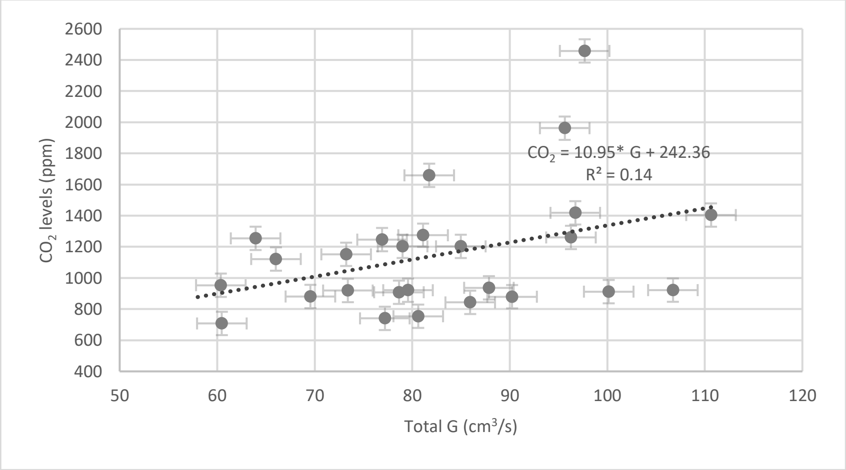


Fig 18. Mean G in each classroom plotted against mean CO_2 levels for both sedentary activities.

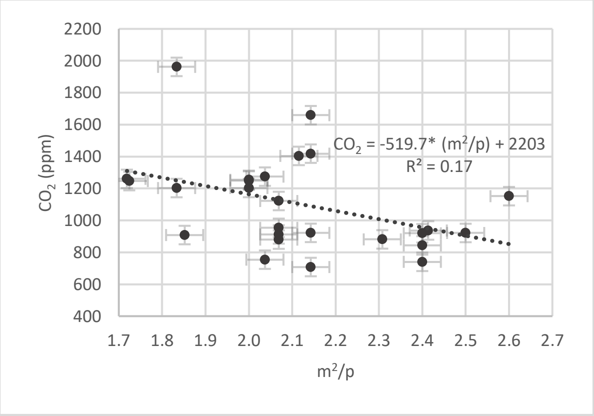
Considering average number of students in this study (25) and one standing teacher, total generation rate for sedentary activities is estimated at around 102 cm^3/s. According to Fig 18, corresponding average CO_2 level for G value of 102 cm^3/s is 1360 ppm. Considering that IAQ decreases when CO_2 production rate is greater than its removal rate [124], it is important to remove high emission rates from the building by the good practice of ABs.

3.2.4. Occupancy Density (OD):

Accumulation of CO_2 levels vary within area and volume of the classroom, therefore, occupancy density should be considered for evaluating IAQ. Occupancy density is defined as the area per number of occupants (m^2/p) [125] or volume per number of occupants (m^3/p). In this study, occupancy density in m^2/p ranges from 1.7-2.6 m^2/p, with a mean of 2.1 m^2/p. Another study suggests occupancy density of 1.8–2.4 m^2/p for school classrooms which is significantly higher than that in offices (10 m^2/person) [57]. Several studies suggest that occupancy density in schools is approximately four times higher than that in office buildings since school occupants are sitting very close [57,58,118]. Occupancy densities (m^2/p) in classrooms are plotted against corresponding mean CO_2 levels in Fig 19. Results show that CO_2 levels and OD (m^2/p) are correlated (Spearman Correlation coefficient=-0.14, $P<0.001$). R^2 value in Fig 19 shows that 17% of CO_2 variations are explained by occupancy density (m^2/p).

Occupancy densities (m^3/p) range from 4.3-9.1 m^3/p, with a mean of 6.3 m^3/p. Occupancy densities (m^3/p) in each classroom are plotted against mean CO_2 levels in Fig 20. Results show that CO_2 levels and occupancy density (m^3/p) are correlated (Spearman Correlation coefficient=-0.13, $P<0.001$). R^2 value in Fig 20 shows that 11% of the variations in average CO_2 levels are explained by occupancy density (m^3/p).

Figs 19 and 20 display that high occupancy densities cause high CO_2 concentrations, as suggested in several other studies [5,55,57,86,108,109,124,126]. Results of this study show that to maintain the average CO_2 level of 1000 ppm, occupant density should be at least 2.3 m^2/p and 7.6 m^3/p, Figs 19 and 20. The suggested OD in this study complies with occupancy density recommended by Eurostat (2011), which is from 2 to 3.1 m^2/person based on 20.8+2.0 students for the average size of primary classrooms in European and American countries [127].



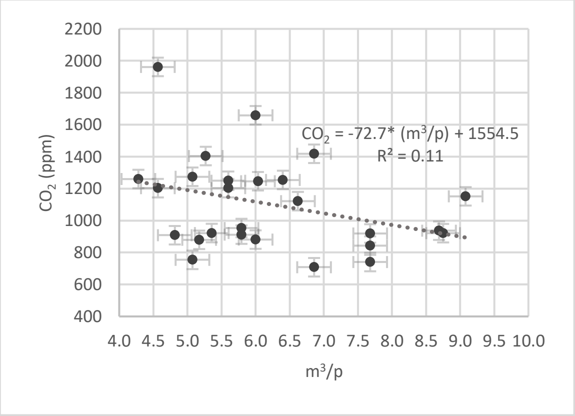


Fig 19. Occupancy Density in m^2/p plotted against mean CO_2 levels. Fig 20. Occupancy Density in m^3/p plotted against mean CO_2 levels.

In this study, there are averagely 27 occupants (25 students+ teacher+ teacher assistant) in each classroom. Results of this study in Figs 19 and 20 show that average occupancy densities to have CO_2 levels of 1000±50 ppm is 2.3±0.05m^2/p and 7.6±0.25 m^3/p. These values correspond to classroom area and volume of 62.1±1.35 m^2 and 205.2±6.75 m^3 with a height of 3.3 m. Building Bulletin 99 (Briefing Framework for Primary School Projects) also suggests that the 'standard' size of a primary classroom for 30 pupils is around 70 m^2 (2.3 m^2 per person) [128]. Considering the shortage of space in the educational sector [129–131], if providing the recommended area is not possible for the designer, classrooms' height can be increased to more than 3.3m to maintain the required volume for maintaining IAQ. The focus of guidelines for recommended OD (m^2/p) is mainly on providing the required area for children's physical activities. However, this study highlights the importance of all three dimensions in OD values (m^3/p) for maintaining IAQ. It is important to keep the number of children in proportion to the classroom's area and volume, also supported in [96], because overcrowded classrooms cause high CO_2 concentrations and high emissions of body odour [30,57,86,109,118,124]. It is shown that high-density classrooms, with too many children or too little space, lead to pupils' stress, reductions in desired privacy levels and loss of control [126].

4. Discussion: The study has investigated occupant-related factors that affect IAQ including occupants' adaptive behaviours, occupancy patterns, occupants' CO_2 generation rate and occupancy density. Table 8 shows correlations and R^2 Values between IAQ and occupant-related factors. Correlations and R^2 values in Table 8 suggest that among all occupant-related factors, occupant's adaptive behaviours have the strongest correlation (-0.40) with CO_2 levels and account for the highest CO_2 variation (17%). Therefore, when children's number and type of activity result in high concentrations, good practice of ABs can clear accumulated CO_2 levels in classrooms.

Table 8. Correlation and R^2 values between CO_2 levels and occupant-related factors

Occupant-related factors affecting IAQ	Correlation	P-value	Correlation by Cohen's Classification	R^2 Value	Interpretation
Occupants' adaptive behaviours: Open Area	-0.40	P<0.001	Negative Moderate	0.17	17% of CO_2 variations are explained by open area (m^2)
Occupants' generation rates (cm^3/s)	0.17	P<0.001	Positive weak	0.14	14% of CO_2 variations are explained by occupants' generation rates (cm^3/s)
Occupancy density (m^2/p)	0.14	P<0.001	Positive weak	0.17	17% of CO_2 variations are explained by occupancy density (m^2/p).
Occupancy density (m^3/p)	0.13	P<0.001	Positive weak	0.11	11% of CO_2 variations are explained by occupancy density (m^3/p).

4.1. Comparing Classrooms' IAQ with Standards:

To evaluate IAQ in each classroom, average CO_2 levels in each classroom are compared with values recommended by EN 13779:2007 [97] and ASHRAE [98]. The last column in Table 9 shows occupant-related factors that potentially lead to high CO_2 levels in classrooms with the following acronyms:

- ***AB for Adaptive Behaviours*** when the poor practice of ABs is a potential reason for high CO_2 levels.
- ***G for Generation Rate*** when G higher than 102 cm^3/s based on 25 sedentary students is a potential reason for high CO_2 levels.
- ***OD for Occupancy Density*** when OD lower than 2.3 m^2/p is a potential reason for high CO_2 levels.

As can be seen in Table 9, the reasons for high concentrations are related to one factor or a mix of occupant-related factors.

Table 9. Comparing mean CO_2 levels in classrooms with Standards

Type	**No.**	**Potentials for ABs**	**Occupant-related factors**					**CO_2**	**EN 13779** [97]	**ASHRAE** [98]	**Factor**
			Open Area	**Practice of ABs**	**Total G**	**m^2/p**	**M^3/p**		**CO_2 level**	**CO_2 level**	
Renovated	1.1	H	5.8	H	164	2.1	6.6	1058	×	×	G, OD
	1.2	H	4.9	H	101	2.4	7.7	961	✓	✓	-
	1.3	H	5.3	H	101	2.4	7.7	772	✓	✓	-
	1.4	H	2.2	L	107	2.1	6.9	781	✓	✓	AB, G, OD
	2.6	H	1.1	L	115	2.2	7.0	1119	×	×	AB, G, OD
	2.7	H	1.2	L	77	3.5	11.2	1352	×	×	AB
	2.8	H	1.2	L	79	4.4	14.0	1228	×	×	AB
	2.9	H	2.5	L	114	2.1	6.9	1434	×	×	AB, G, OD
Existing	3.10	L	0.9	L	89	3.1	10.9	1202	✓	×	AB
	3.11	L	2.0	H	112	2.6	9.0	993	✓	✓	G
	3.12	L	0.6	L	62	4.2	13.5	1369	✓	×	AB
	4.13	L	1.6	H	90	2.5	6.4	890	✓	✓	-
	4.14	L	1.8	H	77	3.7	9.6	881	✓	✓	-
	4.15	L	0.0	L	103	2.2	7.7	1273	✓	×	AB, G, OD
	5.16	H	0.1	L	119	2.1	5.1	1979	×	×	AB, G, OD
	5.18	H	1.3	L	95	2.6	6.4	1308	✓	×	AB,
	5.20	H	1.0	L	105	2.5	6.2	1261	✓	×	AB, G
Renovated	6.21	L	1.3	H	84	2.3	6.4	964	✓	✓	-
	6.22	L	0.0	L	109	2.2	6.2	1740	×	×	AB, G, OD
	6.23	L	0.0	L	110	2.2	6.2	1249	×	×	AB, G, OD
	6.24	L	1.1	H	125	2.2	6.1	909	✓	✓	G, OD
	6.25	L	0.0	L	113	2.0	5.6	980	✓	✓	AB, G
Existing	7.26	L	0.3	L	113	2.5	9.0	956	✓	✓	AB, G, OD
	7.27	H	3.9	H	106	2.0	5.1	761	✓	✓	G
	7.28	H	3.0	L	108	1.9	4.6	1218	✓	×	AB, G
	8.29	L	1.7	H	107	2.3	5.6	887	✓	✓	G, OD
	8.30	L	1.6	H	111	2.1	5.4	899	✓	✓	G
	8.31	L	0.0	L	100	2.3	5.7	2487	×	×	AB, OD
	8.32	L	1.7	H	111	2.1	5.3	1404	×	×	G

Fig 21 shows changes in CO_2 levels by the change in occupant-related factors. Results of the Kruskal-Wallis test show that there is a difference in median CO_2 levels $[X^2(2) = 6.6, p = 0.038]$ when the number of favourable occupant-related factors are different, Fig 21. According to Fig 21, when all occupant-related factors can potentially reduce CO_2 levels, mean concentration is 893 ppm with the maximum of 964 ppm, when one or two occupant-related factors can potentially reduce CO_2 levels, mean concentration is 1122 ppm with the maximum of 1404 ppm and when none of the occupant-related factors can potentially reduce CO_2 levels, mean concentration is 1317 ppm with the maximum of 1979 ppm. This suggests that when all occupant-related factors are favourable, CO_2 levels below 1000 ppm can be maintained. However, when occupant-related factors are not favourable, it is less likely to maintain adequate CO_2 levels.

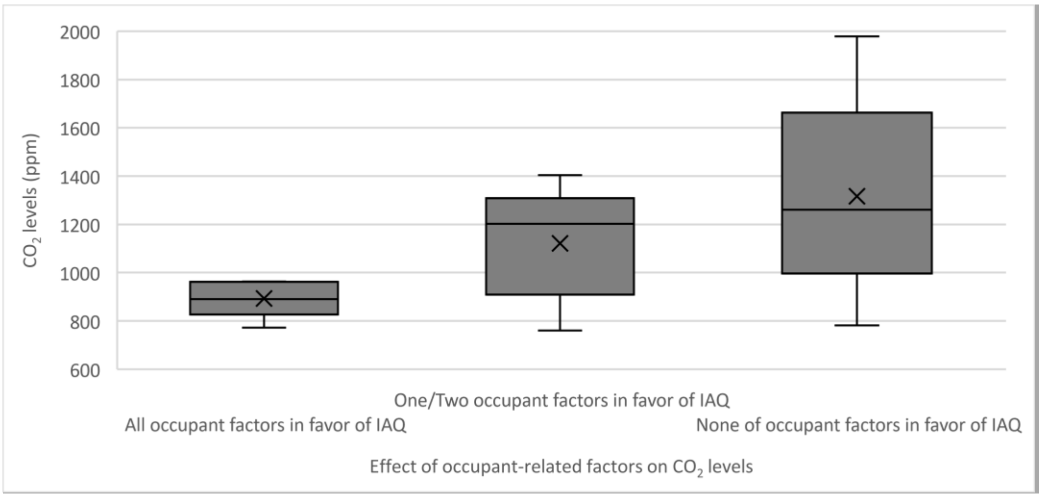


Fig 21. CO_2 level according to the numbers of favourable occupant-related factors

There is evidence that renovated schools provide more suitable conditions compared to non-renovated schools [21,38]. In this study, 54% of renovated classrooms have $CO_{2\ (mean)}$>1000 ppm, among which 73% with the poor practice of ABs. Furthermore, 73% of classrooms with high potentials for ABs have $CO_{2\ (mean)}$>1000 ppm, among which 69% with the poor practice of ABs. This suggests that to maintain IAQ in existing and renovated school buildings, more focus should be directed at school occupants, their occupancy patterns and adaptive behaviours.

5. Conclusion:

This paper was focused on occupants' role for maintaining IAQ in naturally-ventilated primary schools during heating and non-heating seasons. The study highlights that IAQ is closely related to occupants' adaptive behaviour, occupancy patterns, CO_2 generation rates and occupant density, however, the impact of occupants' adaptive behaviours is more significant. Although classrooms' potentials for facilitating adaptive behaviours is fundamental in maintaining IAQ, this study suggests that occupants' interaction with the building (i.e. Good Practice of ABs) is more significant. Therefore, there is a need to encourage and train school occupants (i.e. teachers and children) for Good Practice of Adaptive Behaviours. Furthermore, teachers will have more effective ABs if they are trained about the impact of occupancy patterns and generation rates on CO_2 built-up. For example, when windows are left open during breaks or lunchtime, accumulated CO_2 levels are cleared without comprising children's thermal comfort. Therefore, good practice of ABs is not only limited to occupants' interaction with controls but also related to the correct time for interaction to maintain other elements of comfort (i.e. thermal comfort). Available guidelines mainly focus on OD (m^2/p) in two dimensions to provide the required area for children's physical activities in classrooms; however, this study underlines the importance of height as the third dimension in OD values (m^3/p) to maintain IAQ. This study suggests minimum occupancy densities of 2.3 m^2/p and 7.6 m^3/p for maintaining CO_2 level<1000 ppm in primary school classrooms.

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