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CO_2 Concentration and Occupants' Symptoms in Naturally Ventilated Schools in Mediterranean Climate

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Abstract: A large part of the school building stock in Andalusia lacks ventilation facilities, so that the air renewal of the classrooms is achieved through the building envelope (air infiltration) or the opening of windows. This research analyses the airtightness of the classrooms in Andalusia and the evolution of CO_2 concentration during school hours through in situ monitoring. Pressurization and depressurization tests were performed in 42 classrooms and CO_2 concentration was measured in two different periods, winter and midseason, to study the impact of the different levels of aperture of windows. About 917 students (11–17 years of age) were surveyed on symptoms and effects on their health. The mean n_{50} values are about 7 h^{-1}, whereas the average CO_2 concentration values are about 1878 ppm, with 42% of the case studies displaying concentrations above 2000 ppm with windows closed.

Keywords: air infiltration; school buildings; CO_2 concentration; ventilation; health symptoms

1. Introduction

When the environmental performance of building envelopes is analysed, ventilation is identified as one of the main variables affecting energy demand, the degree of environmental comfort (ISO 7730: 2005; UNE-CR 1752: 2008) [1,2], the accumulation rate of CO_2, suspended particles and pollutants (EN 15251: 2007) [3], and respiratory health in prolonged periods of exposure [4].

In non-residential buildings, European ventilation standards (EN 13779: 2008) [5] establish the need to guarantee a minimum outdoor airflow to ensure adequate Indoor Air Quality (IAQ) control, making it necessary to resort to mechanical ventilation with stages of infiltration. In Spain, it was only in 2007 that the regulations established that the ventilation of the school buildings had to be mechanical in order to ensure an adequate IAQ (Indoor Air Quality) [6]. Consequently, approximately 8000 schools in the school building stock of the Mediterranean area do not meet this requirement [7]. Adapting these buildings would entail major investment, maintenance and energy consumption. For this reason, several public bodies in Spain are promoting natural ventilation as a system for the control of IAQ, contrary to what is established in these regulations.

In Spain, where education is obligatory until the age of 16, students spend an average of six hours a day in these buildings, not counting the hours of extracurricular activities, from Monday to Friday during approximately nine months a year (winter and mid-seasons).

For this reason, the control of the IAQ and energy consumption associated with different ventilation strategies has been studied in various climatic zones. Studies on IAQ control have been carried out in cold [8–11], mild [12] and warm climates [13]. Given the similarities in the climate it is worth noting research in Portugal which examines the relationship between indoor air quality and outdoor pollutants in classrooms with mechanical ventilation systems [14]. In many cases, there is evidence of poor indoor air quality in schools, with negative effects on the health of their occupants, potentially leading to allergic diseases or asthma [15]. In terms of the energy consumption associated with ventilation systems [16–19], a study analysing different ventilation systems and their associated energy consumption in Italy is a notable example in the Mediterranean area.

The main objective of this study is to characterize the indoor environment of the classrooms and the airtightness of the envelope to establish whether the parameters obtained are adequate for learning.

2. Materials and Methods

To develop this study, the following phases were established:

- Sample
- On-site measurement
- Survey design
- Airtightness

2.1. Sample

One to three school buildings were chosen in the most representative climatic areas in Andalusia (zones A4, B4, C3 and C4), following the Spanish energy performance zoning and the studies by De La Flor et al. [20–22]. These areas are classed as Hot-summer Mediterranean climate (Köppen CSa) and Cold Semi-arid climate (Köppen BSk) and include cold to temperate areas in winter (types C, B, or A), as well as warm or average summers (4 or 3). 3 to 10 classrooms were chosen in each of the schools, depending on availability. A total of 42 classrooms from 8 school buildings were sampled (Table 1).

Table 1. Sample by climate zone.

Climate Zone		Location	School	No. of Classrooms	No. of Occupants
Spanish Building Code	Köppen Climate Scale [23]				
A4	BSk	Almería	S 1	4	96
	Csa	Huelva	S 2	2	54
B4	Csa	Sevilla	S 3	8	167
	Csa	Sevilla	S 4	9	158
C3	Csa	Granada	S 5	2	49
	Csa	Granada	S 6	12	287
	Csa	Granada	S 7	3	60
C4	Csa	Jaén	S 8	2	46
TOTAL				42	

All classrooms in Andalusia are standardized and follow the design standards established for non-university educational institutions (ISE 2003) [24]. Classrooms are approximately 50 m^2 and 3 metres high, with a maximum capacity of 30 students. The windows tend to be found to the left and the distribution of the furniture and entrance doors is as shown in Figure 1. None of the measured classrooms have suspended ceilings or perforations in the inner partitions with adjacent classrooms. The external vertical wall is usually composed of a half-brick wall (with or without rendering), air chamber, thermal insulation (projected polyurethane) and a simple hollow brick wall with plaster setting. The internal partitions in particular are composed of a half-brick wall with plaster on either side.

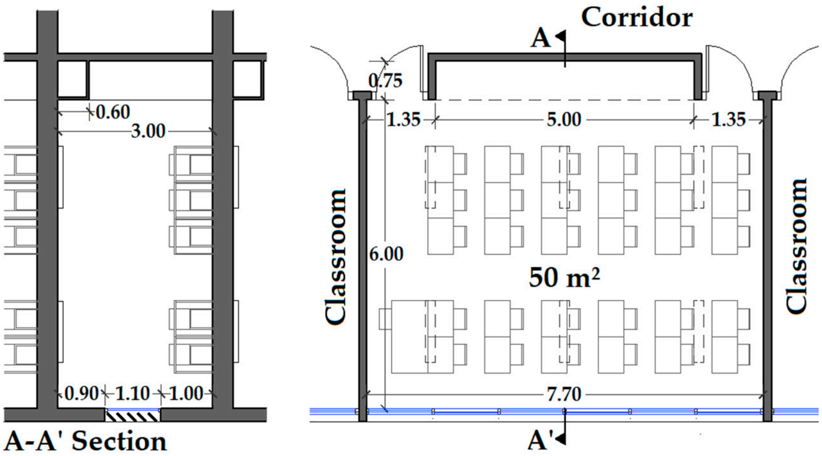

Figure 1. Classroom prototype following design standards for regional educational institutions.

In existing school buildings, a measurement campaign was carried out and a data collection protocol applied to the classrooms selected [25], covering the following aspects:

- Name and type of school building to which the classroom belongs.
- Location, orientation and climatic zone.
- Characteristics of the classroom and the furniture distribution.
- Location and operation of existing HVAC (Heating, Ventilation and Air Conditioning) systems.
- Window dimensions, composition and opening.

2.2. On-site Measurements

Measurement of indoor air quality (temperature, relative humidity and CO_2 concentration) was developed during the normal operation of teaching activities for a period of 45 min per measurement. A dot matrix was established for measurements and a Testo 435-2 data logger with temperature, relative humidity and CO_2 sensors was used. The sensors have an accuracy of 0.3 °C for temperature; 2% for relative humidity; and ± 50 ppm for CO_2 concentration. The measuring points respond to a matrix of 3 × 2 locations at 2 different heights (0.60 and 1.70 m) (Figure 2) [25,26].

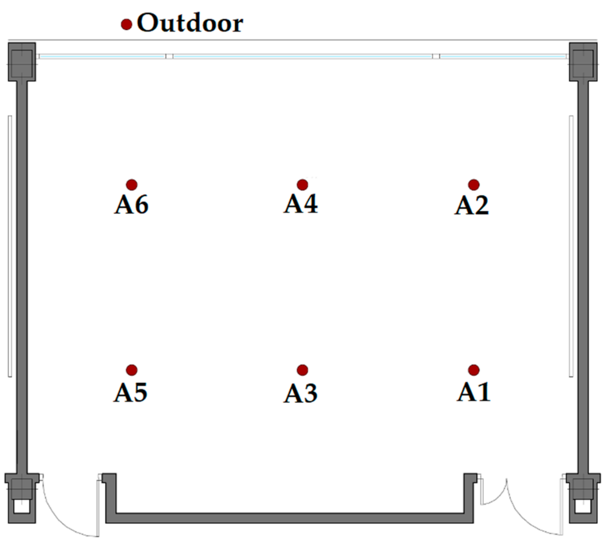

Figure 2. Measuring matrix in the classrooms.

For the analysis of the results, a distinction was made between case studies measured under operational conditions with open windows and those with closed windows.

The measurements were subject to a series of limitations imposed by the sample, including classroom typology climate zones defined in southern Spain and net floor areas < 105 m^2 and window areas < 17 m^2 [27].

2.3. Survey Design

The purpose of the survey was to use a systematic approach to gather information from students and to discretize the findings in order to examine various symptoms and health effects in students. This process took approximately 20 min per classroom. Surveys were collected throughout an entire year in the last 20 min of one subject.

The survey content included questions that covered occupant and building information:

- The respondent's age and sex.
- The occupant's position in the classroom.
- Various symptoms and health effects (Figure 3). The scale for the analysis varies from a score of 0 when they report never suffering from a certain symptom to 1 when reporting it daily.

Symptomatology	Never (score= 0)	Rarely (score=0.2)	Occasionally (score=0.4)	Often (score= 0.6)	Quite often (score=0.8)	Daily (score= 1)
Dizziness	☐	☐	☐	☐	☐	☐
Dry skin	☐	☐	☐	☐	☐	☐
Itchiness	☐	☐	☐	☐	☐	☐
Nausea	☐	☐	☐	☐	☐	☐
Nasal congestion	☐	☐	☐	☐	☐	☐
Eye irritation	☐	☐	☐	☐	☐	☐
Headache	☐	☐	☐	☐	☐	☐
Chest oppression	☐	☐	☐	☐	☐	☐
Tiredness	☐	☐	☐	☐	☐	☐

Figure 3. Extract from student survey.

2.4. Airtightness

The airtight tests were carried out following the protocol established by UNE EN 13829:2002 and using the Minneapolis Blower Door Model4/230 V System. Since the classroom has two access doors, the specific protocols developed below were followed to establish the actual airtightness of the classroom through its envelope (Figure 4):

- Protocol 1 (P1): Blower door was installed in door A. Door B was not sealed (free air passes through its gaps). $V_{50,P1}$ was obtained
- Protocol 2 (P2): Blower door was installed in door B. Door A was not sealed (free air passes through its gaps). $V_{50,P2}$ was obtained
- Protocol 3 (P3): Blower door was installed in door B. Door A was sealed. $V_{50,P3}$ was obtained

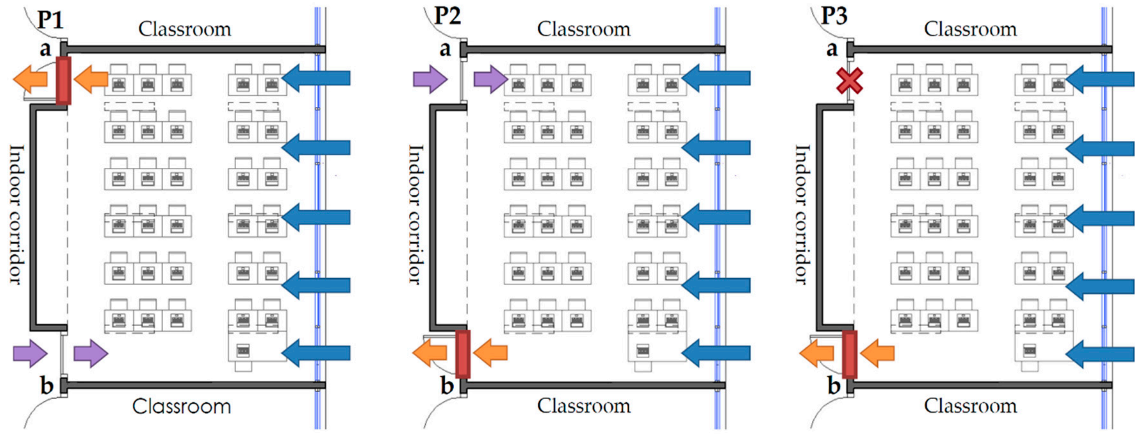

Figure 4. Protocols of Blower Door test.

Equations (1) to (5), deduced from the BS 5925 standard using a simplification of the "crack flow equation" [28], provide the infiltration values measured in each of these three ± 50 Pa sample hypotheses established for each classroom.

$$n_{50,P1} = \frac{V_{50,DoorA} + V_{50,env}}{V} \quad (1)$$

$$n_{50,P2} = \frac{V_{50,DoorB} + V_{50,env}}{V} \quad (2)$$

$$n_{50,P3} = \frac{V_{50,env}}{V} \quad (3)$$

$$n_{50,t} = \frac{V_{50,DoorA} + V_{50,DoorB} + V_{50,env}}{V} \quad (4)$$

$$n_{50,t} = n_{50,P1} + n_{50,P2} - n_{50,P3} \quad (5)$$

where:

- $V_{50,DoorA}$ is the air leakage rate at 50 Pa which circulates through door A, in m^3/h;
- $V_{50,DoorB}$ is the air leakage rate at 50 Pa which circulates through door B, in m^3/h;
- $V_{50,env}$ is the air leakage rate at 50 Pa which circulates through the envelope, in m^3/h;
- V is the internal volume of the room, in m^3;
- $n_{50,P1}$ is the infiltration rate at 50 Pa in protocol 1, in h^{-1};
- $n_{50,P2}$ is the infiltration rate at 50 Pa in protocol 2, in h^{-1};
- $n_{50,P3}$ is the infiltration rate at 50 Pa in protocol 3, in h^{-1};
- $n_{50,t}$ is the infiltration rate at 50 Pa through the envelope and doors of the room, in h^{-1}.

3. Results

3.1. Indoor Air Quality

During the measurement period, 28 case studies had the windows closed (67%); 23 of these were measured in the winter season. Of these 28 case studies, 65% had the heating system working. The measured interior temperature oscillated between 17.8 °C and 22.7 °C in the winter season, the lowest temperature was obtained for a case study with no heating system in the warmer climate zone. Relative humidity ranged from 40.6% to 64.3% (Table 2).

Table 2. Average values of indoor environment parameters with closed windows during the measurement period (45 min per case). Where: "Heating" is the heating system operation (On = 1; Off = 0); "Occupants" is the number of occupants (No.); "$\overline{T_o}$" is the mean outdoor temperature (°C); "$\overline{T_a}$" is the mean indoor air temperature (°C); "$\overline{RH}$" is the relative humidity (°C); "$\overline{CO_2\ conc}$" is the mean indoor CO_2 concentration (ppm).

Case Study	Climate Zone	Season	Start Time	Heating (On = 1; Off = 0)	Occupants (No.)	$\overline{T_o}$ (°C)	$\overline{T_a}$ (°C)	$\overline{RH}$ (%)	$\overline{CO_2\ conc}$ (ppm)
1	A4	Midseasons	12:15	0	23	15.4	21.5	40.6	992
2	A4	Midseasons	10:45	0	25	8.4	19.1	41.4	1995
3	A4	Midseasons	13:15	0	25	15.4	17.8	48.1	852
4	B4	Winter	8:45	1	30	4.3	19.2	52.7	1875
5	B4	Winter	10:45	1	21	10.6	21.6	52.3	2265
6	B4	Winter	12:15	1	22	14.9	22.2	55.8	1876
7	B4	Winter	9:45	1	21	10.6	19.3	47.3	1194
8	B4	Winter	13:15	0	19	14.9	21.0	44.5	1124
9	B4	Winter	10:45	1	20	10.6	19.8	49.6	1505
10	B4	Winter	13:15	1	14	14.9	21.0	46.2	1253
11	B4	Winter	13:15	1	25	14.9	21.1	52.3	1540
12	B4	Midseasons	9:45	0	19	16.7	20.5	59.1	591
13	B4	Winter	9:45	1	25	6.4	21.4	54.3	2044
14	B4	Winter	8:45	1	20	6.4	19.7	58.3	2055
15	B4	Winter	12:15	0	10	10.4	20.4	64.3	3337
16	C3	Winter	10:45	1	24	4.3	20.1	51.5	1650
17	C3	Winter	13:15	0	25	14.9	20.1	58.2	2087
18	C3	Midseasons	13:15	0	29	22.1	24.2	37.3	1290
19	C3	Winter	10:45	1	18	8.9	22.7	41.0	1541
20	C3	Winter	8:45	1	30	6.3	19.5	59.1	2064
21	C3	Winter	12:15	0	18	13.8	19.6	49.5	1442
22	C3	Winter	9:45	1	26	4.3	21.5	55.3	1963
23	C3	Winter	13:15	0	28	14.9	22.6	50.0	2043
24	C3	Winter	12:15	1	27	15.0	21.9	47.5	2457
25	C3	Winter	12:15	1	18	15.0	21.2	45.9	2877
26	C3	Winter	12:15	1	15	15.0	21.9	47.4	2433
27	C4	Winter	9:45	1	23	4.3	22.7	44.4	2832
28	C4	Winter	12:15	1	23	16.7	21.3	55.8	3392

14 of the 42 case studies (33%) had the windows open. Of these, eight cases had windows open in winter, which indicates that the heating systems were not well regulated and the heat had to be dissipated in cases where the interior temperature was higher, or that the students perceived the stale air of the environment prompting a need to ventilate the room, despite the resulting energy loss. The interior temperature ranged from 18.4 °C to 25.6 °C and the relative humidity from 31.2% to 60% (Table 3).

Concentrations of CO_2 fluctuated widely over time in all cases, oscillating between a minimum of 625 ppm and a maximum of 3357 ppm (Figure 5).

Table 3. Average values of indoor environment parameters with open windows during the measurement period (45 min per case). Where: "Heating" is the heating system operation (On = 1; Off = 0); "Occupants" is the number of occupants (No.); "$\overline{T_o}$" is the mean outdoor temperature (°C); "$\overline{T_a}$" is the mean indoor air temperature (°C); "$\overline{RH}$" is the relative humidity (°C); "$\overline{CO_2\ conc}$" is the mean indoor CO_2 concentration (ppm).

Case Study	Climate Zone	Season	Start Time	Heating (On = 1; Off = 0)	Occupants (No.)	$\overline{T_o}$ (°C)	$\overline{T_a}$ (°C)	$\overline{RH}$ (%)	$\overline{CO_2\ conc}$ (ppm)
29	A4	Midseasons	10:25	0	23	8.4	20.9	33.4	1337
30	B4	Winter	12:35	0	24	13.1	22.5	48.7	1499
31	B4	Winter	9:45	1	25	10.6	18.4	56.6	1123
32	B4	Midseasons	12:25	0	20	19.0	21.4	60.0	625
33	B4	Midseasons	13:05	0	15	21.4	25.6	46.9	999
34	B4	Midseasons	12:15	0	22	21.4	24.9	48.9	1037
35	B4	Winter	13:05	1	10	10.4	18.8	49.2	894
36	B4	Winter	13:20	1	17	10.4	20.1	54.6	1768
37	C3	Midseasons	13:20	0	16	24.5	24.8	31.2	921
38	C3	Midseasons	12:15	0	29	24.5	24.1	40.6	1266
39	C3	Midseasons	12:35	0	17	22.3	23.8	35.3	1108
40	C3	Winter	9:20	1	31	8.9	20.5	54.3	1355
41	C3	Winter	12:20	0	31	13.8	22.5	48.0	1720
42	C3	Winter	13:30	0	14	13.8	22.8	43.8	1374

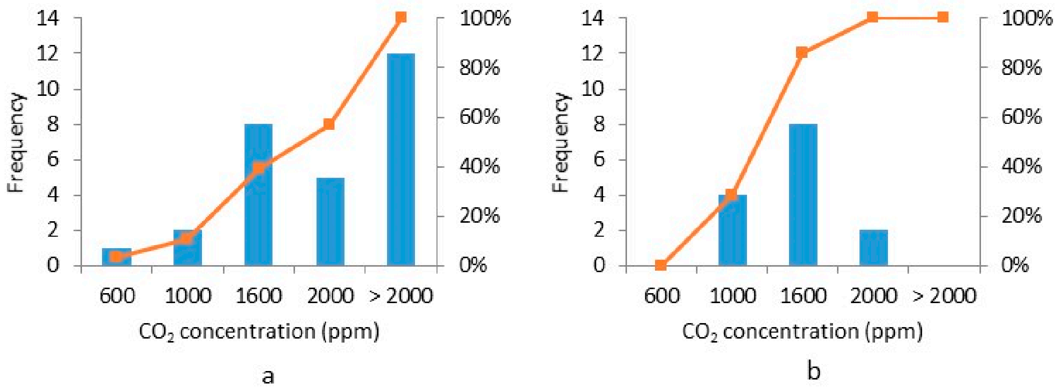

Figure 5. Accumulated frequency and percentage of measured CO_2 concentration in classrooms with closed windows (**a**) and open windows (**b**).

The CO_2 concentration measured usually exceeds WHO recommendations (which set a limit value of 1000 ppm for healthy environments) [29] pointing to low refurbishment rates and the potential risk of air-quality associated problems. This aspect is highly important when windows are closed, with 89.3% above the threshold. Average values below 1600 ppm were only recorded in 39% of classrooms, with 43 % of classrooms displaying concentrations above 2000 ppm.

When the windows were open, CO_2 concentration fell below 1000 ppm in 28% of case studies. As expected, values above 2000 ppm were not recorded when the windows were open, although values between 1600 and 2000 ppm were recorded in two case studies.

3.2. Health symptoms

The symptoms that most students report according to the surveys are dizziness, dry skin, headache and tiredness, both with windows closed (Table 4) and with windows open (Table 5). These conditions have been expressed in almost all case studies in climatic zones C3 and C4, in some in B4. They are also reported in some case studies in A4, albeit with lower values.

Table 4. Average values of health symptoms in case studies with closed windows. Legend: Case study (CS), Climate zone (CZ), Dizziness (D), Dry Skin (DS), Itchiness (I), Nausea (N), Nasal congestion (NC), Eye Irritation (EI), Headache (H), Chest oppression (CO), Tiredness (T).

CS	CZ	Ds	DS	I	N	NC	EI	H	CO	T
1	A4	0.10	0.12	0.01	0.05	0.15	0.07	0.10	0.07	0.08
2	A4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	A4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	B4	0.18	0.23	0.10	0.08	0.06	0.07	0.14	0.10	0.22
5	B4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	B4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	B4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	B4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	B4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	B4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	B4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	B4	0.09	0.01	0.00	0.00	0.01	0.00	0.04	0.01	0.06
13	B4	0.41	0.20	0.18	0.08	0.10	0.18	0.35	0.21	0.37
14	B4	0.41	0.24	0.14	0.15	0.16	0.13	0.29	0.28	0.28
15	B4	0.36	0.22	0.18	0.18	0.11	0.16	0.22	0.22	0.31
16	C3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	C3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	C3	0.44	0.31	0.16	0.16	0.16	0.18	0.34	0.22	0.36
19	C3	0.38	0.36	0.24	0.19	0.24	0.12	0.31	0.13	0.41
20	C3	0.48	0.30	0.16	0.23	0.20	0.20	0.37	0.33	0.42
21	C3	0.55	0.32	0.15	0.20	0.19	0.13	0.33	0.15	0.42
22	C3	0.38	0.26	0.13	0.07	0.12	0.10	0.27	0.14	0.34
23	C3	0.40	0.32	0.19	0.07	0.16	0.13	0.27	0.16	0.35
24	C3	0.34	0.28	0.24	0.11	0.16	0.13	0.28	0.22	0.42
25	C3	0.41	0.20	0.05	0.14	0.12	0.11	0.28	0.18	0.32
26	C3	0.51	0.31	0.13	0.19	0.09	0.20	0.24	0.14	0.36
27	C4	0.28	0.38	0.25	0.26	0.28	0.07	0.15	0.17	0.47
28	C4	0.23	0.27	0.24	0.15	0.23	0.13	0.15	0.24	0.31

Table 5. Average values of health symptoms in case studies with open windows. Legend: Case study (CS), Climate zone (CZ), Dizziness (D), Dry Skin (DS), Itchiness (I), Nausea (N), Nasal congestion (NC), Eye Irritation (EI), Headache (H), Chest oppression (CO), Tiredness (T).

CS	CZ	D	DS	I	N	NC	EI	H	CO	T
29	A4	0.13	0.11	0.03	0.08	0.14	0.03	0.12	0.05	0.08
30	B4	0.23	0.18	0.10	0.07	0.07	0.11	0.19	0.08	0.25
31	B4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
32	B4	0.08	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.07
33	B4	0.37	0.44	0.24	0.16	0.19	0.21	0.43	0.24	0.24
34	B4	0.43	0.25	0.15	0.08	0.13	0.10	0.28	0.16	0.37
35	B4	0.33	0.27	0.07	0.07	0.09	0.09	0.20	0.20	0.29
36	B4	0.25	0.26	0.14	0.10	0.08	0.13	0.31	0.18	0.29
37	C3	0.43	0.43	0.16	0.32	0.17	0.19	0.35	0.36	0.45
38	C3	0.31	0.41	0.21	0.19	0.21	0.11	0.26	0.21	0.37
39	C3	0.40	0.36	0.14	0.09	0.18	0.13	0.33	0.25	0.33
40	C3	0.39	0.31	0.11	0.25	0.15	0.16	0.41	0.24	0.33
41	C3	0.43	0.32	0.29	0.21	0.24	0.22	0.31	0.17	0.29
42	C3	0.34	0.26	0.12	0.05	0.31	0.06	0.20	0.17	0.28

The symptom which has been reported least frequently in the classroom is eye irritation. 42% of the case studies with the closed windows do not report any symptoms, while only 14% report no symptoms of any sort in the case studies with open windows.

3.3. Airtightness

The values of n_{50} range from 2.6 h^{-1} (minimum) to 10 h^{-1} (maximum), both recorded in the B4 climate zone with the highest number of samples. The average value of n_{50} is 6.97 h^{-1}, with a standard deviation of 2.06 h^{-1}; and models with the lowest n_{50} values are those in the C3 climate zone, where the lowest average temperature values are recorded in the winter. The highest values are in zone B4, where great attention has been paid to the construction of the envelopes, despite the fact that these areas with no coast and lower wind speeds are not necessarily warmer (Figure 6 and Table 6).

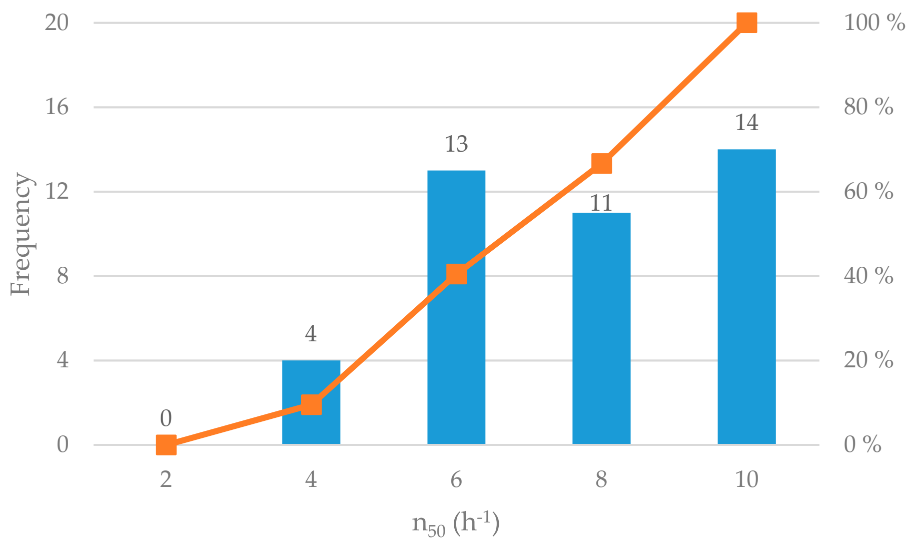

Figure 6. n_{50} measured frequency.

Table 6. Average values and standard deviation of n_{50}.

Climatic Zone	Mean n_{50} (h^{-1})	Standard Deviation
A4	6.53	0.94
C3	6.12	1.67
B4	7.89	2.45
C4	7.6	0.56
Mean	6.97	2.06

4. Discussion

The measurements were subject to a series of limitations imposed by the sample: classroom typology, climate zones defined in southern Spain, and occupants aged between 11 and 17.

The coefficients of linear correlation between n_{50} and the different environmental parameters, exterior and interior temperatures, interior wind speed and CO_2 concentration, are quite low, especially in cases where the windows are open and used as a control group. The correlation with CO_2 concentration is almost negligible, indicating that other factors such as time previously spent in the classroom, the time of measurement, or if the window or door has been opened prior to the measurement, are more important in the airtightness of the enclosure (Table 7).

Table 7. Correlations between environmental parameters and n_{50}.

	n_{50} (Closed Windows)	n_{50} (Open Windows)
Temperature $_{Outdoor}$	−0.27	0.12
Temperature $_{Indoor}$	−0.13	0.18
Wind velocity $_{Indoor}$	−0.28	0.08
CO_2 concentration $_{Indoor}$	0.12	−0.19

In all cases, the correlation coefficients between the CO_2 concentration and the different symptoms shown by the students during the measurement period are positive, although R^2 values are very low, ranging from 0.12 to 0.30 for the case with windows closed and almost zero values with the windows open.

When the windows were closed, the symptoms of itchiness and nasal congestion were reported in over 30% of the cases in correlation with the CO_2 concentration, with correlation coefficients of 0.554 and 0.441, respectively. Other factors with a high correlation coefficient are chest oppression and nausea (Figure 7).

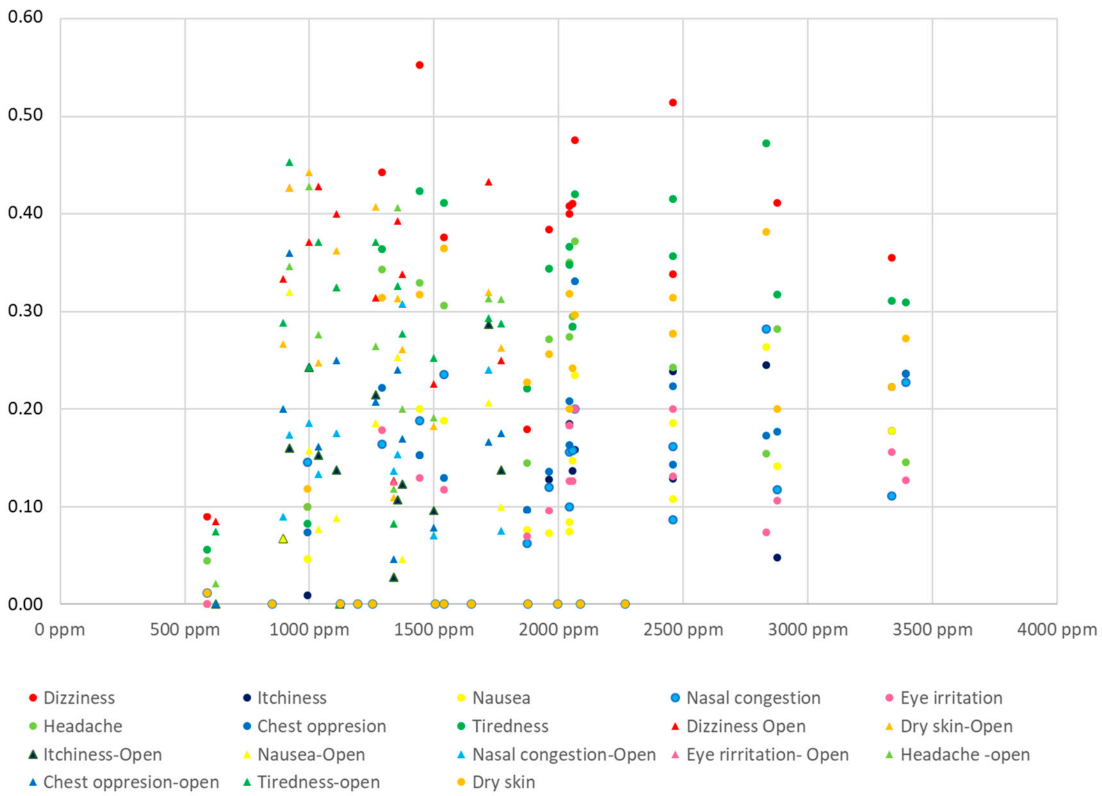

Figure 7. Scatter plot showing CO_2 concentration and student symptomatology.

In the case studies where the windows are open, the symptom showing the highest correlation is itchiness with a value of 0.369, although this only accounts for 14% of the cases (Table 8).

In Figure 7, the different case studies have been represented in a scatter plot. The symptomatology shown by the students in the case studies with open windows (triangles) displays higher values than those found in the case studies with closed windows and higher concentrations of CO_2. In the case of closed windows, a higher frequency of symptomatology is observed by students in higher indoor CO_2 concentrations. When the windows are open almost all the subjects of the sample report dry skin and headaches, whereas with the windows closed, dizziness accounts for the highest values.

Table 8. Correlations between CO_2 concentration and student symptomatology.

Symptomatology	CO_2 Concentration (Closed Windows)	CO_2 Concentration- (Open Windows)
Dizziness	0.401 (R^2 = 0.16)	0.130 (R^2 = 0.02)
Dry skin	0.469 (R^2 = 0.22)	0.142 (R^2 = 0.02)
Itchiness	0.554 (R^2 = 0.31)	0.369 (R^2 = 0.14)
Nausea	0.523 (R^2 = 0.27)	0.171 (R^2 = 0.03)
Nasal congestion	0.441 (R^2 = 0.30)	0.319 (R^2 = 0.10)
Eye irritation	0.462 (R^2 = 0.21)	0.303 (R^2 = 0.09)
Headache	0.346 (R^2 = 0.12)	0.263 (R^2 = 0.07)
Chest oppression	0.551 (R^2 = 0.20)	−0.002 (R^2 = 0.10)
Tiredness	0.500 (R^2 = 0.25)	0.133 (R^2 = 0.01)

5. Conclusions

In the wide study sample of classrooms with no mechanical ventilation system in middle schools in the Mediterranean area, no direct relationship has been identified between the airtightness of the envelope and the internal concentration of CO_2. This indicates that there is a significant influence from other factors affecting the quality of the indoor environment, including class schedules and the opening and closing of windows and doors. In addition, the measured CO_2 concentration exceeded the WHO recommendations (a 1000 ppm threshold is set for healthy environments) even when the windows were open, with CO_2 concentration falling below 1000 ppm in only 28% of case studies with open windows and in 17% of the total case studies. This consequence is especially interesting, as the role of the envelope as a predictor of indoor air-quality behaviour is reduced and the need for mechanical ventilation is emphasized, something which must be taken into account in the generation of models of this type of building.

As expected, CO_2 levels were higher in closed classrooms than in those ventilated by opening windows. However, cases were identified in which—in response to the air quality perceived—users were willing to sacrifice thermal comfort in winter in exchange for better ventilation. In some classrooms windows were opened to control the interior atmosphere causing interior temperatures to fall below 20 °C with the heating system in operation. In addition to the effect that this has on indoor air-quality conditions in the classroom, the impact on energy consumption is an important factor to be taken into consideration.

One of the main findings of this work is that, as noted, there was a higher level of symptomatology, or level of discomfort perceived by the occupants, when the windows were open. In 42% of the case studies with closed windows no symptomatology of any sort is reported, despite the presence of objective indicators of poorer quality of the internal atmosphere. In contrast, with open windows, only 14% of the case studies do not report symptoms in their responses. This indicates the presence of degradation factors of environmental quality, such as external contamination and the presence of biological or chemical aerosols, which are not being measured or incorporated into the analysis. Other factors include changes in personal perception associated with the room in free evolution, compared to rooms with controlled conditions, or rooms at least decoupled from the external environment. This opens a future pathway of discussion over the dilemma for better ventilation strategies and the problem of the urban actual degradation. Despite the usual assumptions, in this large study sample there is a greater symptomatology experienced with open windows, while 72% of the measured values of CO_2 concentration levels were above 1000 ppm in these classrooms.

As a counterpoint, certain symptoms, such as itchiness and nasal congestion can be identified in periods when the windows are closed, since they appear when the CO_2 level rises. In the case studies with windows closed, the average CO_2 concentration was 1878 ppm, with the symptom onset level appearing at around 1400 ppm.

The findings of this study further highlight the need for adequate controlled ventilation systems, as the relatively low CO_2 levels when operating under natural ventilation conditions (but in general above 1000 ppm) do not reflect the real air-quality problems and cannot ensure an adequate thermal environment is maintained.

It also seems appropriate to complement the role of CO_2 as a standalone reference indicator of indoor air quality in schools. Findings show the need for further studies that include other complementary indicators associated with the operating regime and pollutants found in the air to assure a correct interpretation of data. It can be established that, although the values of CO_2 concentration are lower when the windows are open, this is not guaranteeing a complete acceptance by the occupants, given that there is an additional set of conditions related to other environmental parameters of the exterior that cannot be identified exclusively with this single CO_2 control parameter.

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