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# Indoor Air Quality in Naturally Ventilated Classrooms. Lessons Learned from a Case Study in a COVID-19 Scenario

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**Abstract:** This paper describes the implementation of a series of ventilation strategies in a nursery and primary school from September 2020, when the government decided to resume the students' face-to-face activity in the middle of a COVID scenario. Air quality and hygrothermal comfort conditions were analysed before the pandemic and compared for different ventilation configurations in a post-COVID scenario. Ventilation strategies included the protocols issued by the Public Administration, while others were developed based on the typological configuration and use of the school. Results revealed that it is advisable to implement certain strategies that reduce the risk of infection among the occupants of the spaces, without a significant decrease in hygrothermal comfort. Given the importance of maintaining better IAQ in the future within classrooms, and regarding the pre-COVID situation, these strategies may be extended beyond this pandemic period, through a simple protocol and necessary didactic package to be assumed by both teachers and students of the centre.

**Keywords:** indoor air quality; COVID-19; educational buildings; natural ventilation

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## 1. Introduction

The face-to-face return to classrooms in Spain in September 2020 during the global pandemic and after a long period of confinement opened up a debate in society about health security and air quality. The discussion was reinforced when the scientific community began to show evidence of greater transmission by aerosols than by fomites [1]. Poor indoor air quality (IAQ) was already an existing problem in naturally ventilated schools, but awareness was only raised after the COVID crisis. During the past school year, recommendations and protocols have been developed by different institutions and organisations to improve the ventilation performance of classrooms.

The objective of this study is the evaluation of the main protocols presented to improve natural ventilation systems (NVS) in schools, as well as the assessment of their possible adaptations to a post-COVID scenario, through the analysis of a case study.

Before the beginning of this global pandemic (February 2020), measurements were carried out in a nursery and primary school, which yielded worrying results: throughout a winter week of monitoring, the $CO_2$ concentration in classrooms exceeded 1000 ppm during 88.75% of the teaching time, reaching maximum values of 3628.8 ppm. These poor results are in line with those obtained in various previous studies (Table 1).

Inside classrooms, pupils and teachers are commonly the only sources of $CO_2$. Therefore, $CO_2$ is considered a good IAQ indicator, which shows the relationship between ventilation rate and occupancy.

**Table 1.** Comparison $CO_2$ values in different studies.

| Reference | City Country | Year | Studied Classrooms | Ventilation System | Main Results |
|---|---|---|---|---|---|
| University of Burgos & PSBP [2] | Spain | 2020 | 36 | Natural Ventilation | More than 1000 ppm during 67.6% of the teaching time |
| Jørn Toftum et al. [3] | Denmark | 2015 | 820 | Natural & Mechanical | More than 1000 ppm during 66% of the teaching time |
| Almeida et al. [4] | Viseu (Portugal) | 2017 | 76 | Natural Ventilation | More than 2000 ppm during 25% of the teaching time. Maximum above 3000 ppm |
| Turanjanin [5] | Serbia | 2014 | 5 | Natural Ventilation | More than 1000 ppm during 50.0% of the teaching time. Maximum above 3600 ppm |
| Settimo et al. [6] | Rome (Italy) | 2020 | 24 | Not Specified | Daily values from 653 to 1352 ppm. Maximum average value of 2386 ± 480 ppm |
| Vassura et al. [7] | Bologna (Italy) | 2015 | 2 | Not Specified | Maximum average value of 3000 ± 1000 ppm |

In addition, $CO_2$ has been associated with the presence of other pollutants [4,8]. The presence of pollutants like bioaerosols, Particle Matter (PM), or Total Volatile Organic Compounds (TVOCs) [9] is harmful to a pupil's health and productivity [10–12]. $CO_2$ must be taken into account as a pollutant, too, because, although not injurious at the levels that have been recorded in schools, it can cause adverse effects on the academic performance of the occupants [13].

TVOCs have diverse sources, mainly from the interior. These can come from cleaning products, construction materials or furniture, and, in the case of educational environments, from school materials such as glue, paint, etc. [14].

The approach to improve IAQ in schools is to increase ventilation rates. The first regulatory requirement in Spain for ventilation in schools dates from 1981 [15], which was endorsed in the "Regulation of thermal installations in buildings" (RITE) (1998) [16], and by its subsequent revision in 2007, currently in force with modifications [17].

Since in Castilla y León, 51% of public schools were built before 1980, and the vast majority of these centres lack ventilation systems, which involves addressing natural ventilation performance. This percentage is very similar to the Spanish average [18].

The requirements inside the classrooms are comparable between the different countries, according to Table 2.

**Table 2.** $CO_2$ concentration requirements inside the classrooms in different countries.

| Region and Policy | $CO_2$ Concentration [ppm] |
|---|---|
| Europe [EN 16798-1:2020] [1] | 950 [2] |
| Finland [Decree Indoor Climate and Ventilation 1009 (2017)] | 1200 [2] |
| Germany [DIN 1946-4 (2005)] | 1500 |
| Portugal [RECS (2013)] | 1250 |
| Spain [RITE (2007)] | 900 [2] |
| United Kingdom [Building Bulletin 101 (2018)] | 1500 [3] |
| USA [ASHRAE 62.1 (2019)] | 1100 [2] |

[1] Value for Category I (educational buildings—new buildings and renovations). [2] Outdoor air concentration was assumed as 400 ppm. [3] Value obtained for up to 20 min.

The uncertainty regarding the real performance of ventilation systems in educational centres has promoted different studies on the improvement of natural ventilation.

Almeida et al. (2015) compared the IAQ between two refurbished and two non-refurbished classrooms for two months in Spring. All of them had a central heating system with hot-water radiators as terminal units. A mechanical ventilation system (MVS) provided with $CO_2$ and temperature sensors (indoors and outdoors as a reference value) was implemented in the refurbished classrooms. The results obtained revealed that the natural ventilation system was not able to provide adequate IAQ for the whole school day. The $CO_2$ concentration levels were over 1500 ppm for 20% of the time. On the other hand, while using an MVS a good IAQ was maintained [19].

Also in a mild-climate location, Fernández-Agüera et al. (2019) [20] found that a large part of the schools lacked ventilation systems. Therefore, the air renewal of the classrooms was achieved by means of uncontrolled airflow through the building envelope (air infiltration) or the manual opening of windows. The data showed that, when the windows remained closed, the $CO_2$ concentration reached values over 1000 ppm during 89.3% of the time.

Vasella et al. (2021) [21] studied the impact of an NVS protocol implemented in a hundred schools in Switzerland for four days during the cold season with outdoor temperatures below 15 °C (please note that these are similar climate conditions to the ones of the present study). The protocol consisted of the brief opening of doors and windows between different classes and for a longer period at the lunch break when the students had to leave the classroom for its ventilation. The measures implemented included an application to calculate the duration of the brief apertures, and teaching materials to promote the importance of IAQ and ventilation. The protocol implemented reached $CO_2$ concentration levels under 1400 ppm during 70% of the school time, whereas those levels were only achieved during 30% of the time before its implementation, and the mean temperature was between 19.9 °C and 20.5 °C.

Similar research in the Netherlands carried out in 2008 [22] demonstrated that when protocols have been implemented to raise awareness of the problem among students and teachers, it is possible to achieve a necessary longer-lasting effect. Therefore, before the intervention, the $CO_2$ concentration exceeded 1000 ppm for 64% of the school day, whereas after the intervention, ventilation was significantly improved even though the $CO_2$ concentration still exceeded 1000 ppm for more than 40% of the school day.

Thus, there is enough existing evidence to indicate that it is necessary to control IAQ in schools. However, it is also necessary to evaluate what success it could achieve, and how it could affect the thermal comfort in schools in Castilla y León.

In a scenario in which health had to be prioritised, certain ventilation protocols that compromised thermal comfort were reappraised. To determine the scenarios subject to study, the main mandatory protocols and guidelines published to date were taken into account:

- On 19 June 2020, the government of Castilla y León issued "Prevention and organisation protocol for the return to school activity in the educational centres of Castilla y León for the school year 2020/2021" [23];
- In June 2020, the Harvard T.H. Chan School of Public Health published the guide "Healthy Schools: Risk reduction strategies for reopening schools" [24], and in August 2020 "5-step guide to checking ventilation rates in classrooms" [25];
- In October 2020, CSIC-IDAEA released the "Guide to classroom ventilation," which has some common ground with the one just mentioned. In December 2020 this guide was upgraded with results obtained from real cases [14];
- In February 2021, the report of CSIC-LIFTEC "Continuous Ventilation vs. Flashing Ventilation" was published [26].

## 2. Methodology

### *2.1. Site and Building*

The case of study is a primary public school in Valladolid (Castilla y León, Spain). The building is placed in a plot mostly occupied by the playground, and it is next to other public buildings to the north and south sides, a park to the east and a four-lane avenue with medium-high traffic volume to the west (Figure 1). Valladolid has a Continental Mediterranean climate with cold winters and minimum temperatures below zero

(Csb-Temperate, dry and temperate summer). As a consequence, maintaining the indoor temperature efficiently becomes an important factor.


**Figure 1.** Aerial view of the school from Google Earth Pro (2021).

The building, which was built in 1980, has a construction system that was widespread in the construction of public educational buildings built in the same decade: a reinforced concrete structure and vertical envelope composed of brick masonry, a non-ventilated air chamber (insulated only on some occasions) and single-hollow brick as the inner layer. It has a ground floor and two additional floors, with a central corridor and classrooms on each side (oriented to north and south). Each classroom (Figure 2) has a rectangular floor area of 60 $m^2$ and is 2.85 m in height. The classrooms have two doors to the corridor, with a panel of adjustable methacrylate slats over them, and four tilt-and-turn PVC windows with integrated shutters to the exterior (the original exterior windows were recently replaced).

**Figure 2.** 360° view from a tested classroom.

The building is naturally ventilated, and the heating system has a central boiler and aluminium radiators, with uninsulated pipes through the classrooms.

The usual class schedule is Monday through Friday from 9:00 a.m. to 2:00 p.m., with an intermediate break time of 30 min.

### 2.2. Test Design

Different parameters that define IAQ in classrooms were compared in different ventilation scenarios. In the first phase (pre-COVID-19), IAQ parameters before the pandemic under no ventilation protocol were collected. Next, scenarios A and B, which emerged from the protocol prescribed by the public administration in Castilla y León [21], were assessed. Finally, alternative scenarios (C, D and D′) were defined according to the guidelines proposed by the Harvard T.H. Chan School of Public Health and CSIC [22–24]. At the same time, hygrothermal comfort conditions for the different ventilation configurations were analysed, considering their viability in a post-COVID time.

For each test, measurements were carried out simultaneously in two facing representative classrooms (Figure 3), with the aim of evaluating the impact of cross-ventilation. In this regard, cross-ventilation was determined from the data monitored in the corridor from the simultaneous opening of doors and windows in facing classrooms. This resulted in a significant increase in the ventilation flow by the pressure gradient between the windward and leeward façades.

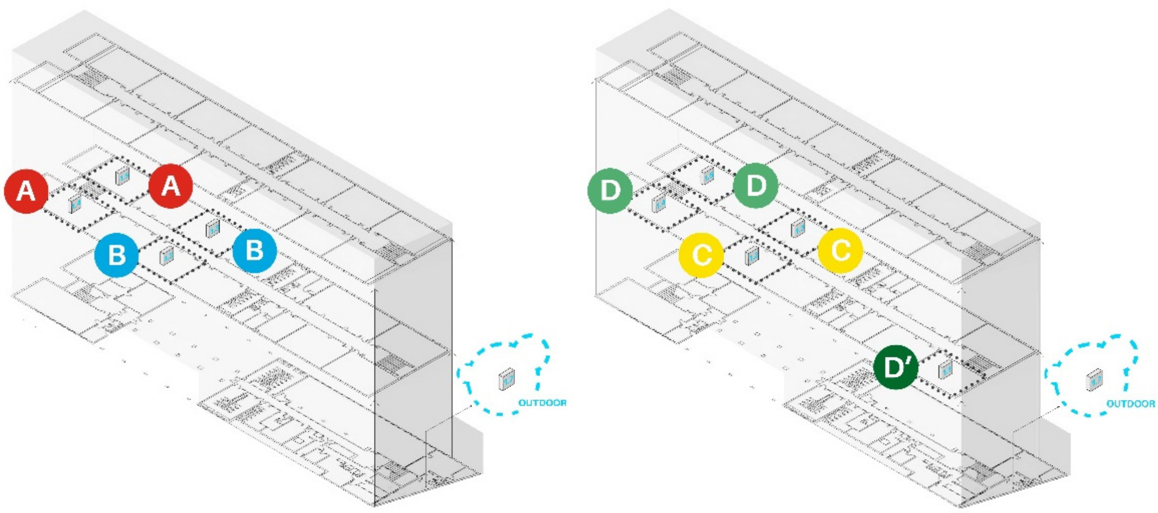


**Figure 3.** Scenario locations and classrooms within the building.

All tests were carried out during the cold season. The data collection for the pre-COVID-19 scenario was carried out for 5 school days (Monday–Friday), 3 days (Wednesday–Friday) for scenarios A and B and 5 school days (Monday–Friday) for scenarios C, D and D′ (Table 3). During all the test phases the occupation of the classrooms was constant.

**Table 3.** Organisation of classrooms and test protocols.

| Classroom | Pre-COVID-19 | Scenario A | Scenario B | Scenario C | Scenario D | Scenario D′ |
|---|---|---|---|---|---|---|
| Preschool | | | | | | X |
| Level 1°A | X | X | | | X | |
| Level 1°C | | X | | | X | |
| Level 1°D | | | X | X | | |
| Level 2°A | X | | | | | |
| Level 2°C | X | | X | X | | |

Other sensors took measures outdoors and in the corridor, respectively.

- Scenario A: IAQ was monitored in the classrooms under the application of the government protocol. This regulation established protection measures (mandatory use of a face mask for all students over 6 years old), safety distancing (chairs at a minimum distance of 1.5 m, preventing the occupants from sitting facing each other) and the ventilation of classrooms. Mandatory ventilation had to take place between 10 and 15 min before the arrival of the students, at the end of each school class (5 min after a 55-min non-ventilated period), during the break (30 min) and at the end of the day. (The teachers and students were unaware of the nature of the sampling carried out on these days.);
- Scenario B: a similar situation to the previous one, but $CO_2$ sensors were provided to teachers so that, in light of the protocol, they could act according to their criteria in case excessive concentrations were detected during the tests;
- Scenario C: the continuous opening of the windows was tested. Thus, the four windows in each classroom were kept open in an oscillating position (approximately 0.18 $m^2$ of free surface each) throughout the school day. Moreover, to maintain cross-ventilation, at least one of the two doors to the hall was open. During the break, two windows were completely open (0.72 $m^2$ of free surface each), while the other two remained in the aforementioned position. In addition, it was possible to assess not only the suitability of the indoor air renewal but also the operability of the situation. Likewise, the teachers had $CO_2$ sensors in case excessive concentrations were detected during the tests;
- Scenario D: the windows of the classroom were opened at specific times. All four windows (0.72 $m^2$ of free surface each) and both doors (1.65 $m^2$ of free surface each) were completely opened for 5 min after a 25-min non-ventilated period. For example, if the class started at 9:00 a.m., users opened the windows at 9:25 and closed them at 9:30 a.m., and so on for the whole school day. During the break, all the windows were kept open in an oscillating position (0.18 $m^2$ of free surface each) and doors were completely opened. The operation was carried out simultaneously in the facing classrooms to force cross-ventilation;
- Scenario D′: a slight variant of Scenario D. In this case, the scheme of apertures was the same as Protocol D, but the classrooms were ventilated constantly through the small slats over the doors (0.35 $m^2$ of free surface each), while the doors (1.65 $m^2$ of free surface each) were kept closed. This means that there was not important cross-ventilation.

In all cases, the opening scheme could be modified at the discretion of the teachers and such circumstances were registered.

### *2.3. IAQ Monitoring*

The sensors used were AirQualityEgg, which measure several IAQ conditions, specifically: air temperature, relative humidity (RH), $CO_2$, TVOC, $PM_{10}$, $PM_{2.5}$ and $PM_{1.0}$. The systematic measurement error (bias) of the different sensors integrated were:

- $CO_2$: ±30 ppm/±3% of the measured value;
- TVOC: Sensor IAQ—Core Indoor Air Quality (Resolution 16 bits);
- PM: ±10%;
- Humidity sensor: ±2%RH;
- Temperature sensor: ±0.3 °C.

Measurements were taken every five minutes from the previous hour, before the academic activity, up to one hour after its completion. The position of the measurement devices within the classroom was determined by previous tests, to limit distortions produced by the occupancy, academic material, blackboards, windows and doors. Sensors were kept between 1 and 2 m away from the area where the students were, and at least 1 m away from other possible disturbance sources. Regarding height, negligible variations of less than 3% in $CO_2$ and pollutant levels were observed between the breathing plane of the students in a sitting position (1.20 m) and 1 m above (2.20 m above the floor level).

### *2.4. IAQ Limit Values*

The limits established for the different pollutants were determined based on the criteria established by different regulations and guidelines:

- Operative temperature: between 21 °C and 23 °C during the heating season [17];
- RH: between 40% and 50% during the heating season [17];
- $CO_2$: 900 ppm (absolute value, i.e., 500 ppm over outdoor $CO_2$ concentration), defined as InDoor Air level (IDA) 2 for educational buildings [17];
- PM: since 2005, the World Health Organization (WHO) recommends a daily mean concentration of $PM_{2.5}$ below 25 µg/m$^3$, and below 50 µg/m$^3$ in the case of $PM_{10.0}$ [27];
- TVOC: 1.00 mg/m$^3$ or 500 ppb are considered adequate limits [28].

## 3. Results

The results obtained in this study are structured in three phases. Firstly, the data obtained during the winter season in 2020, in a pre-COVID-19 situation, are shown. Afterwards, Phases 1 and 2, with the data of the different ventilation protocols evaluated, during the winter season in 2021 and in a COVID-19 scenario, are presented (Table 4).

In the scenario pre-COVID-19, the monitoring results obtained in the classrooms (Level 2°C, 1°A, 2°A and Pre-school) revealed very poor values, achieving a maximum $CO_2$ concentration gradient indoors of 4025 ppm, more than six times above the limit set for RITE [17]. Taking into account the $CO_2$ concentration, its level was out of the normative range between 81% and 93% of the school time. The TVOC concentration was out of the range between 3% and 50% of the time, with a maximum value of 767 ppm reached in Level 2°A. In all cases, the level of PM was adequate under the maximum recommended levels. The ventilation was quite low, and cross-ventilation was close to zero. The rare opening of windows entailed that the only air change occurred through air infiltration. The lack of ventilation also caused the increase in temperature during the school day and poor IAQ.

Furthermore, cross-ventilation was an active strategy within scenarios C and D. In these scenarios, the classrooms maintained an average comfort temperature throughout the day, but there were significant periods with out-of-range conditions. In all cases, the mean $CO_2$ concentration level during the school day was within the adequate range. However, there were short periods in which $CO_2$ levels were above the maximum recommended values, namely for scenarios A (7.10%) and D (6.23%). This implies that the classroom had inadequate ventilation rates for 20 min per school day. PM was not a problem in any case. Instead, TVOC levels were over the recommended level of 500 ppm in certain moments, in a small percentage.

Finally, it is worth mentioning that during the performance of the tests, the conditions of the outdoor environment were continuously monitored (Table 5). The average outdoor temperature and the temperature differential between the hour before the start of the activity and the average temperature during the day were practically the same. Of particular importance are the $CO_2$ values outdoors since they serve as a reference in most of the regulations based on the concentration gradient between the inside and the outside.

**Table 4.** Results.

| Test | Occupation | Ventilation | | | Temperature | | | RH | | $CO_2$ INDOOR | | | PM | | | TVOC | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | n° | Mean Window Opening [m²] | Mean Door Opening [m²] | Cross-Ventilation | Max. [°C] | Min. [°C] | Time out of Range | Mean | Time out of Range | Max. [ppm] | Mean [ppm] | Time out of Range | Mean $PM_{2.5}$ [µg/m³] | Mean $PM_{10}$ [µg/m³] | Time out of Range | Mean [ppb] | Time out of Range |
| pre-COVID-19 Level 2°C | 22 | 0.01 | 0.01 | 0.1% | 25.4 | 20.7 | 1.4% | 45.5% | 15% | 3764 | 2264 | 93% | 5.5 | 7.2 | 0.0% | 485 | 50% |
| pre-COVID-19 Level 1°A | 21 | 0.13 | 0.48 | 0.1% | 26.5 | 21.4 | 0.0% | 38.3% | 58% | 2486 | 1422 | 81% | 9.6 | 10.7 | 0.0% | 302 | 3% |
| pre-COVID-19 Level 2°A | 23 | 0.03 | 0.14 | 0.1% | 25.5 | 21.1 | 0.0% | 46.0% | 9% | 4025 | 2232 | 93% | 4.8 | 5.8 | 0.0% | 483 | 38% |
| pre-COVID-19 Level Preschool | 21 | 0.06 | 0.17 | 0.1% | 26.6 | 21.5 | 0.0% | 40.6% | 47% | 3629 | 1918 | 88% | 7.2 | 8.7 | 0.0% | 416 | 25% |
| Scenario A Level 1°A & C | 18 | 0.98 | 0.92 | 46% | 22.4 | 17.5 | 65.8% | 37.6% | 87% | 1255 | 628 | 7.1% | 11.5 | 14.1 | 0.0% | 294 | 10% |
| Scenario B Level 1°D & 2°A | 19 | 0.97 | 0.79 | 18% | 25.2 | 17.5 | 41.8% | 35.4% | 93% | 1044 | 577 | 1.9% | 9.6 | 11.9 | 0.0% | 298 | 10% |
| Scenario C Level 1°D & 2°A | 20 | 1.02 | 1.18 | 100% | 24.5 | 19.2 | 18.7% | 38.3% | 81% | 1011 | 638 | 0.3% | 14.6 | 16.9 | 0.0% | 287 | 3% |
| Scenario D Level 1°A & C | 18 | 0.52 | 0.43 | 79% | 23.0 | 18.8 | 46.6% | 39.7% | 53% | 1047 | 707 | 3.4% | 15.3 | 17.4 | 2.5% | 320 | 9% |
| Scenario D′ Level Preschool | 17 | 0.85 | 0.55 | 0.0% | 24.5 | 18.9 | 11.0% | 37.7% | 89% | 1200 | 668 | 6.2% | 13.5 | 15,5 | 0.0% | 319 | 6% |

**Table 5.** Outdoor conditions for each test Phase.

| Week | Day | Temperature [°C] | RH [%] | Wind Speed [km/h] | $CO_2$ [ppm] | $PM_{2.5}$ [μg/m$^3$] | $PM_{10}$ [μg/m$^3$] | TVOC [ppb] |
|---|---|---|---|---|---|---|---|---|
| Phase pre-COVID February 2020 | Mon. | 12.1 | 68.6 | 6.8 | 440 | 5.3 | 5.7 | 227 |
| | Tues. | 7.1 | 60.7 | 3.9 | 443 | 7.2 | 7.8 | 281 |
| | Wed. | 5.2 | 60.7 | 3.9 | 450 | 16.0 | 17.3 | 405 |
| | Thurs. | 5.3 | 57.6 | 2.9 | 452 | 24.7 | 27.2 | 424 |
| | Fri. | 9.0 | 70.9 | 2.8 | 442 | 25.8 | 28.1 | 202 |
| | Mean | 7.8 | 63.9 | 4.1 | 446 | 15.8 | 17.2 | 308 |
| Scenarios A & B February 2021 | Wed. | 11.3 | 59.9 | 12.0 | 426 | 10.7 | 14.2 | 202 |
| | Thurs. | 11.9 | 55.6 | 6.1 | 420 | 9.4 | 13.9 | 193 |
| | Fri. | 8.8 | 62.5 | 8.0 | 457 | 20.1 | 23.26 | 344 |
| | Mean | 10.7 | 59.4 | 8.7 | 433 | 13.4 | 17.1 | 246 |
| Scenarios C, D & D′ February 2021 | Mon. | 10.6 | 59.6 | 6.9 | 439 | 20.2 | 24.8 | 227 |
| | Tues. | 10.8 | 63.2 | 5.0 | 434 | 23.0 | 27.3 | 225 |
| | Wed. | 9.9 | 63.4 | 4.0 | 428 | 19.5 | 22.4 | 221 |
| | Thurs. | 12.2 | 59.4 | 3.0 | 440 | 21.7 | 25.7 | 230 |
| | Fri. | 9.6 | 65.4 | 6.0 | 421 | 27.0 | 32.5 | 182 |
| | Mean | 10.6 | 62.2 | 4.9 | 432 | 22.3 | 26.6 | 217 |

*Inquiry to the Teachers*

After the tests, a brief survey was sent to the ten teachers of the classrooms studied, with two questions related to their experience during the process:

- Question 1: In a COVID-19 scenario, would it be possible and realistic to keep this ventilation protocol in the classrooms?
- Question 2: In a post-COVID-19 scenario, would it be possible and realistic to introduce a ventilation protocol which is less restrictive into your daily routine for the long term?

They could also make additional comments or clarifications (Table 6).

**Table 6.** Survey to the teachers after the tests (1 teacher per class, 2 teachers per scenario).

| Scenario | Question 1 | | Question 2 | | Comments |
|---|---|---|---|---|---|
| | Yes | No | Yes | No | |
| A | 2<br>100% | 0<br>0% | 2<br>100% | 0<br>0% | |
| B | 2<br>100% | 0<br>0% | 2<br>100% | 0<br>0% | |
| C | 2<br>100% | 0<br>0% | 2<br>100% | 0<br>0% | |
| D | 0<br>0% | 2<br>100% | 2<br>100% | 0<br>0% | Rigid protocol to diary routine |
| D′ | 2<br>100% | 0<br>0% | 2<br>100% | 0<br>0% | Cold/Perception of poor ventilation |

## 4. Discussion

In pre-COVID cases, the lack of ventilation is evident. In some situations, there is almost none, except when the windows and doors are rarely opened during the midday break. Only in the scenario pre-COVID-19 Level 1°A was the intention of a routine indoor air renewal perceived; thus, even if ventilation is scarce, it is enough to maintain adequate TVOC concentration for most of the time. In this classroom, the average indoor $CO_2$ was 34% below the other classrooms, but even so, during 81% of the week's school time, or for 4 out of the 5 teaching hours, $CO_2$ levels exceeded the limit set by Spanish regulations.

From the tests performed on the scenarios (A–D′), the most important aspects of the impact of ventilation on the monitored contaminants were analysed:

- $CO_2$: in all scenarios, the average $CO_2$ concentration was low, well below the range established by regulations (around 900 ppm), so good IAQ conditions were guaranteed throughout the school day. Scenario C guaranteed better IAQ since the time out of the quality standards was negligible;
- Scenarios A and D′ were the most unfavourable in terms of time out of range and maximum values obtained. Although the time with $CO_2$ concentration levels out of range did not exceed 19 min, which could be acceptable, the maximum values recorded rose up to 1255 ppm, 33.3% above the limit, which makes it not a recommended solution.
- TVOC: comparing the pre-COVID-19 scenario and COVID-19 scenarios, mean concentration levels during school hours in the classrooms improved from 421 ppm to 320 ppm, and from 29.0% of the out-of-range time to 10%. Therefore, overall, it can be said that the proposed ventilation scenarios succeeded to register adequate TVOC concentration in the classrooms.
- In Scenario C, with continuous ventilation, the average TVOC concentration was lower than the average registered in other scenarios and, also, the time out of range was notably lower. This may be due to the fact that, in cases where ventilation is rarely promoted, there were long periods when TVOCs accumulated, especially when school materials that are VOC sources (markers, paints and other handicraft materials) were used.
- PM: this did not entail a problem within the classrooms. The presence of PM inside the classrooms was conditioned by the outdoor concentrations. Despite the fact that aerosols are vectors of SARS-CoV2, the presence of these does not necessarily imply a greater probability of infection since the external particles are assumed not contaminated and the transmission is carried out through the human-produced aqueous bioaerosols.

Regarding the indoor temperature conditions throughout the school day, it was observed that scenarios C and D′ were the most favourable, with values of just 18.7% and 11.0% of the time outside the acceptable temperature range.

One last aspect to consider for any natural ventilation strategy to be valid is its feasibility to be lasting over time. In other words, it must be compatible with the daily routine of the classroom. The surveys carried out revealed that the punctual opening entailed a great difficulty because, in order to be effective (cross-ventilation), coordination between two classrooms was needed. Therefore, it would be a solution with little scope. Additionally, to achieve the durability of the protocol, Geelen et al. (2008) [22] pointed out the need for a didactic package attached to the scenario of application, for both a COVID-19 or post-COVID-19 scenario. This may have failed in Scenario A, as reflected in the results.

This study was limited to a case study, so it would be necessary to evaluate its applicability to other educational centres in order to achieve a larger sample and representativeness.

## 5. Conclusions

Despite the limitations that a case study supposes, the proposed methodology and proceedings can serve as guidelines for a post-COVID-19 scenario.

Considering IAQ, thermal comfort and the practicality of the scenarios, scenario C is the most effective for this case study. Thus, the mixing model, which ensures the removal of pollutants, is guaranteed by continuous cross-ventilation. It can be reached using different opening levels, depending on the use and occupation of the classroom, which contributes to acquiring an adequate air quality for the use of the space. Air flow regulation reduces the thermal effects of the new air coming from outdoors.

A similar air flow can be obtained by fully opening doors and windows in designated moments of the day. However, there is both a thermal loss and an absence of cross-ventilation while teaching. These conditions promote an air quality fluctuation value, while a constant value is preferred for these kinds of spaces. This can be observed in the application of Scenario B, with similar ventilation values but 82% lower cross-ventilation, where adequate thermal comfort results were not achieved.

As demonstrated in Scenario B and Scenario D, having specific openings set was only effective if there was cross-ventilation. As a result, if the layout of the classrooms require coordination between them, it cannot be considered functional since its application over time would be compromised.

Overall, two types of protocols are suggested to be applied in naturally ventilated classrooms: one for health emergency scenarios, in which higher ventilation rates are required, and another for non-emergency situations, in which ventilation rates are not that demanding.

Finally, all these natural ventilation scenarios are influenced by the pollutants present outdoors. This aspect should contribute to defining criteria to operate the openings by the constant monitoring of those pollutants. In this case study, high-pollutant values were not detected, neither in PMs nor TVOC. For instance, it was possible to verify that the indoor concentration of pollutants is ruled by a proportional relationship with the values registered outdoors.

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