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Assessment of indoor air quality and risk of COVID-19 infection in Spanish secondary school and university classrooms

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ABSTRACT

Despite the risk of transmission of SARS-CoV-2, Spanish educational centers were reopened after six months of lockdown. Ventilation was mostly adopted as a preventive measure to reduce the transmission risk of the virus. However, it could also affect indoor air quality (IAQ). Therefore, here we evaluate the ventilation conditions, COVID-19 risk, and IAQ in secondary school and university classrooms in Toledo (central Spain) from November 2020 to June 2021. Ventilation was examined by monitoring outdoor and indoor CO_2 levels. CO_2, occupancy and hygrothermal parameters, allowed estimating the relative transmission risk of SARS-CoV-2 (Alpha and Omicron BA.1), H_r, under different scenarios, using the web app *COVID Risk*^{airborne}. Additionally, the effect of ventilation on IAQ was evaluated by measuring indoor/outdoor (I/O) concentration ratios of O_3, NO_2, and suspended particulate matter (PM). University classrooms, particularly the mechanically ventilated one, presented better ventilation conditions than the secondary school classrooms, as well as better thermal comfort conditions. The estimated H_r for COVID-19 ranged from intermediate (with surgical masks) to high (no masks, teacher infected). IAQ was generally good in all classrooms, particularly at the university ones, with I/O below unity, implying an outdoor origin of gaseous pollutants, while the source of PM was heterogeneous. Consequently, controlled mechanical ventilation systems are essential in educational spaces, as well as wearing well-fitting FFP2–N95 masks indoors is also highly recommended to minimize the transmission risk of COVID-19 and other airborne infectious diseases.

1. Introduction

When the pandemic of the coronavirus disease COVID-19 hit in 2020, teaching transitioned to completely online learning, with no students in classrooms, because COVID-19 outbreaks occur indoors [1,2] and long-range transmission beyond 1.5 m has been well-documented in conditions of low ventilation rates [3]. Since classroom closures were costly and potentially affect the learning of students, educational centers were later reopened despite the risk of transmission of the virus. The face-to-face return to classrooms in September 2020 opened a debate about health security and indoor air quality (IAQ). Reopening classrooms required facilities to be accommodated to the new situation, so operating healthy classrooms and self-protection was a foundational necessity for battling the pandemic. Furthermore, the new academic year was challenging, especially because of a high transmission of SARS-CoV-2 (Severe Acute Respiratory Syndrome Coronavirus 2) in the different outbreaks.

Since the airborne transmission of SARS-CoV-2 has been widely proven by the scientific community [4–10], with documented outbreaks in educational facilities [11,12], the removal of the virus-laden aerosols from indoor air by ventilation has become a top concern for living and learning. Effective ventilation is, therefore, an important part of COVID-19 prevention, as well as proximity and duration of contact, as these factors increase an individual's exposure to respiratory aerosols. Even wearing a multi-layer mask indoors, if it is not well-fitted, the risk of transmission can be high in bad-ventilated environments without any

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other way of removing the infected aerosols, e.g., air filtration. Particularly in classrooms, ventilation was an important issue to be addressed in the 2020–2021 academic year, since previous studies in classrooms of southern Spain [13–18], France [19], Portugal [20,21], Italy [22–24], and other Mediterranean locations [25] had shown poor indoor conditions, both in terms of thermal comfort and clean air, due to the lack of a proper ventilation. According to the literature on how schools had to operate after the lockdown, they all had in common the general principle of increasing ventilation by renewal with outdoor air [26–28].

If there are no other significant sources or sinks of indoor carbon dioxide (CO_2), its accumulation relative to the background outdoor level is only due to human exhalation and a lack of ventilation. Therefore, monitoring differential CO_2 concentrations (*Δ[CO₂]*), CO_2 can be used as a tracer gas to estimate ventilation rates, especially in environments with high occupant density such as classrooms [29–33]. Monitoring indoor CO_2 can also be used to estimate risk of other respiratory diseases, since virus-laden aerosols may easily accumulate as CO_2 does. In this way, it is possible to assess the infection risk of SARS-CoV-2 in each indoor space using CO_2 as a proxy through adaptations of the Wells-Riley model [33,34] among other methods, as in previous examples of studies in university classrooms in Italy [35].

Apart from CO_2 concentrations and the risk of COVID-19 infection indoors, IAQ is also becoming a global concern as people spend more than 90% of their time in different indoor settings, such as offices, homes, care centers, schools, universities, shopping centers, etc. [36–39]. Other harmful pollutants may also be present in these environments, *e.g.*, ozone (O_3), nitrogen oxides (NO_x), volatile organic compounds (VOCs), or particulate matter (PM). Many studies on IAQ have been performed mostly in elementary schools all over the world [13,40–44]. However, in secondary schools and universities IAQ studies are less extensive [13,45–48], and barely provide insights on the thermal comfort for occupants, particularly under ventilation protocols such as those adopted during the COVID-19 pandemic.

The aim of this work was to assess the ventilation conditions, the risk of infection by COVID-19, and IAQ in four occupied classrooms (two at a secondary school and two at a university campus) located in central Spain (Toledo), after their reopening during the COVID-19 pandemic (November 2020 to June 2021). The classrooms differed in their location and size/volume, occupancy, and the type of ventilation (natural or mechanical). The ventilation conditions were examined by monitoring indoor CO_2 levels. The CO_2 concentrations and the thermal comfort parameters, relative humidity (*RH*) and air temperature (T_a), allowed us, together with the occupancy, to estimate the attack rate of the Alpha and Omicron BA.1 variants of SARS-CoV-2 for different scenarios with one infected person (the teacher or a student) in each classroom, using the web app COVID Risk Airborne. IAQ was evaluated by monitoring O_3 and NO_2 concentrations and the suspended PM levels. Indoor/outdoor (I/O) ratios for these pollutants were calculated for getting a deeper insight into their origin in the classrooms and for comparing them with the WHO guidelines.

The effectiveness of natural ventilation in high-occupancy spaces will be discussed in terms of CO_2 levels and IAQ and will be compared with those of a mechanically ventilated space. The estimation of transmission risk for COVID-19 in these indoor environments could be used to predict the ventilation conditions needed if the occupancy varies or if the number of infected people increases in the classrooms. The present results can be used to develop appropriate control strategies to improve IAQ in classrooms and improve the safety of their occupants minimizing the transmission capacity of COVID-19 and other airborne infectious diseases.

2. Materials and methods

2.1. Description of the local context and educational buildings

The study was conducted during the 2020–2021 academic year at Toledo (central Spain). Toledo has a Mediterranean climate (mean annual rainfall of 340 mm), with mean temperatures varying from 6.4 °C in January to 26.8 °C in July [49]. The *RH* ranges from 40 to 45% in summer to 75–80% in winter due to the influence of the Tagus River.

Two classrooms of a secondary school (SS, identifier) and two classrooms at the campus of the University of Castilla-La Mancha (UN, identifier) were monitored. SS and UN classrooms were located just 1 km away with different surroundings; they differed in terms of their situation within the building (basement, ground or first floor), size/volume, occupancy, and type of ventilation systems (Fig. 1). The university campus was placed in a quiet area, with low vehicle traffic, next to the Tagus River with abundant vegetation. The university campus is located at the Royal Weapons Factory, which was created in 1761 by King Charles III. Following the closure of the factory in the 1980s, the buildings were restored (starting in 1998) to place the university campus. The two university classrooms studied were placed at the ground floor, had different types of ventilation, and the teaching was on-site (Fig. 1). Classroom UN1 is naturally ventilated –with a direct expansion heat treatment system–, while UN2 is mechanically ventilated with a roof-top system which is complemented with two additional duct-type fan-coil units, which does not efficiently retain fine ($PM_{2.5}$) and ultrafine particles ($PM_{0.1}$).

The secondary school was located about 1 km away in a busier area, and with more traffic problems. Because the building was built in 1958, it does not accomplish the requirements of ventilation given by the Spanish regulation on HVAC [50] and natural ventilation is the only possibility in classrooms SS1 and SS2, while heating treatment is relied on hot water (HW) radiators. While SS1 was in the basement of the building and the teaching was face-to-face, SS2, was on the second floor, and the teaching was in semi-attendance (Fig. 1).

2.2. Measurements of CO_2, thermal comfort, and estimation of COVID-19 risk transmission

2.2.1. Measurement of CO_2

Indoor and outdoor CO_2 levels were monitored by a portable non-dispersive infrared (NDIR) sensor (Testo, model 315-3), which has a precision of ±10 ppm (parts per million) and a measurement range of 0–10,000 ppm. The physical parameters T_a and *RH* were also measured with the Testo model 315-3 equipment. The absolute uncertainty is ±2.5% and ±0.5 °C in *RH* and T_a, respectively.

The change in CO_2 concentration with respect to the outdoor level was calculated from Equation (1).

$$[CO_2] = [CO_2]_{indoor} - [CO_2]_{outdoor} \quad (1)$$

The prediction of the mean value of occupants' hygrothermal comfort can be developed using the Predicted Mean Vote (PMV) indicator [51,52], which uses thermophysiological parameters to estimate the vote of a theoretical occupant in a seven-point thermal scale of −3 (cold) to +3 (hot). This index can be used for a basic approach in Mediterranean naturally ventilated spaces, especially for educational buildings, if minor adjustments are made in their correspondence with the Predicted Percentage of Dissatisfied (PPD) [15,53].

2.2.2. Estimation of the thermal comfort conditions

PMV is based on a thermal balance calculation of the human body, which is influenced by the characteristics of the person (physical activity, height and weight, and clothing insulation), as well as physical parameters (T_a, mean radiant temperature $\overline{t_r}$, *RH*, and air velocity v_a). Given the usual medium/high occupation density of the spaces and their occupancy schedules, and according to previous field studies on thermal comfort carried out in naturally ventilated classrooms (with open windows) in Spain [15,16], it can be considered that:

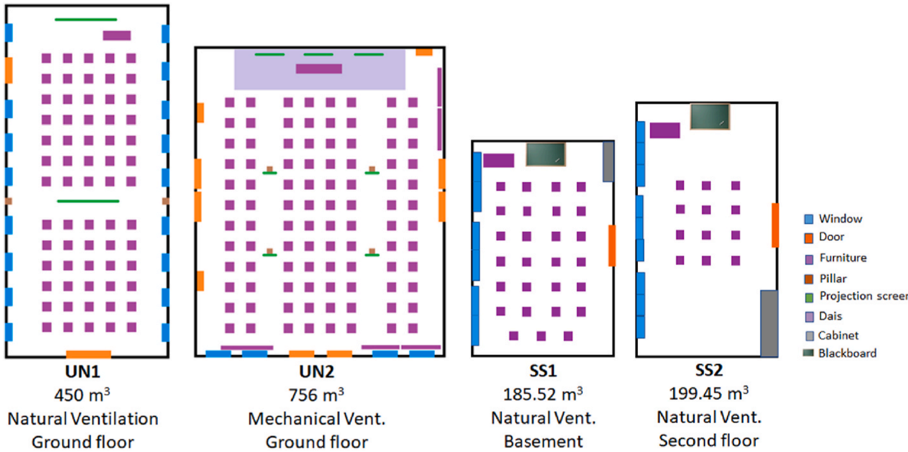

Fig. 1. Schematic floor plans of the university (UN1, UN2) and secondary school (SS1, SS2) classrooms.

- Mid-season and winter: $\overline{t_r}$ is equal to T_a when there are HW radiators operating (from 18 to 21 °C), or 1-2 °C lower than T_a if there is a warm air system or the space is in free-running conditions.
- Summer conditions, $\overline{t_r}$ is 1–2 °C higher than T_a.

This assumption is a simplification which allows a first approximation to the existing thermal environment of these spaces. In addition, v_a was considered to be lower than 0.20 m/s, according to the previous experiences of the above-mentioned studies in classrooms. Regarding to the characteristics of the potentially infected person, the estimated metabolic rate was 1.2 met (sedentary activity), with a body surface area of an average human being [54] and an estimated clothing insulation of 1.0 clo in winter and 0.7 clo in summer, according to ISO 7730 [52]. In addition, the Spanish Royal Decree 486/1997 [55], which stablishes the minimum requirements for safety and health at the workplace, determines that the temperature of the spaces with sedentary work -*e.g.,* educational buildings-must be between 17 and 27 °C (to avoid thermal stress).

2.2.3. Estimation of the COVID-19 infection risk

COVID-19 infection risk in each classroom was estimated using the free online estimator COVID Risk$^{\text{Airborne}}$ (https://www.covidairborneris k.com/), developed by Ref. [56] and based on the adaptation [33,57] of the Wells-Riley model for simulating disease propagation –strictly via medium/long range aerosols [58]. This calculator is a very helpful tool to assess the infection risk by different variants of SARS-CoV-2 under different indoor conditions (occupancy, metabolic and vocalization activity of the occupants, room volume, airflow and type of ventilation, number of infected people or use and fit of masks), considering measured physical variables such as the CO_2 level, T_a, and *RH*.

This mathematical procedure, refined and adapted by Peng et al. [33, 59] and Buonanno et al. [60], estimates the infection risk through the calculation of how many 'quanta' could inhale each occupant during a given event considering that there is one or more infectious occupants in the premise. Note that a 'quantum' is dose of airborne droplet nuclei required to cause infection in 63% of susceptible occupants. The quanta emission rate of the infectious subject (ER_q) [61] is determined through the Monte Carlo method [60], enhancing the basic 'quanta' exhalation rate (E_{p0}, for a "resting, oral breathing activity") according to their age, metabolic, and vocalization activity. Then, the 'quanta' concentration in the environment of the premise throughout the event duration can be estimated by also incorporating the effect of the various aerosol removal (ventilation, air filtration and the use of masks and respirators), the surface deposition rate [62], and the decay rate of infection intensity of the virus-laden aerosols. Finally, the number of 'quanta' inhaled by a susceptible person present in the space (n) is calculated using the inhalation rate for short-term exposures, according to sex, age and activity [63], during the exposure period. The average excess CO_2 level during the event is used as a risk proxy in this calculation, given that both CO_2 and the virus-laden aerosols are emitted during the respiratory process [33].

Nevertheless, this statistical methodology simplifies the existing problem by considering that the atmosphere in the given premise is uniformly distributed, therefore the results may differ slightly from real cases (despite the model has been previously validated by comparison with existing outbreaks in medium/large premises [33,59]). In addition, this procedure also excludes droplet and contact/fomite transmission, and it assumes that 2 m (6 ft) social distancing is honored, since it works with medium/long range aerosols. Otherwise, the infection rates calculated would be higher, especially for occupants close to the infectious subjects.

To carry out this statistical estimation of medium-long range transmission, it has been considered that:

- E_{p0} was 18.6 infectious doses (quanta) per hour for the Wild-type of SARS-CoV-2, assuming an 85% percentile of viral exhalation rate from the mean value of 2.0 $q{\cdot}h^{-1}$ [64], as recommended [33,59]. This is based on the hypothesis that the aerosols emitted by an infected subject contain the same viral load as a sputum (copies per mL) [64], while the quantity and volume distribution of these aerosols were characterized experimentally by Morawska et al. [65] for various forms of human respiratory exhalation flows (breathing and vocalization activities).
- The predominant variant of SARS-CoV-2 during the first part of 2021 was B1.1.7 (Alpha), which was progressively replaced by B.1.617.2 (Delta) [66]. In addition, the variant of SARS-CoV-2 that mostly circulates during the investigated period was B.1.1.529 (the so-called "Omicron"). Thus, calculations have been performed both for Alpha and Omicron variants.
- The enhancement factor, defined as the ratio of the effective reproduction number (R_e) of the variant under study to that of the baseline variant, of Alpha variant was 1.5 [66], while the value for Omicron BA.1 was 2.5, which was estimated using a conservative R_e ranging from 2.43 to 5.11 [67].

Four scenarios were considered in the present study:

- CASE 1a: The teacher us infected by SARS-CoV-2 (standing, speaking) and the rest of occupants are wearing a non-fitted surgical mask.
- CASE 1b: The teacher is infected, and no one is wearing a mask in the classroom.

- CASE 2a: One infected student (seated, oral breathing) and the rest of occupants are wearing a non-fitted surgical mask.
- CASE 2b: One infected student, with no masks in the classroom.

The main boundary conditions for the risk assessment for these four scenarios are listed in Table 1. Quanta emission rate values of each SARS-CoV-2 variant also include the effect of the enhancement factor.

The results of this statistical study are presented through two indicators, both referred to the inhalation risk during the event of the necessary infectious dose of virus-laden aerosols to become infected per susceptible occupant ('quanta'), therefore they can be used regardless of the number of people vaccinated or the effectiveness of the different vaccines. The two indicators are the attack rate (*AR*) and the relative risk of infection (H_r).

The *AR* is epidemiologically defined as the ratio between the number of infection cases (*C*) and the number of exposed susceptible and healthy individuals (*S*) which were exposed to a non-zero quanta concentration [60]. Moreover, *AR* also represents the individual risk of infection (*R*) in a hypothetical scenario and can be calculated from Equation (2),

$$\mathrm{AR} = \mathrm{C} / \mathrm{S} = \mathrm{R} \equiv 100 \cdot (1\text{-}e^{-n}) \tag{2}$$

where *n* is the infectious dose inhaled by a susceptible person present in the premise during the event (quanta) (see Equations 3-6).

$$n = r_{ss} \cdot E_p \cdot f_e \cdot f_i \cdot B \cdot D / (V \cdot \lambda) \tag{3}$$

$$E_p = E_{p0} \cdot r_E \cdot E_F \tag{4}$$

$$B = B_0 \cdot r_B \tag{5}$$

$$\lambda = \lambda_0 + \lambda_{cle} + \lambda_{dec} + \lambda_{dep} \tag{6}$$

where:

r_{ss} is multiplicative factor applied for events too short to approximately reach steady state (dimensionless)
E_p is the quanta exhalation rate for a person with a given metabolic and vocalization activity (quanta/h)
f_e is the penetration efficiency of virus-carrying particles through masks or face coverings for exhalation (dimensionless)
f_i is the penetration efficiency of virus-carrying particles through masks or face coverings for inhalation, which considers the effect of the fraction of occupants wearing face coverings (dimensionless)
B is the breathing volumetric flow rate of susceptible persons (m^3/h)
D is the duration of exposure (h)
V is the volume of the space (m^3)
λ is the rate of removal of quanta (h^{-1})
E_{p0} is the basic quanta exhalation rate for a person resting and only orally breathing (quanta/h)
E_F is the enhancement factor of a variant of the given airborne disease (dimensionless)
r_E is the relative increase of the emission with activity (dimensionless)
B_0 is the average volumetric breathing rate of a sedentary susceptible person, according to age and size (m^3/h)
r_B is the relative breathing rate enhancement factor (dimensionless)
λ_0 is the first-order rate of removal of quanta by ventilation with outdoor air (h^{-1})
λ_{cle} is the removal of quanta by air cleaning devices (h^{-1})
λ_{dec} is the infectivity decay rate of the virus (h^{-1})
λ_{dep} is the deposition rate of airborne virus-containing particles onto surfaces (h^{-1})

Likewise, when *n* is low, *R* is also equivalent to the proportion of susceptible occupants in the event who can inhale a 'quantum' (thus, secondary cases), applying the Wells-Riley infection model to the amount of infectious doses inhaled [6], as it is shown in Equations (2) to (6). It should be noted that inhaling a quantum does not necessarily imply becoming infected, since the subject may not be vulnerable (due to a previous infection or vaccination) or, by definition, may not be part of the 63% of people who become infected by inhaling that dose.

The relative risk of infection (H_r, in h^2/m^3): Indicator of the increase of the risk (Equation (7) [33,59]), common for airborne diseases, through evaluation of the relative increase of the emission with activity (r_E) –from seated and oral breathing– and the variation of the inhalation air flow due to the activity (r_B) –from seated and oral breathing– of a single vulnerable person, for a given exposure time (*D*) in a premise of the volume specified (*V*), also incorporating the rate of removal of quanta (λ) of the mitigating measures (such as masks and ventilation). As it can be seen in Equation (7), this indicator does not depend on specific diseases/variants since it is calculated using the "quanta" emission enhancement due to activity/vocalization (r_E) and the variation of the inhalation air flow due to the activity (r_B). Thus, it allows to estimate the overall risk of airborne disease transmission in a premise during a given event, to be analyzed in terms of individual risk.

$$H_r = r_{ss} \cdot r_E \cdot r_B \cdot f_e \cdot f_i \cdot D / (V \cdot \lambda) \tag{7}$$

Three categories of H_r (low, medium, and high) are established according to a given value of AR, as it can be seen in Table 2, being adapted to each variant according to their enhancement factor. These limits were established considering that, for the Wild-type SARS-CoV-2, there are no documented outbreaks when *AR* was under 0.5% ($H_r < 0.001$) [59].

Table 2
Enhancement factor and limits for relative risk (H_r) and attack rate (*AR*) indicators [33] for Wild-type SARS-CoV-2 and corrected for Alpha and Omicron BA.1 variants.

Variant of SARS-CoV-2	Enhancement Factor per variant	AR (%)	H_r (h^2/m^3)		
			Low	Medium	High
Wild-type	x1.0	<0.5	<0.0010	<0.0100	≥0.0100
Alpha	x1.5 [66]	≥5.0	<0.0007	<0.0064	≥0.0064
Omicron BA.1	x2.5 [67]	<5.0	<0.0005	<0.0038	≥0.0038

Table 1
Boundary conditions for the risk assessment of the four scenarios.

Scenario		Infectious occupant (exhalation)			Susceptible occupant (inhalation)		
		Activity	Quanta emission rate (q/h)	Mask efficiency (%)	Activity	Inhaled flow rate (m^3/h)	Mask efficiency (%)
CASE 1a	Alpha Omicron	Standing, speaking	293.0 488.3	32.5	Seated, oral breathing	0.32	25.0
CASE 1b	Alpha Omicron	Standing, speaking	293.0 488.3	0.0	Seated, oral breathing	0.32	0.0
CASE 2a	Alpha Omicron	Seated, oral breathing	55.8 93.0	32.5	Seated, oral breathing	0.32	25.0
CASE 2b	Alpha Omicron	Seated, oral breathing	55.8 93.0	0.0	Seated, oral breathing	0.32	0.0

2.3. IAQ measurements

Monitoring of O_3, NO_2, and different size PM was carried out indoors and outdoors the classrooms in parallel. On one hand, O_3 was measured with a semiconductor sensor (Aeroqual, model SM-70 with a resolution of 0.001 ppm, and a measurement range of 0–0.15 ppm. On the other hand, NO_2 was measured with an electrochemical sensor head fitted onto a monitor Aeroqual, series 200. This sensor head has a resolution of 0.001 ppm in the 0–1 ppm range. The PM concentration was measured with a handheld laser particle counter (Kanomax, model 3887), which simultaneously measures particles of $PM_{0.3}$ and $PM_{0.5}$, with a sample flow of 2.83 L/min. Moreover, $PM_{2.5}$ and PM_{10} were monitored with a portable particulate laser sensor. This sensor head was fitted onto another Aeroqual (series 200) monitor, and it measured PM from 0.001 to 1.000 mg/m^3 with a resolution of 0.001 mg/m^3. All instruments were calibrated within the year preceding this study.

2.4. Data collection

CO_2 levels, T_a, and RH, O_3, NO_2, and PM were monitored outdoors and indoors three days per week once a month between November 2020 and June 2021. However, neither in January (Filomena snowstorm) nor in May (administrative problems) measurements could be carried out in the SS classrooms. During the monitoring days, the indoor measurements were taken while teaching for 15 min every 2 h, from 8:15h to 14:15h at the secondary school, and from 9:10h to 14:00h at the university. In every measurement, the occupancy (number of people) and the number of open windows/doors in the classroom were annotated. The outdoor measurements were carried out in parallel during 15 min at the garden of the university campus in front of the classrooms, meanwhile in the secondary school they were performed in the playground. In the case of the secondary school, there was a break at 11:00h (period of non-occupancy of the classrooms), which lasted approximately 30 min. During this break, measurements of the concentration of all pollutants and the physical parameters were also taken to ensure that without occupancy they reached the outdoor levels. Inside the classrooms, all devices were placed at a height coinciding with the breathing zones of the students, maintaining a distance of at least 1.5 m from walls and 1 m from the students, avoiding any direct disturbance by experienced researchers [68].

3. Results and discussion

3.1. Ventilation, thermal comfort, and COVID-19 infection risk

3.1.1. Evaluation of the ventilation conditions from CO_2 concentrations

In Table S1 of the Supplementary Material 1, the mean, maximum, and minimum CO_2 concentration measured in the four classrooms are listed. Note that the maximum CO_2 concentrations were reached in November 2020 in the secondary school classrooms, with peaks over 1120 ppm in SS1, which is not surprising since this classroom was located in the basement of the building. These CO_2 measurements allowed us to revise and change the (natural) ventilation protocol at the secondary school. Since December 2020, the maximum CO_2 concentrations decreased, in general, down to the threshold of 700 ppm of CO_2 recommended by the Spanish Ministry of Science and Innovation, although in SS1 classroom maximum values of CO_2 were still registered over this threshold in some months. In contrast, at the university classrooms CO_2 concentrations were always at or below 700 ppm, accomplishing the recommendations of the authority, and thus no change of the ventilation protocol was necessary.

In all classrooms, the maximum CO_2 concentrations in most cases were below 1000 ppm and under the optimal cognitive performance level, getting better levels at university classrooms than those at the secondary school. Absolute values of CO_2 over 1000–2000 ppm may directly affect higher-level cognitive performance, which includes problem resolution and high decision-making [69–72]. In addition, absolute values of CO_2 over 1000 ppm were also associated with an increased risk of experiencing rhinitis –sneezing/runny nose/nasal congestion [73].

The current Spanish regulation of thermal installations in buildings [50] (RITE, Spanish acronym for the "Reglamento de Instalaciones Térmicas en los Edificios") establishes that the minimum air renewal in classrooms must be 45 m^3 of clean air per hour and person, i.e., 12.5 L/s per person (Indoor Air Quality type 2). In addition, the Spanish regulation RITE also allows the management of the mechanical airflow supply for these spaces by controlling the maximum CO_2 level, with a maximum value of 500 ppm above the outdoor level for spaces with permanent occupation). Nevertheless, this high $\Delta[CO_2]$ was not advised in the pandemic situation caused by an airborne virus like SARS-CoV-2. Under these circumstances, the Spanish Ministry of Science and Innovation recommended not to exceed 700 ppm of CO_2 indoors (absolute value, assuming an outdoor level of 400–420 ppm), *i.e.* a $\Delta[CO_2]$ of around 300 ppm [74]. However, the COVID-19 protocol recommended by the Spanish Ministry of Education consisted in ventilating the classrooms for at least 10 min only at the beginning and at the end of the day and "as long as possible", but without clear instructions. Therefore, each educational center had to adapt this ventilation protocol to its needs. In the present study, the mechanically ventilated classroom (UN2) was used as a reference. In the naturally ventilated classrooms, all windows and doors were opened during this study. Nevertheless, at the high school the protocol was initially not adequate in November 2020, and windows and doors were only opened during the break and 10 min at the beginning and at the end of the day.

The monthly variation of $[CO_2]$ observed in all investigated classrooms was below the threshold recommended by the pre-pandemic Spanish regulations ($[CO_2]$ = 500 ppm), except for classroom SS1 in November 2020 (Fig. 2). Furthermore, we found that in classroom SS1 the incremental CO_2 level in November 2020 also exceeded the current (pandemic situation) Spanish regulation. As it can also be seen in Fig. 2, $\Delta[CO_2]$ in the university classrooms UN1 and UN2 were more than 100 ppm below that threshold since the beginning of the COVID-19 pandemic, which reinforce the results obtained for absolute measurements of CO_2.

3.1.2. Hygrothermal comfort

Adequate thermal comfort in classrooms improves concentration and attention of students [75–77]. Some studies have shown that students would feel more comfortable when the temperature of the classroom was slightly elevated [78–80], despite their cognitive performance was higher with slightly cooler air temperature values [72]. However, in situations of COVID-19 transmission, ventilation was prioritized against the thermo-hygrometric conditions (RH and T_a) necessary for thermal comfort or energy efficiency requirements.

In addition to hygrothermal comfort, RH and T_a have been proven to impact the SARS-CoV-2 transmission. The risk of transmission of this airborne virus in dry indoor areas is higher than in humid ones and higher in cold regions [81–83]. For example, a negative correlation was found between the average temperature per country and the number of cases of SARS-CoV-2 infection [84]. Thus, indoor RH and T_a are also essential parameters to be monitored under real conditions, *i.e.*, with real occupancy and ventilation conditions to estimate the aerosol transmission risk of SARS-CoV-2. As shown in Fig. 3, the indoor RH is generally within the optimal range for human health, 40%–60% [81, 82], except for some days in March, where RH were below 40% and the chances of airborne transmission of SARS-CoV-2 were higher.

Table 3 shows the percentage of occupied time in which the minimum values of thermal comfort [52] and thermal stress [55] were achieved. Thermal comfort is commonly quantified as the percentage of time where the occupants are dissatisfied in terms of temperature. When the % of occupied time is lower or equal to 10%, thermal comfort lies in the category B (CAT B), which corresponds with the recommended

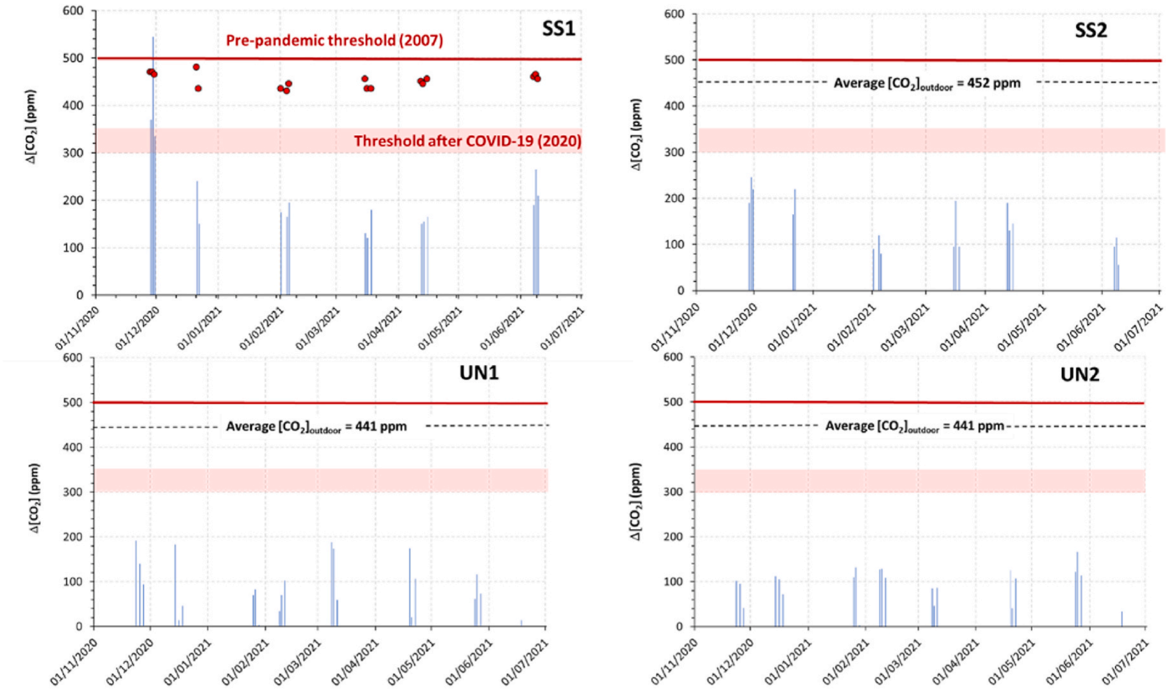

Fig. 2. Evolution of the incremental CO_2 concentration, *[CO2]*, between November 2020 and June 2021. Red circles represent outdoor CO_2 measurements and dashed lines average CO_2. The red line represents the threshold *[CO2]* in classrooms established before the COVID-19 pandemic. The shaded red zone delimits the recommended threshold of *[CO2]*≃300 ppm for a pandemic situation in Spain.

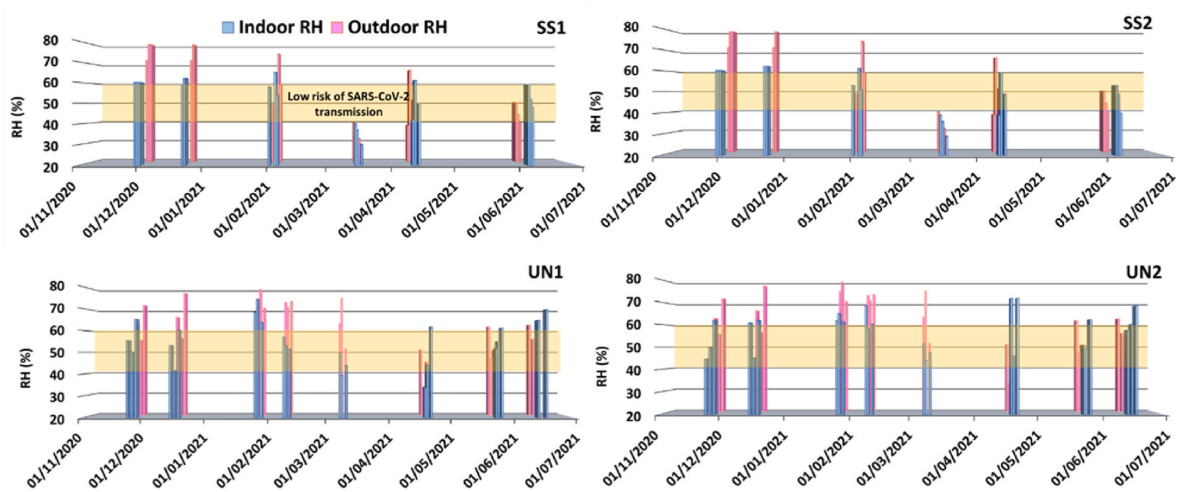

Fig. 3. Time evolution of indoor RH compared with outdoor levels. The shaded zone delimits the indoor relative humidity with low risk of SARS-CoV-2 transmission.

Table 3
Percentage of occupied time in which the values of thermal comfort, expressed as the % predicted of dissatisfied, and thermal stress are in the appropriate range.

		Predicted Percentage of Dissatisfied[a]				Thermal Stress[b]		
Classroom	m^2 per occupant	% in CAT B (≤10%)	% Per cold (*PMV* < −0.5)	% Thermal neutrality	% Per hot (*PMV* > +0.5)	% in range 17–27 °C	% <17 °C	% >27 °C
SS1	9.1 ± 2.8	0.0	78.6	0.0	21.4	71.4	21.4	7.1
SS2	20.3 ± 6.4	7.1	71.4	7.1	21.4	64.3	14.3	21.4
UN1	11.3 ± 5.3	40.0	55.0	45.0	0.0	70.0	30.0	0.0
UN2	16.3 ± 7.4	18.8	81.3	18.8	0.0	68.8	31.3	0.0

[a] [52].
[b] [55].

thermal limit on the 7-point scale of Predicted Mean Vote (*PMV*), which is between −0.5 (slightly cool) and 0.5 (slightly warm).

In general, there was a low percentage of the time of occupation in which the occupants could be in thermal comfort conditions, given the higher requirements of ventilation due to the sanitary situation. This could be observed especially in the SS classrooms, where the percentage of hours outside CAT B was greater than 90%, especially in winter season, as well as in summer and spring seasons in a lower grade.

The difference of around 7% both in thermal stress and in thermal comfort between SS1 classroom and SS2 may be due to different location of the classrooms in the building (SS1 in the basement and SS2 on the second floor). The air temperature values tended to be lower and more stable in SS1 classroom (18.4 ± 3.7 °C compared to 19.3 °C±4.2 °C), despite its higher occupancy density. Thus, the thermal results in summer conditions were more favorable in the SS1 classroom (period in which no thermal treatment was carried out in either of the two classrooms), while the SS2 classroom obtained slightly better results in winter and mid-season.

In the case of the university classrooms under study, there was a slightly higher percentage of values in CAT B of thermal comfort (18.8–40.0% of time in CAT B), especially for UN1 (40%), with a higher occupancy density (but lower than in the case of the SS1 classroom). These values are not adequate either, as they are outside the thermal comfort range most of the time. UN2 classroom, equipped with a controlled mechanical ventilation system, has a lower percentage of thermal neutrality than UN1, since it has both a lower occupation density and a constant supply of outdoor air flow without heat recovery. When heat stress in university classrooms is analyzed, it can be seen that there are no heat stress situations, because there is a cooling system operating in both spaces, unlike in SS classrooms. In addition, UN classrooms were not heated by HW radiators but warm air systems, also having a higher ventilation than in the case of the SS classrooms (average $\Delta[CO_2]$ value of 97 ppm in UN compared to 144–220 ppm in SS). Therefore, the estimated values of operating temperature in the UN classrooms (and thus thermal stress) were slightly lower in winter and mid-season than in SS classrooms.

3.1.3. Estimation of the relative infection risk by SARS-CoV-2

The obtained mean values of H_r and *AR* parameters per classroom are listed in Table 4 (Alpha) and Table 5 (Omicron BA.1) for all study cases, while Table 6 presents the percentage of occupied time with an *AR* value over 5, 10 and 20%, per variant, classroom and case study. More information is provided in Supplementary material 2. An example of the relationship between mean values of H_r and *AR* per case, variant and day for the worse scenario (classroom SS1) is also shown in Fig. 4. This figure also includes some of the main documented COVID-19 outbreaks (Wild-type) which were previously used to validate the calculation methodology by Peng et al. [33,59].

Despite the difference in the air volume per occupant in the classroom, the estimated H_r values from the UN classrooms under study were similar in the four cases investigated here (240 min event duration). There is a low risk (Alpha)/medium-low risk (Omicron BA.1) of aerosol transmission when the infected person by SARS-CoV-2 is a student, with or without masks. This risk increases to a medium-high (Alpha)/high probability (Omicron BA.1) of an outbreak if the infected person is the teacher, given vocalization activity. Whether they do not wear a mask, *AR* would be over 7%/10% (Alpha and Omicron BA.1, respectively), while it decreases down to 4%/7% (Alpha and Omicron BA.1, respectively) if they wear a surgical mask. For the classroom with mechanical ventilation (UN2), the relative risk values for both variants are lower and with a smaller deviation of the mean, since the mechanical ventilation system guarantees a constant flow of fresh air.

In the SS classrooms (330 min event duration, 37% longer than in UN classrooms), even though there was a greater variability in the ratio of air volume per occupant (higher for the SS2 classroom), a higher risk of outbreak (*AR*>5% for Alpha and *AR*>8% for Omicron BA.1) was found when one of the students is infected and nobody is wearing a mask. The relative risk lowers to medium risk (Alpha)/medium-high risk (Omicron BA.1) when the occupants used surgical masks. When it is considered that the infected person is the teacher, the risk —with or without masks—was significantly increased, with attack rate values around 35%/50% without masks (Alpha and Omicron BA.1, respectively), and 20%/30% with a surgical mask. This increase in *AR* is due to the different vocalization activity of the teacher, as in the previous cases of the secondary school. It should be noted that the risk values for SS2 classroom are higher than those for SS1, because the average $\Delta[CO_2]$ values (220 ppm in SS1 compared to 144 in SS2) are proportionally higher with respect to the occupancy (21 people in SS1 compared to 11 people in SS2), which indicates a lower dilution due to ventilation.

3.2. Air quality in the classrooms

3.2.1. O_3 and NO_2 concentrations

In the SS1 classroom, the maximum monthly indoor O_3 value reached in April and June was 58.9 μg/m^3, while in SS2 this value was much higher (100.1 μg/m^3 in June), being the outdoor level 115.8 μg/m^3 (Table S1). This value was achieved because SS2 had better ventilation favored by bigger windows, and exceeded the allowable limit 8 h mean concentration of 100 μg/m^3, recommended by the updated air quality guidelines [85]. O_3 is recognized to cause acute and chronic health effects, even at low amounts [86], and induces reactions with a negatively impact on IAQ since they produce secondary pollutants such

Table 4

Mean values of Attack Rate (*AR*) and Relative Risk of infection (H_r) of SARS-CoV-2 (Alpha) per classroom and case, based on indoor boundary conditions.

		Indoor mean boundary conditions					Case 1a		Case 1b		Case 2a		Case 2b	
		Occupants	Volume per occupant (m^3/occupant)	*Ta* (°C)	*RH* (%)	$\Delta[CO_2]$ (ppm)	Teacher - surgical mask		Teacher - no masks		Student - surgical mask		Student - no masks	
							AR (%)	H_r (h^2/m^3)	*AR* (%)	H_r (h^2/m^3)	*AR* (%)	H_r (h^2/m^3)	*AR* (%)	H_r (h^2/m^3)
SS1 (330 min)	Mean value	21	9.1	18.4	53	220	18.0	0.0251	32.2	0.0496	2.6	0.0033	5.1	0.0065
	Deviation	±4	±2.8	±3.7	±10	±108	±6.1	±0.0098	±9.6	±0.0193	±0.9	±0.0012	±1.8	±0.0023
SS2 (330 min)	Mean value	11	20.3	19.3	51	144	23.0	0.0329	40.0	0.0649	3.3	0.0042	6.4	0.0083
	Deviation	±3	±6.4	±4.2	±11	±57	±5.8	±0.0095	±8.9	±0.0188	±0.9	±0.0011	±1.7	±0.0022
UN1 (240 min)	Mean value	47	11.3	19.2	53	97	4.0	0.0052	7.6	0.0099	0.6	0.0007	1.1	0.0014
	Deviation	±17	±5.7	±3.0	±10	±57	±2.4	±0.0031	±4.7	±0.0064	±0.3	±0.0004	±0.6	±0.0008
UN2 (240 min)	Mean value	55	16.3	18.2	57	97	3.5	0.0044	6.7	0.0087	0.5	0.0006	0.9	0.0011
	Deviation	±21	±7.4	±2.4	±10	±24	±1.3	±0.0017	±2.4	±0.0033	±0.2	±0.0002	±0.3	±0.0004

Table 5
Mean values of Attack Rate (*AR*) and Relative Risk of infection (H_r) of SARS-CoV-2 (Omicron BA.1) per classroom and case.

		Case 1a		Case 1b		Case 2a		Case 2b	
		Teacher - surgical mask		Teacher - no masks		Student - surgical mask		Student - no masks	
		AR (%)	H_r (h^2/m^3)	*AR* (%)	H_r (h^2/m^3)	*AR* (%)	H_r (h^2/m^3)	*AR* (%)	H_r (h^2/m^3)
SS1 (330 min)	Mean value	28.0	0.0251	47.1	0.0496	4.3	0.0033	8.3	0.0065
	Deviation	±8.7	±0.0098	±11.8	±0.0193	±1.5	±0.0012	±2.8	±0.0023
SS2 (330 min)	Mean value	35.1	0.0329	56.9	0.0649	5.5	0.0042	10.5	0.0083
	Deviation	±8.1	±0.0095	±10.5	±0.0188	±1.4	±0.0011	±2.7	±0.0022
UN1 (240 min)	Mean value	6.6	0.0052	12.2	0.0099	0.9	0.0007	1.8	0.0014
	Deviation	±3.8	±0.0031	±7.3	±0.0064	±0.5	±0.0004	±1.0	±0.0008
UN2 (240 min)	Mean value	5.7	0.0044	10.9	0.0087	0.8	0.0006	1.5	0.0011
	Deviation	±2.1	±0.0017	±3.8	±0.0033	±0.3	±0.0002	±0.5	±0.0004

Table 6
Percentage of occupied time with an Attack Rate (*AR*) value over 5, 10 and 20%, per classroom and case.

		Case 1a Teacher - surgical mask		Case 1b Teacher - no masks		Case 2a Student - surgical mask		Case 2b Student - no masks	
		% Occupied time		% Occupied time		% Occupied time		% Occupied time	
		Alpha	Omicron BA.1	Alpha	Omicron BA.1	Alpha	Omicron BA.1	Alpha	Omicron BA.1
SS1 (330 min)	***AR* > 5%**	**100**	**100**	**100**	**100**	**0**	**29**	**41**	**100**
	AR > 10%	100	100	100	100	0	0	0	29
	AR > 20%	29	88	100	100	0	0	0	0
SS2 (330 min)	***AR* > 5%**	**100**	**100**	**100**	**100**	**0**	**59**	**75**	**100**
	AR > 10%	100	100	100	100	0	0	0	59
	AR > 20%	65	100	100	100	0	0	0	0
UN1 (240 min)	***AR* > 5%**	**25**	**60**	**70**	**85**	**0**	**0**	**0**	**0**
	AR > 10%	0	20	25	60	0	0	0	0
	AR > 20%	0	0	0	20	0	0	0	0
UN2 (240 min)	***AR* > 5%**	**6**	**59**	**76**	**100**	**0**	**0**	**0**	**0**
	AR > 10%	0	6	6	59	0	0	0	0
	AR > 20%	0	0	0	6	0	0	0	0

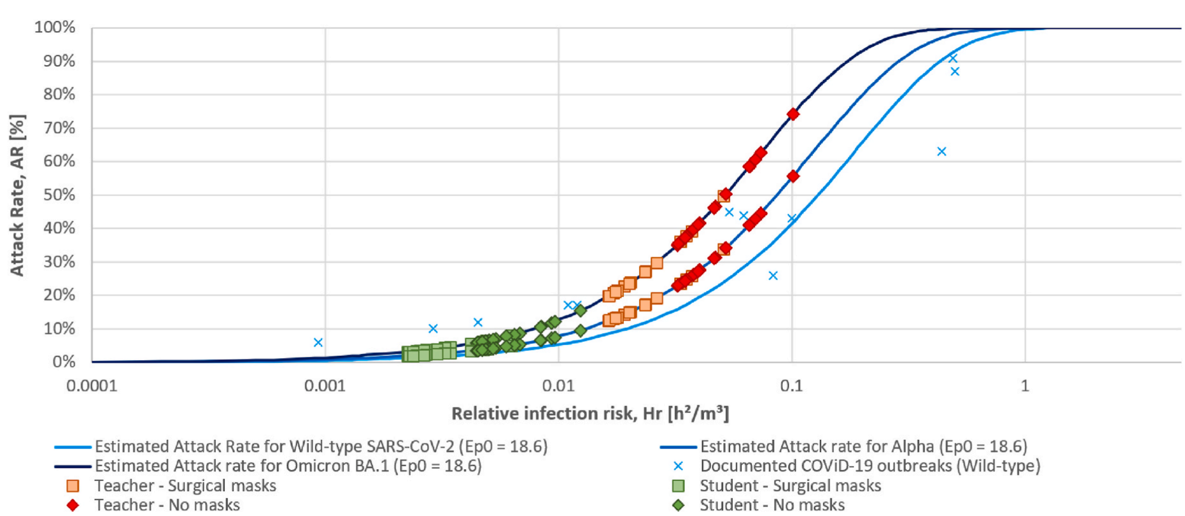

Fig. 4. Example of the relationship between AR and H_r in the worse scenario at the SS1 classroom, both for Alpha and Omicron BA.1 variants.

as submicron particles [87]. Regarding the university classrooms, mean values of O_3 concentrations in UN1 were slightly higher than for the mechanically ventilated classroom, UN2. The peak ozone concentration was reached with values of 72.6 μg/m^3 in January (outdoor 74.6 μg/m^3) for UN1, and 64.8 μg/m^3 in May (outdoor 97.5 μg/m^3) for UN2 (see Table S1). O_3 is an atmospheric trace gas formed from reactions between NO_x and volatile organic compounds (VOCs) in the presence of sunlight [88]. Consequently, outdoor is the most common source of O_3 in indoor environments [89]. The outdoor O_3 concentration tends to vary seasonally, being maximum during the summer and early fall months. However, in wintertime high surface O_3 levels can also be observed in the early morning. This increase in O_3 concentrations is due to the mixing between air aloft and the surface caused by inversion conditions. Moreover, the transport of ozone and its precursors downwind from industrial areas is also possible [90].

As shown in Fig. 5, the I/O ratios were found to range between 0.5 and 0.95, indicating that the source of O_3 in the classrooms was predominantly external rather than being formed from any internal source. This agrees with other previous estimations [91]. Indeed, in the studied classrooms, no additional indoor sources of O_3 (e.g., air purifiers, laser printers, photocopiers) were present. Depending on the air exchange rate and the ozone removal rate, indoor O_3 concentrations are expected to be 20%–60% of outdoor levels when specific indoor sources are not present [92]. Occasionally, values close to 1 were measured in UN2.

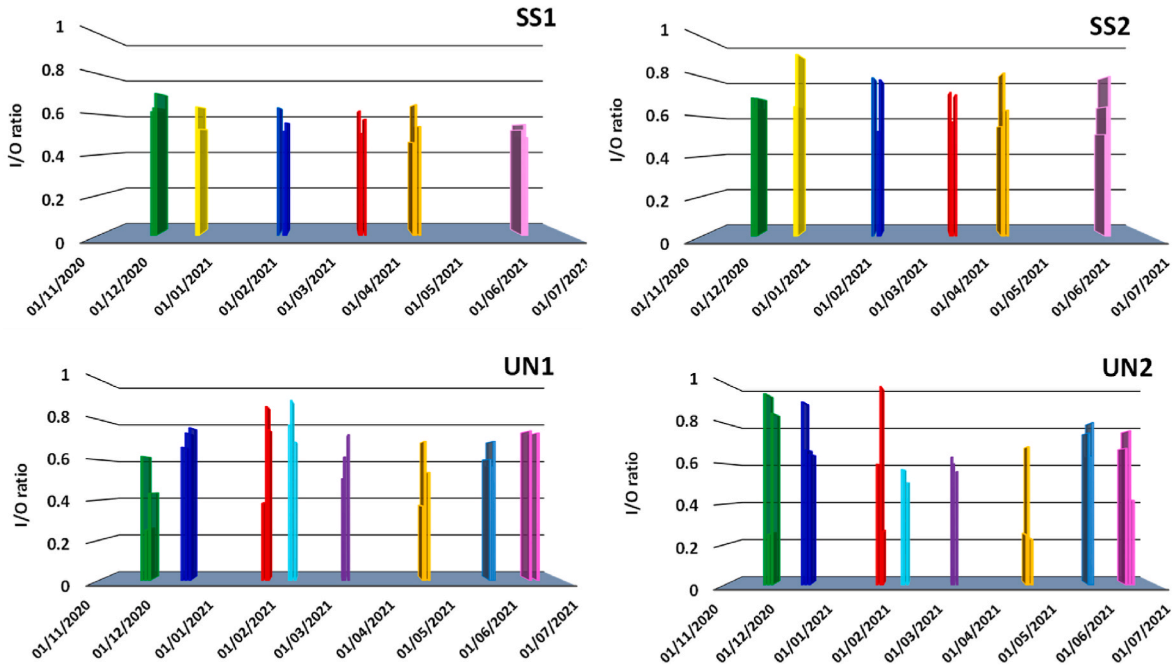

Fig. 5. Temporal evolution of the indoor/outdoor ratio for the O_3 concentration.

NO_2 levels measured were mostly below the detection limit of the apparatus (i.e., 9 μg/m^3); however, occasionally, the registered values were above the WHO guideline of 25 μg/m^3 for the daily mean concentration (Table S1). Higher values were measured at secondary school, especially in SS1, with a maximum concentration of 84.7 μg/m^3 in November, while outside was 44.2 μg/m^3. At the university campus, the NO_2 concentrations were lower, similar for both classrooms, except for November maximum indoor values (39.5 μg/m^3) at UN1 which exceeded outdoors (14.0 μg/m^3).

NO_2 is linked to negative health effects even at levels within ambient air quality standards European Directive 2008/50/EC or WHO guidelines [93]. Indoor NO_2, especially in urban areas, is normally influenced by on-road traffic and industries [94,95]. However, higher NO_2 concentrations can generally be found in outdoor air compared to indoor air, if no specific indoor sources are available [96]. As described in Section 2.1, the traffic near the secondary school was heavier than in the campus, where the use of vehicles is restricted. Therefore, in the secondary school classrooms, higher NO_2 concentration was detected, particularly at SS1 classroom in November. Apart from the outdoor source of NO_2, possibly the cafeteria (gas cooking), and the gasoil boiler room, that were on the same floor (basement), may have increased the indoor levels of this pollutant at SS1.

3.2.2. *Particle concentration*

The measured indoor levels of $PM_{0.3}$ and $PM_{0.5}$ were generally low, except for November and February in all classrooms (Table S1). Overall, secondary classrooms presented higher fine particle values than university classrooms. SS1 reached the maximum value of 1.14 μg/m^3 for $PM_{0.3}$ in November, while outdoors was 0.45 μg/m^3. An important contribution of fine PM could be either of primary origin (mainly emitted during combustion processes) or of secondary origin, resulting from photochemical reactions [97–100]. Oxidants can react with specific VOCs, both outdoor (if the reaction rate in faster than air exchange rate) and indoor [101]. For example, at indoor, the VOCs components of the spray disinfectant [102] could generate products with a range of volatilities, and the use of these was observed especially at SS1. The less volatile products condense on existing particles or nucleate, producing secondary organic aerosols (SOAs). These SOAs are typically ultrafine particles (<0.1 μm diameter) [103–105], which further grow forming larger particles, such as $PM_{0.3}$ and $PM_{0.5}$. The production of this kind of particles could vary with oxidants concentration and be episodic, such as during the use of scented cleaning products [106]. Regarding the I/O ratio, it was heterogeneous for $PM_{0.3}$ and $PM_{0.5}$, being lower than 1 in most cases for $PM_{0.3}$ at UN2 and $PM_{0.5}$ at SS2 (Fig. 6 and Figs. S1 and S2 of the Supplementary Material 3). Regarding $PM_{2.5}$, secondary school classrooms showed the highest levels, which exceeded in most cases the recommended daily limit concentration of 15 μg/m^3 by the WHO [85] (Table S1). The maximum monthly indoor concentration was achieved in April (40 μg/m^3) in the SS1 for $PM_{2.5}$, being higher than outdoors (12 μg/m^3). Conversely, at the university the maximum $PM_{2.5}$ limit was exceeded only in December.

Regarding coarse particle PM_{10}, in none of the classrooms was surpassed the daily WHO limit recommended concentration of 45 μg/m^3. Furthermore, in the UN2 classroom (mechanically ventilated) the overall values were the lowest registered, except for December with 35 μg/m^3 when outdoors was 65 μg/m^3. Exposure to PM has been associated with adverse health outcomes which depends not only on its mass concentration, but also on many other properties such as size and chemical composition [107]. Fine and coarse mode particles differ not only in size and morphology, but also in formation mechanisms, sources, physical and biological properties. The use of chalk on blackboards (face-to-face teaching) in the SS1 classroom, but also to the contribution of the incoming PM from the cafeteria (cooking) could influence in those values. Moreover, the students' movement could lead to the re-suspension of settled particles and could affect indoor PM levels through personal clouds [108–111]. Furthermore, the use of ethanol-based disinfectant sprays generates inhalable coarse particles ($PM_{2.5\text{-}10}$) [112]. In the SS classrooms, a sanitizer spray was used by the teachers, especially in SS1, to disinfectant the furniture. Regarding the university classrooms, mean values of PM concentrations in UN1 were higher than for the mechanically ventilated classroom UN2.

The daily average I/O ratios for $PM_{2.5}$ and PM_{10} were found to be principally >1 in all the classrooms (lower in the UN2-mechanical ventilation which would indicate that it works for these sizes of PM, Fig. S3), showing that the PM formation was mostly indoor (Fig. 6 and Figs. S1 and S3 of the Supplementary Material 3). As an example, Fig. 6 shows the temporal evolution of the I/O ratio for the PM concentration in SS1 classroom.

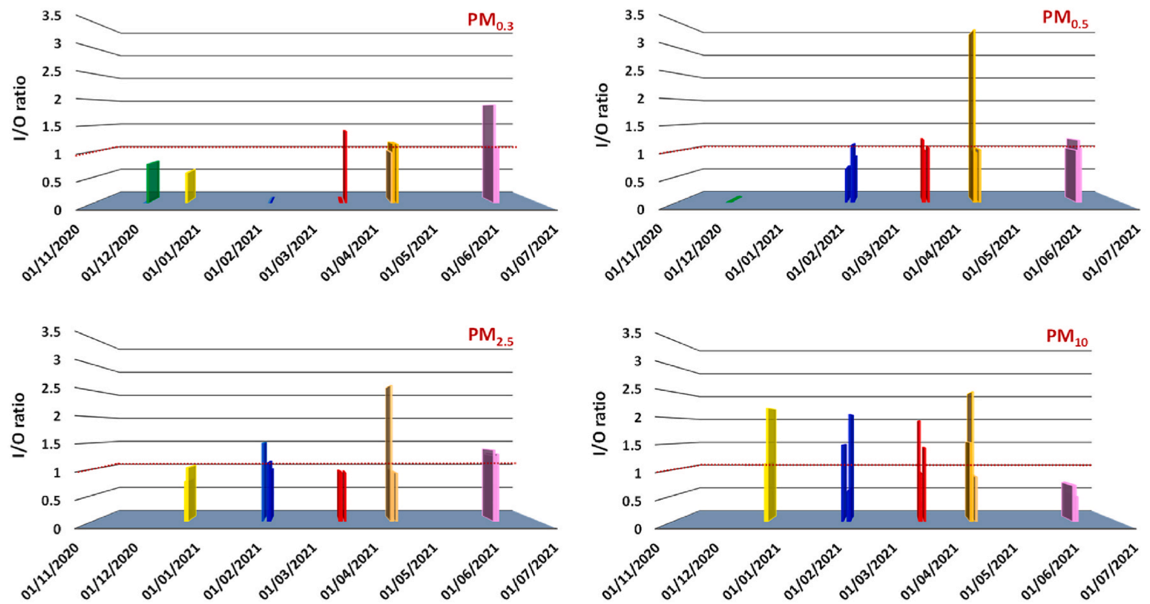

Fig. 6. Temporal evolution of the I/O ratio for the PM concentration in the SS1 classroom.

4. Conclusions

The present study shows that in all investigated classrooms the indoor CO_2 concentration did not exceed the recommended limit of 700 ppm, except for the SS1 classroom in November 2020 (natural ventilation was initially discontinue) and in June 2021 (no teaching and students were playing in the classroom). After this assessment, the ventilation conditions in SS1 were improved at the expense of thermal comfort, given the inability of the buildings' heat treatment systems to meet the increase in heat demand -especially in the case of the secondary school. Thus, their occupants were outside the range of thermal comfort during practically all the occupied time, and they were also subjected to thermal stress conditions 20% of that time. However, the estimated relative risk of SARS-CoV-2 transmission (Alpha and Omicron BA.1 variants) in the classrooms under study was medium when no one was wearing masks, being increased to medium-high (Alpha) and high risk (Omicron BA.1) when the teacher was considered as the infectious occupant, given the higher level of vocalization. The use of mechanical ventilation in the university classroom UN2 contributed to reduce the percentage of time under thermal stress conditions, while maintaining an acceptable risk of transmission —low or medium—, especially when the use of masks was considered. The estimated relative risk was only considered high when the teacher —without a mask— was defined as the infectious occupant.

Overall, the IAQ measured inside the classrooms was good. Nonetheless, it was worse in the high school classrooms than in the university. Indoor O_3 levels were lower than the corresponding outdoor levels in all the classrooms since there were no internal sources. NO_2 levels were higher at secondary school due to traffic and the internal sources such as cafeteria and gasoil boiler room, exceeding in some cases the daily value established by the WHO. The presence of important indoor sources of fine and coarse particles markedly increased PM levels during class hours, with a major impact on the $PM_{2.5}$ fraction. In several cases, indoor $PM_{2.5}$ exceeded the corresponding daily guideline values established by the WHO. $PM_{0.3}$ and $PM_{0.5}$ indoor levels were principally affected by indoor sources in all the classrooms, although mean values were measured to be low.

In conclusion, buildings play a critical role in minimizing, or conversely exacerbating, the spread of airborne infectious diseases. Proper ventilation is hence a key prevention strategy for maintaining healthy environments and, along with other preventive actions, can reduce the likelihood of spreading airborne diseases. Note that, depending on the area, IAQ can be strongly affected by outdoor pollution when a room is naturally ventilated. In the classroom with mechanical ventilation (UN2), as the outdoor air was partially filtered, the levels of pollutants were generally lower than in UN1. Consequently, controlled mechanical ventilation systems are essential in educational spaces, including outdoor air filtration and air-to-air energy recovery to limit the entry of external PM and minimize both energy consumption and thermal stress. Moreover, wearing well-fitting FFP2–N95 masks indoors is also highly recommended during periods of high transmission, especially by teachers, as fundamental combined measure to reduce the risk of contagion of the most recent Omicron BA.1 variant to acceptable values ($AR<0.5\%$), even with average CO_2 differentials below 300 ppm (optimal air quality in terms of CO_2 concentration).

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CRediT authorship contribution statement

Diana Rodríguez: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis. **Itziar R. Urbieta:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis. **Ángel Velasco:** Writing – review & editing, Supervision, Project administration, Formal analysis. **Miguel Ángel Campano-Laborda:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis. **Elena Jiménez:** Writing – review & editing, Writing – original draft, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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