

Article

Experimental Assessment of Mechanical Ventilation Strategies on Indoor Air Quality in a School Classroom

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Abstract

Indoor air quality in school classrooms is strongly influenced by ventilation strategies, which in most existing buildings rely on manual window opening rather than controlled mechanical systems. This study investigates real indoor CO₂ conditions in an Italian secondary school classroom equipped with a decentralised heat recovery ventilation unit (HRV) and evaluates the effectiveness of an automated control strategy in improving air quality. Continuous CO₂ monitoring was conducted over two consecutive school years using calibrated sensors. During the first year, ventilation management was left entirely to occupant discretion; in the second, an automated scheduling strategy was implemented via a low-cost smart plug, progressively extending daily HRV operation from 1.5 to 5.0 h across the winter months. During the uncontrolled year, the HRV was never activated despite being installed, and 3.92% of total teaching time during the winter season was spent under Category IV conditions ($\Delta\text{CO}_2 > 1350$ ppm). The automated strategy during the winter reduced Category IV exposure to 1.63% and was associated with a 32.3% reduction in student absences. These findings confirm that the primary barrier to effective mechanical ventilation in schools is not hardware availability, but the absence of a structured operational strategy.

Keywords: indoor air quality; school classrooms; carbon dioxide; mechanical ventilation; occupant behavior; experimental

1. Introduction

The quality of indoor air in school buildings has become a subject of increasing scientific and practical relevance, driven by the substantial time that students and teachers spend inside classrooms and by the well-documented influence of indoor environmental conditions on occupant health, comfort, and cognitive performance [1,2].

Classrooms represent particularly sensitive environments: high occupant density, extended lesson duration, limited operational flexibility, and the frequent absence of purpose-designed mechanical ventilation systems all contribute to indoor pollutant accumulation and make it difficult to maintain stable air quality conditions throughout the school day [3]. The COVID-19 pandemic amplified awareness of ventilation in educational settings and prompted a broader reassessment of school building operation [3,4]. However, the underlying challenges—inadequate air exchange, occupant-driven ventilation behaviour, and the absence of continuous monitoring—predate it and remain largely unresolved in a significant portion of the existing school building stock [5].



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Among the indicators used to assess Indoor Air Quality (IAQ), carbon dioxide (CO_2) concentration plays a central role, serving as a simple yet effective proxy for the adequacy of ventilation relative to occupancy levels [6,7]. In school environments, where occupants represent the dominant emission source, CO_2 monitoring provides an immediate means of identifying insufficient ventilation conditions and comparing different air renewal strategies [7].

The European standard EN 16798-1 classifies indoor air quality as a function of the CO_2 increment above outdoor concentrations (ΔCO_2), defining four categories: Category I ($\Delta\text{CO}_2 \leq 550$ ppm), Category II ($\Delta\text{CO}_2 \leq 800$ ppm), Category III ($\Delta\text{CO}_2 \leq 1350$ ppm), and Category IV ($\Delta\text{CO}_2 > 1350$ ppm), the latter indicative of severely degraded air quality [8]. This classification is reported in Figure 1.

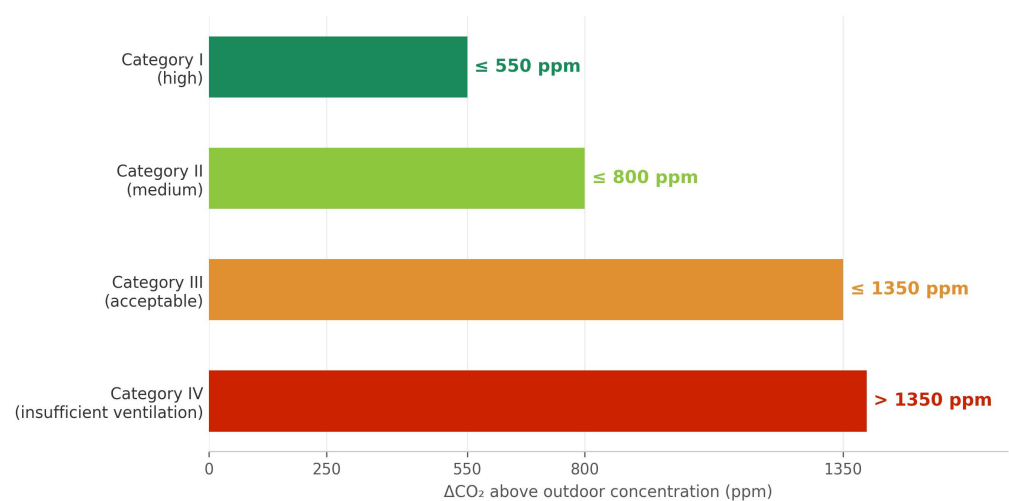


Figure 1. Indoor air quality categories according to EN 16798-1 [8].

However, these benchmarks are mainly design parameters for HVAC systems and are rarely verified under actual seasonal operation [9]. In several European countries, including Italy, no universally enforced CO_2 limit applies in school classrooms, and compliance with ventilation requirements is seldom subject to continuous monitoring [10].

The interest in limiting CO_2 concentrations in schools is closely linked to cognitive performance and learning quality: elevated CO_2 levels correlate with reduced decision-making ability, impaired attention, and decreased perceived wellbeing [11,12]. For instance, in the COGfx Study, Allen et al. found that increasing CO_2 from 550 to 950 ppm was associated with an approximately 15% reduction in decision-making performance, while 1400 ppm produced larger impairments, up to 40–50% in some higher cognitive function metrics [12]. Wargocki and Wyon demonstrated that improving classroom ventilation increased pupils' work performance [13], while Fisk linked poor ventilation to absenteeism and lower academic outcomes [14]. Haverinen-Shaughnessy et al. further quantified this relationship, finding that each 1 L/s per person increase in ventilation rate was associated with a 1.6% reduction in illness-related absenteeism across 162 monitored elementary school classrooms [15]. Although these findings cannot be directly generalised to all classrooms, they support CO_2 containment as a relevant management objective in learning environments.

In the existing school building stock, ventilation is commonly maintained through natural ventilation strategies, relying primarily on manual window opening and, in some cases, door opening [16,17]. This approach is simple and inexpensive, but strongly dependent on occupant behaviour, classroom layout, and external climate [18]. Literature has repeatedly highlighted the limitations of ventilation strategies based solely on human action: scheduled opening can improve conditions but requires sustained engagement and

is difficult to maintain without automation or sensor support [19,20]. Freeman et al. [20] found that spontaneous window opening left to teachers' discretion often leads to elevated CO₂ peaks during maximum occupancy. Real-time CO₂ feedback can improve ventilation behaviour, although its effect tends to diminish without structural reinforcement [15,21].

Climatically unfavourable periods add further constraints. In winter, window opening can create local thermal discomfort and cold draughts near glazed surfaces [22], while in urban settings it may increase indoor noise to levels incompatible with teaching [23]. Natural ventilation therefore depends on a fragile balance between air renewal needs and occupants' preference for immediate thermal and acoustic comfort [24].

In this context, decentralised heat recovery ventilation units (HRV) represent one of the most promising solutions for improving air quality in existing school buildings, as they allow air renewal to be decoupled from manual window operation without requiring extensive ductwork installation [25,26]. Yet their mere presence does not guarantee expected outcomes: user behaviour, activation logic, schedules, noise perception, and energy concerns can strongly affect real performance [27,28]. The relationship between system availability and actual management in schools remains insufficiently addressed [29]. Even technically adequate units may provide only partial or intermittent benefits if left to unstructured manual activation [30,31].

Against this background, the present study experimentally investigates a real Italian secondary school classroom equipped with a decentralised HRV unit, over two consecutive school years. During the first year, air renewal was left entirely to occupant discretion. In the second year, an automated control strategy was progressively introduced and optimised. The original contributions of this work are fourfold. (1) The study provides a two-year experimental characterisation of indoor CO₂ conditions in a real occupied classroom, documenting in quantitative terms the occupant behaviour patterns that govern ventilation in the absence of a structured control strategy. (2) A systematic measurement campaign was conducted to quantify the ventilation flow rates associated with all available air renewal mechanisms in the monitored space—including envelope infiltration, door diffusion, mechanical ventilation at all three speed levels, and window opening under varying outdoor boundary conditions—providing a comprehensive hierarchy of ventilation potential rarely reported in the existing literature at this level of detail. (3) A statistically significant correlation between mean outdoor temperature and mean indoor CO₂ concentration was identified and quantified, confirming the seasonal predictability of air quality risk in naturally ventilated classrooms. (4) The study demonstrates that the primary barrier to effective mechanical ventilation in school buildings is not the absence of suitable hardware, but the absence of a structured operational strategy: the same HRV unit that remained unused for three years under unmanaged conditions delivered a 58% reduction in Category IV exposure once operated through a simple automated scheduling logic.

The paper is organised as follows. Section 2 describes the experimental setup and instrumentation. Section 3 presents the ventilation characterisation methodology. Section 4 analyses the results from the uncontrolled year. Section 5 presents the outcomes of the controlled year. Section 6 discusses the results of the experimental activity. Section 7 reports the conclusions of the paper.

2. Materials and Methods

This section describes the experimental setting, the measurement instrumentation, and the monitoring protocol adopted for the two-year campaign. The study site and its climatic context are presented first, followed by a description of the sensor network, the mechanical ventilation system, and the experimental design.

2.1. Study Site and Climatic Context

The experimental campaign was carried out in a classroom of a state secondary school located in Ascoli Piceno, in the Marche Region of central Italy (latitude 42.85° N, longitude 13.57° E, altitude 154 m a.s.l.). The site falls within Italian climate zone D, with a degree-day value of 1698, characterised by cold winters and mild springs. During the monitored school periods, mean outdoor temperatures recorded over the day ranged approximately between 4 °C in winter months and 18 °C in spring, providing a varied climatic backdrop against which ventilation behaviour and indoor air quality could be assessed across different seasonal conditions.

The monitored classroom is located on the second floor of a three-storey school building with four exposed façades. The layout of the classroom is presented in Figure 2. Its rectangular floor plan measures 5.85 m × 9.20 m, yielding a usable area of approximately 54 m² and, combined with an internal height of 3.30 m, a total volume of 178 m³. Three hot-water radiators, positioned beneath the glazed surfaces, provide space heating and generate vertical convective airflows along the façades. The room features three sliding windows oriented towards the South–South–West ($\approx 160^\circ$), each measuring 1.70 m × 1.50 m with approximately 50% openable area, and two outward-opening doors on the opposite side, oriented towards the North–North–West ($\approx 340^\circ$), each measuring 2.15 m × 0.90 m and communicating with the internal corridor (Table 1). The windows overlook a large internal courtyard of approximately 100 m × 50 m, which provides good exposure to natural wind-driven ventilation. However, the surrounding residential buildings partially shield the courtyard, potentially reducing the effective wind pressure available at the façade under certain wind direction conditions.

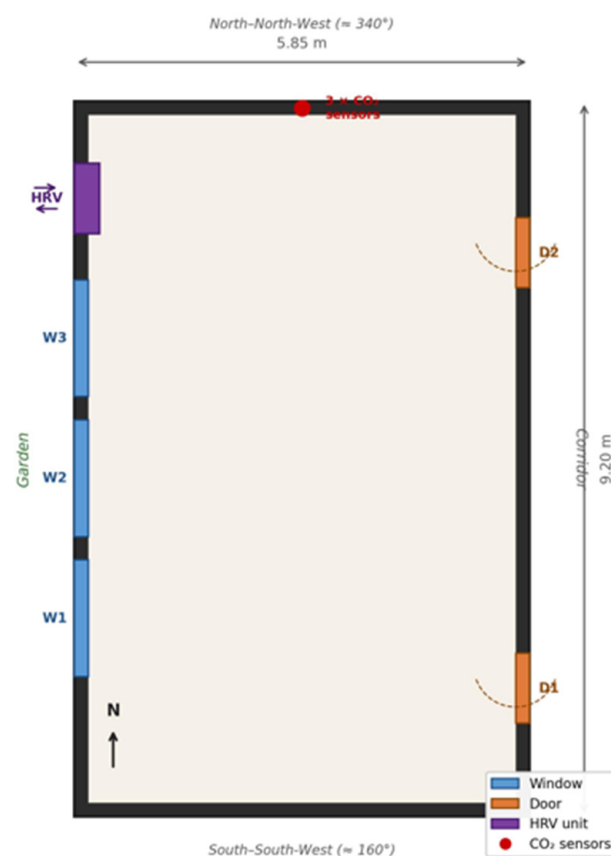
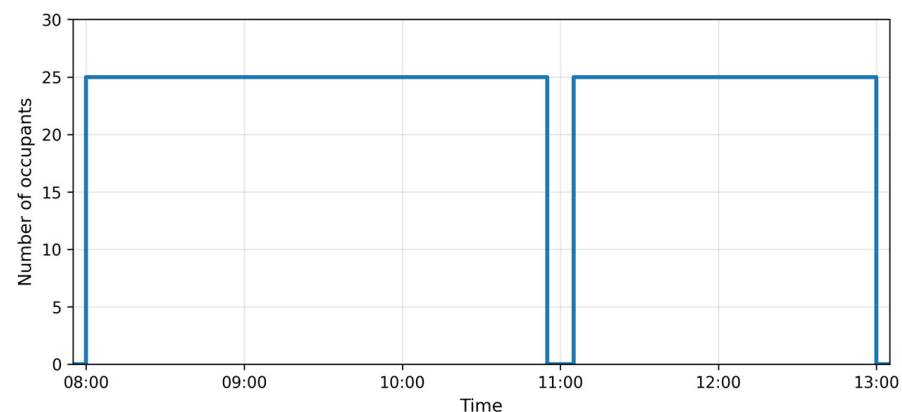


Figure 2. Plan view of the monitored classroom.

Table 1. Geometrical and architectural characteristics of the monitored classroom.

Parameter	Value
Location	Ascoli Piceno, central Italy
Latitude	42.85° N
Longitude	13.57° E
Altitude	154 m a.s.l.
Italian climate zone	D
Degree-days	1698
Mean outdoor temp	≈4–18 °C
Number of students	23
Floor plan dimensions	5.85 m × 9.20 m (53.8 m ²)
Internal height	3.30 m
Classroom volume	178 m ³
Number of windows	3
Window dimensions	1.70 m × 1.50 m
Window opening type	Sliding (≈50% openable area)
Window orientation	South–South–West (≈160°)
Number of doors	2
Door dimensions	2.15 m × 0.90 m
Door orientation	North–North–West (≈340°)

During the monitoring period, the classroom was regularly occupied by a class of 23 students (mean age approximately 13 years), accompanied by one or two teachers. This occupancy level corresponds to a density of approximately 0.43 persons/m², broadly representative of standard operating conditions in Italian secondary school classrooms. The monitored classroom was typically occupied from 08:00 to 13:00. A 10 min break was scheduled from 10:55 to 11:05, during which the average occupancy decreased to nearly zero (Figure 3).

**Figure 3.** Typical classroom occupancy profile.

2.2. Measurement Instrumentation and Data Acquisition

Indoor CO₂ concentration was measured using three HOBO MX1102A data loggers (Onset Computer Corporation, Bourne, MA, USA). These devices employ non-dispersive infrared (NDIR) sensing technology and have a declared measurement accuracy of ±50 ppm or ±5% of the reading, whichever is greater, over a measurement range of 0–5000 ppm (Table 2).

Table 2. Technical specifications of the HOBO MX1102A data loggers.

Parameter	Value
Model	HOBO MX1102A
Sensing technology	Non-dispersive infrared (NDIR)
Measured parameters	CO ₂ , air temperature, relative humidity
CO ₂ range	0–5000 ppm
CO ₂ accuracy	±50 ppm or ±5% of reading (whichever greater)
Temperature range	−20 to +70 °C
RH range	1–100%
Number of units	3

During the monitoring years, data were logged at a sampling interval of 2 min, a resolution that provides a sufficiently high-resolution time series for capturing the transient phenomena of interest. Prior to installation, all sensors were co-located outdoors under stable atmospheric conditions and simultaneously exposed to ambient air for a period of approximately 10 min, sufficient to verify mutual consistency and establish a common baseline. The mean outdoor CO₂ concentration recorded during this calibration procedure was approximately 450 ppm, a value consistent with current background concentrations in peri-urban environments and adopted as the outdoor reference for the calculation of indoor CO₂ increments (ΔCO_2) in accordance with EN 16798-1 [8].

The representativeness of point CO₂ measurements was assessed through a dedicated preliminary campaign conducted over the first three months of monitoring. In a first configuration, the three sensors were deployed at the same height (approximately 2 m above floor level), each mounted at the centre of a different wall (north, south, and west), so as to characterise potential horizontal concentration gradients across the room. The simultaneous records showed a strong mutual agreement throughout the entire period. Pearson correlation coefficients between sensor pairs ranged from 0.95 to 0.98, and the coefficient of variation computed across the three measurement points remained within 5–10%, with no evidence of systematic spatial patterns. The observed inter-sensor differences were consistent with the declared instrumental uncertainty and did not suggest the presence of meaningful horizontal gradients under the monitored occupancy and ventilation conditions.

From 6 December 2024 onwards, the sensor layout was reconfigured to examine the vertical distribution of CO₂ within the occupied zone. The three devices were repositioned along a single wall at heights of 0.55 m, 1.65 m, and 2.75 m above the floor (Figure 4), spanning the full height of the room from near-floor level to the vicinity of the ceiling. The vertical campaign yielded results consistent with those obtained in the horizontal phase. Correlation coefficients remained high across all height combinations, and the spatial coefficient of variation was lower than the values recorded in the first configuration. No systematic height-dependent trend was identified, indicating that thermal stratification and buoyancy-driven CO₂ accumulation were negligible under the examined conditions. Taken together, the two campaigns confirm that the indoor air in the monitored classroom behaves as a well-mixed volume, justifying the use of a single representative measurement point for all subsequent analyses (Table 3).

Table 3. Summary of sensor comparison results under different configurations.

Configuration	Sensor Placement	Mean CO ₂ (ppm)	Pearson r (–)	CV (%)
November	Three different walls, same height (2 m)	1019	0.95–0.98	5–10
January	Same wall, 55 cm spacing	1060	0.97–0.99	3–6

CV: coefficient of variation; r: Pearson correlation coefficient.

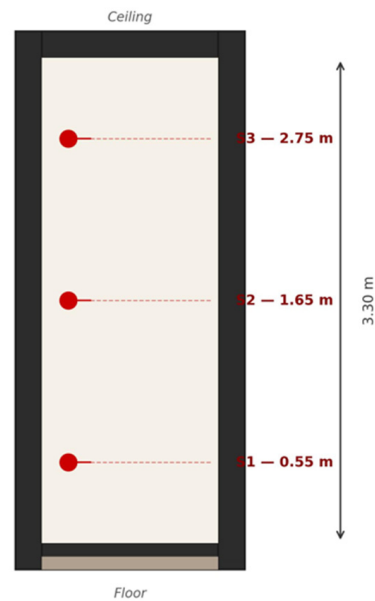


Figure 4. Elevation of the monitored classroom wall showing CO₂ sensor positions.

2.3. Mechanical Ventilation System

The classroom is equipped with a decentralised heat recovery ventilation unit (HRV), model Innova HRC+ 60 H/HV (Innova S.r.l., Storo (TN), Italy; Figure 5), installed through the perimeter wall (Figure 2) and connected to the outdoor environment via two dedicated circular ducts of 200 mm diameter, serving supply and exhaust air, respectively. The unit incorporates pleated particulate filters of class ePM1 70%, ensuring effective removal of fine particulate matter from the incoming airstream. The system operates at three discrete flow rate levels: low (165 m³/h), medium (355 m³/h), and high (620 m³/h). The declared heat recovery efficiency of the unit is 86.1%, while the sound pressure levels at 3 m distance are 33, 36, and 41 dB(A) for the three levels, respectively.



Figure 5. HRV unit installed in the monitored classroom (Innova HRC+ 60 H/HV).

2.4. Monitoring Protocol and Experimental Design

The monitoring campaign spanned two consecutive school years. During the first year, no structured control logic was applied to the HRV unit: both window opening and mechanical ventilation activation were left entirely to the discretion of the classroom occupants, reflecting a condition of unmanaged ventilation representative of common practice in Italian schools [28]. This phase allowed the characterisation of spontaneous occupant behaviour and its effects on indoor CO₂ levels across different seasons.

During the second year, a dedicated automated control strategy was progressively introduced and refined over the winter season. The control logic was calibrated on the basis of occupancy schedules and CO₂ concentration thresholds, with the aim of maintaining indoor air quality within Category III of EN 16798-1 [8] while minimising unnecessary HRV operation outside occupied hours. This two-phase experimental design enables a direct comparison between unmanaged and managed ventilation conditions within the same classroom, isolating the effect of the control strategy from confounding factors related to building characteristics and occupancy patterns.

3. Methodology

This section presents the experimental characterisation of all ventilation mechanisms available in the monitored classroom. Infiltration through the building envelope is quantified first by means of a Blower Door Test and CO₂ decay experiments, followed by the characterisation of the HRV unit, door diffusion, and natural ventilation through window opening.

3.1. Infiltration Rate Characterisation—Blower Door Test

In any enclosed space, a fraction of air renewal occurs unintentionally through gaps, joints, and discontinuities in the building envelope, including window and door perimeter seals, service penetrations, and construction joints. This phenomenon, commonly referred to as air infiltration, is governed primarily by pressure differentials between the indoor and outdoor environment, driven by wind action and thermal buoyancy [32]. To quantify the infiltration rate of the monitored classroom, a Blower Door Test was performed in accordance with standard pressurisation methodology with an Infiltec Digital Blower Door model E3-A-DM4-110/60. The test consists of inducing a controlled pressure difference across the building envelope by means of a calibrated fan system, while simultaneously measuring the airflow required to maintain each imposed pressure level. By repeating the measurement at multiple pressure steps, a characteristic infiltration curve—relating airflow to pressure differential—is obtained and used to extrapolate infiltration rates under ordinary operating conditions (Figure 6).

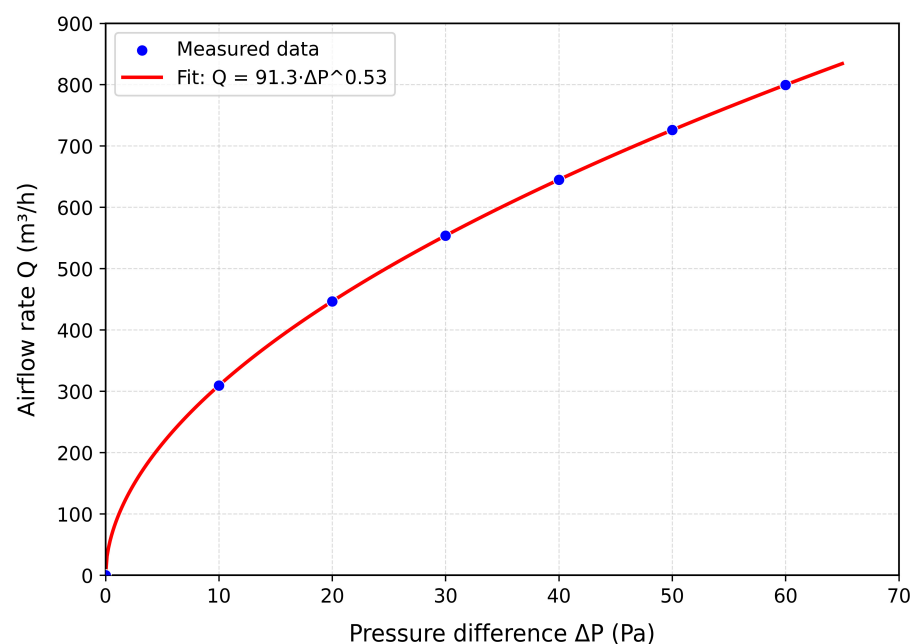


Figure 6. Blower door test curve.

To verify the consistency of the Blower Door Test estimate, two independent CO₂ concentration decay experiments were conducted under closed-envelope conditions. Two representative days were selected on the basis of low wind speed conditions, with mean outdoor wind velocities ranging between 0.2 and 0.9 m/s as recorded by the Ascoli Piceno meteorological station [33]. These calm-wind conditions were intentionally targeted to minimise the wind-driven pressure component in the infiltration rate estimate, ensuring that the measured decay curves would be predominantly governed by envelope leakage under near-still-air conditions.

Assuming a well-mixed indoor environment and negligible internal CO₂ generation after occupancy, the temporal evolution of indoor CO₂ concentration can be described by the following mass balance equation [34]:

$$\frac{dC(t)}{dt} = -\frac{Q}{V}(C(t) - C_{ext}) \quad (1)$$

where

- $C(t)$ is the indoor CO₂ concentration (ppm);
- C_{ext} is the outdoor CO₂ concentration (ppm);
- Q is the ventilation flow rate (m³/h);
- V is the room volume (m³).

The analytical solution of the equation leads to an exponential decay:

$$C(t) = C_{ext} + (C_0 - C_{ext})e^{-\frac{Q}{V}t} \quad (2)$$

where C_0 is the initial indoor CO₂ concentration at the beginning of the test.

The first decay experiment was carried out on 18 January 2025 (mean outdoor wind speed = 0.69 m/s [33]). Starting from an initial indoor CO₂ concentration of approximately 1150 ppm at 13:00, the measured decay curve showed a profile consistent with an infiltration rate of 35 m³/h that means 0.20 Air Changes Per Hour (ACH), requiring approximately 14 h to approach the outdoor reference concentration of ~500 ppm (Figure 7).

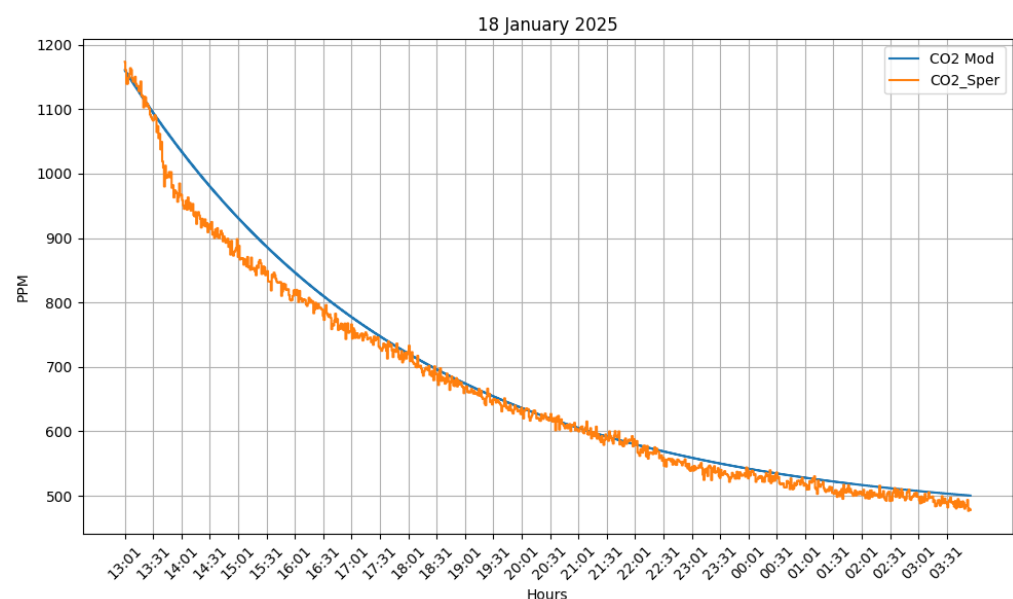


Figure 7. Decay curve to study infiltration during 10 h.

A second decay experiment was conducted on 26 October 2024 (mean outdoor wind speed = 0.83 m/s [33]), exploiting a one-hour absence of students during a physical educa-

tion lesson (Figure 8). The observed decay was again consistent with an infiltration rate of 0.20 ACH.

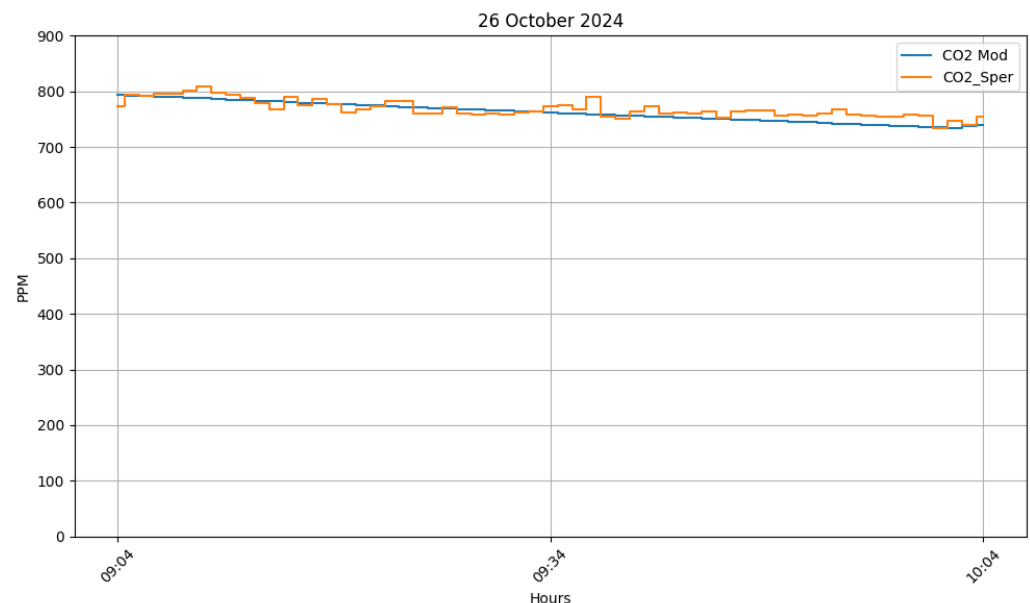


Figure 8. Decay curve to study infiltration during 1 h.

Drawing on the Blower Door Test characteristic curve, a mean wind speed of approximately 0.6 m/s acting perpendicularly on the windward façade generates an estimated pressure differential of approximately 0.21 Pa across the building envelope. Substituting this value into the characteristic curve yields an equivalent infiltration flow rate of approximately 38 m³/h, corresponding to 0.22 ACH. Analysis of wind speed records from the Ascoli Piceno meteorological station over the full monitoring period confirms that mean wind speeds during school hours typically ranged between 0.2 and 0.9 m/s [33], consistent with the conditions under which the decay experiments were conducted.

The convergence of two independent experimental methods—pressurisation testing and tracer gas decay—on a consistent infiltration rate of approximately 0.20–0.22 ACH provides reasonable confidence in the adopted value, notwithstanding the limited number of decay experiments and the use of remotely recorded wind speed data rather than on-site anemometric measurements. Given the inherent measurement uncertainty of the CO₂ sensors (± 50 ppm or $\pm 5\%$ of reading), the infiltration rate is conservatively assumed as 0.20 ACH $\pm$ 0.02 ACH for all subsequent analyses.

3.2. HVAC Ventilation

In order to establish a reliable and experimentally grounded estimate of the actual airflow delivered by the HRV unit under real operating conditions, a dedicated characterisation test was conducted on 16 March 2026, prior to the analysis of the controlled ventilation year. This step was considered necessary to verify the in situ performance of the unit relative to its nominal specifications, and to ensure that subsequent analyses of indoor air quality improvement were based on a measured—rather than assumed—mechanical ventilation flow rate.

The mean wind speed recorded at the Ascoli Piceno meteorological station on that day was approximately 0.33 m/s [33]. The test was performed at speed level 1—the lowest available operating mode—for which the manufacturer’s catalogue specifies a nominal supply flow rate of 165 m³/h. The experimental procedure followed the same concentration decay methodology adopted in Section 3.1. At the end of the school day, once all occupants had left the classroom, the HRV unit was activated at speed level 1 while

all windows and doors were maintained closed. The temporal evolution of indoor CO₂ concentration was continuously recorded until near-complete dilution to outdoor reference levels was achieved.

Since the total measured decay rate incorporates both the mechanical ventilation contribution and the background infiltration through the building envelope, the effective HRV flow rate was isolated by subtracting the previously determined infiltration term:

$$Q_{HRV} = Q_{tot} - Q_{inf} \quad (3)$$

where Q_{tot} is the total air change rate measured during the HRV experiment and Q_{inf} is the infiltration rate assumed to be equal to approximately 0.22 ACH.

The decay analysis returned a measured supply flow rate of approximately 160 m³/h at speed level 1, equivalent to 0.90 ACH referred to the total classroom volume (Figure 9). Compared to the nominal catalogue value of 165 m³/h, this corresponds to an in situ ventilation effectiveness of approximately 97%, a result well within the expected range for a wall-mounted HRV unit operating through short ductwork under realistic filter loading conditions. Starting from an initial indoor CO₂ concentration of approximately 1000 ppm, the HRV unit required roughly 3 h to dilute the indoor air to approximately 500 ppm.

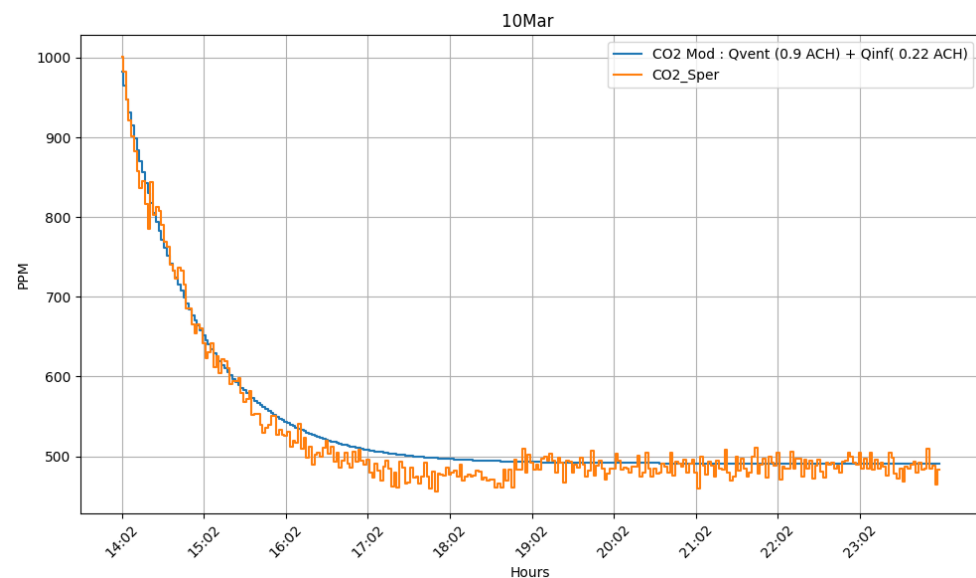


Figure 9. Decay curve to study HVR ventilation.

3.3. Doors Ventilation

When classroom windows are closed and doors connecting to the adjacent corridor are left open, the dominant air exchange mechanism shifts from convective ventilation to molecular diffusion driven by the CO₂ concentration gradient between the two communicating spaces. This process can be described by Fick's first law of diffusion [34], which expresses the CO₂ mass flux through the opening as:

$$Q_{CO_2} = D \cdot A_{door} \cdot \frac{\Delta C}{L} \quad (4)$$

where D is the molecular diffusion coefficient of CO₂ in air, assumed equal to 1.6×10^{-5} m²/s [34], A_{door} is the free cross-sectional area of the door opening, ΔC is the CO₂ concentration difference between the classroom and the adjacent corridor, and L is the characteristic diffusion path length. It should be noted that this diffusion-dominated regime is only valid when the windows on the opposite façade remain closed. If windows were simultaneously open, convective airflows would develop between the window and door

openings, establishing a cross-ventilation pattern that would overwhelm the diffusive transport mechanism.

To quantify the contribution of door opening to classroom air renewal, a dedicated CO₂ concentration decay experiment was conducted on 14 December 2024. At the end of the school day, once all occupants had vacated the classroom, both corridor doors were left fully open while all windows were kept closed. The measured decay curve exhibited a well-defined exponential profile, from which the characteristic diffusion path length L was calibrated by fitting the Fickian model to the experimental data. A value of $L = 0.001$ m was found to reproduce the observed CO₂ decay with a mean relative error of 11% over the 2.5 h simulation period. Applying the same exponential decay model (Equation (2)), the equivalent ventilation flow rate induced by door opening was determined to be approximately 0.90 ACH (Figure 10). This indicates that the air exchange induced by leaving both corridor doors open (combined free area of approximately 3.87 m², equivalent to 7.2% of the classroom floor area) produces a ventilation effect broadly comparable to that of the HRV unit operating at its lowest speed level. This finding carries a relevant practical implication: door opening represents a simple, cost-free ventilation strategy capable of delivering meaningful reductions in indoor CO₂ concentration.

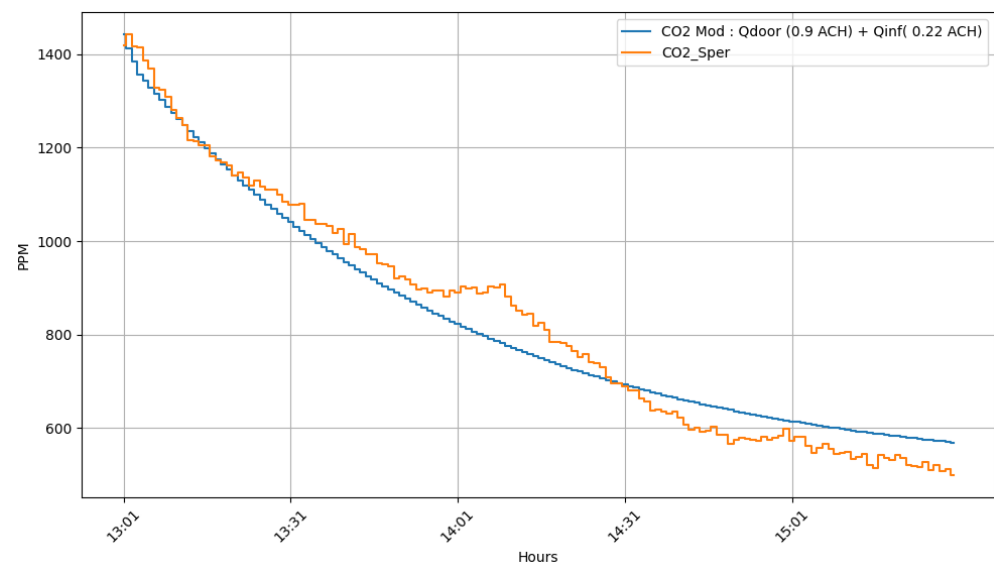


Figure 10. Decay curve to study Fick's effect at doors.

However, its actual effectiveness in real school conditions is significantly limited by occupant behaviour. In practice, teachers frequently prefer to keep classroom doors closed in order to minimise noise intrusion from the corridor and to maintain a quieter environment conducive to learning. As a result, this ventilation pathway, despite its potential, tends to be underutilised in everyday school operation.

3.4. Windows Ventilation

Natural ventilation through window openings is governed by two primary physical mechanisms: thermal buoyancy, arising from density differences between indoor and outdoor air, and wind pressure acting on the building envelope [35–37]. The combination of these phenomena determines the airflow through the opening and, consequently, the effective air change rate within space. When indoor air temperature exceeds that of the outdoor environment, a natural convective motion known as the stack effect develops: warmer, less dense indoor air tends to rise and exit through the upper portion of the window opening, while cooler, denser outdoor air enters through the lower section [34–36]. This

mechanism promotes air mixing within the occupied volume. The interaction with external wind can either amplify or inhibit this process depending on wind direction and intensity relative to the exposed façade. Under moderate wind impinging on the opposite façade, a negative pressure zone may develop that enhances indoor air extraction; conversely, direct frontal wind generates overpressure that counteracts the upward stack-driven outflow.

When additional openings are available—such as doors on the opposite side of the room—bidirectional airflow can develop, with supply through the windward opening and exhaust through the leeward one, substantially improving ventilation effectiveness [35,36]. When windows are present on one perimeter wall only, as in the monitored classroom, the phenomenon is appropriately described by a single-sided ventilation model [35]. It should be noted that the scope of the present work does not include the validation of existing single-sided ventilation models—such as those proposed by De Gids and Phaff [37] or Larsen and Heiselberg [38]—nor the assessment of their applicability under combined window and door opening conditions. The experimental results presented here are intended instead to provide order-of-magnitude estimates of the ventilation flow rates achievable under different opening configurations, to be used as a reference for comparison with the mechanical and infiltration-driven air exchange rates characterised in Sections 3.1–3.3.

Given the climatic context of the study site and the sheltered nature of the courtyard onto which the windows face, wind speeds recorded during the monitoring period were consistently low, ranging between 0.2 and 1.9 m/s [33]. Under these conditions, the buoyancy term—driven by the indoor-outdoor temperature difference ΔT —is expected to represent the dominant contribution to the ventilation flow rate, in accordance with the structure of the De Gids and Phaff formulation [37] in which the wind-dependent term becomes negligible at low wind speeds.

Three dedicated CO₂ concentration decay experiments were conducted between December 2024 and January 2025, under varying combinations of window opening configurations and outdoor boundary conditions. In each case, measurements were carried out at the end of the school day in the absence of occupants, with CO₂ concentration, indoor and outdoor temperature, and wind speed continuously monitored. The effective ventilation flow rate for each test was determined by fitting the exponential decay model (Equation (2)) to the measured CO₂ concentration time series (Table 4). The three window decay experiments were conducted under the following boundary conditions: 1 window open on 4 December 2024 ($\Delta T = 13.0$ °C, wind speed = 4.17 m/s, yielding 6.0 ACH); 2 windows open on 19 December 2024 ($\Delta T = 14.0$ °C, wind speed = 9.26 m/s, yielding 4.2 ACH); and 1 window open on 21 December 2024 ($\Delta T = 17.0$ °C, wind speed = 5.00 m/s, yielding 2.7 ACH).

Table 4. Comparative summary of all ventilation mechanisms characterised in the monitored classroom, ranked by increasing air change rate.

Mechanism	Configuration	Open Area	ACH
Infiltration	All openings closed	—	0.22
HRV level 1	HRV + windows and doors closed	—	0.84
Door diffusion	2 doors open, windows closed	7.2%	0.90
Window—min	1 window open, doors closed	2.3%	2.7
Window—med	2 windows open, doors closed	4.7%	4.2
Window—max	3 windows open, doors closed	7.1%	6.0

The data highlight a clear hierarchy among the available ventilation strategies. Window opening by far represents the most effective air renewal mechanism, delivering flow rates between 2.7 and 6.0 ACH even under moderate outdoor conditions [38]—values three

to seven times higher than those achievable through the HRV unit (Innova HRC+ 60 H/HV) at its lowest operating level (0.84 ACH). Door diffusion and mechanical ventilation at low speed provide comparable contributions in the range of 0.90 ACH.

However, as discussed in the following sections, the high ventilation potential of window opening is rarely exploited in practice. When air renewal is left entirely to occupant discretion, window opening events tend to be sporadic, brief, and unevenly distributed throughout the school day, resulting in highly intermittent CO₂ dilution that is insufficient to maintain stable indoor air quality within the recommended thresholds [39]. This gap between the theoretical ventilation potential and its actual utilisation under unmanaged conditions constitutes the central motivation for the automated HRV control strategy investigated in the second monitoring year.

4. Results: Uncontrolled Ventilation Year (2024–2025)

This section analyses the indoor air quality conditions recorded during the first monitoring year, when no structured ventilation protocol was in place. Occupant behaviour under free-running conditions is described first, followed by an analysis of characteristic CO₂ concentration patterns, the seasonal distribution of critical events, Category III exposure, and the correlation between outdoor temperature and indoor CO₂ concentration. The data recorded by the monitoring sensors were exported in CSV format and subsequently processed using Microsoft Excel. The datasets were filtered to retain only the time intervals relevant to the analysis, while missing values (NaN) and incomplete records were removed. The processed datasets were then analysed using custom Python (version 3.13.5) scripts to calculate the investigated parameters, perform the statistical analyses, and generate the figures and tables presented in this work.

4.1. Ventilation Behaviour Under Free-Running Conditions

During the 2024–2025 school year, indoor CO₂ concentration was monitored continuously from September through May. Throughout this period, no structured ventilation protocol was in place: both window operation and HRV activation were left entirely to the spontaneous initiative of classroom occupants. The HRV unit, operable via a remote control freely accessible in the classroom, was never switched on during the entire school year—a circumstance confirmed both by the monitoring data and by direct feedback from the class at the end of the year. It is worth noting that the HRV unit had been installed in the classroom approximately three years prior to the start of the monitoring campaign. A survey administered to the teaching staff at the end of the school year confirmed that the system had never been regularly operated during this period, having been activated only on isolated occasions outside the normal teaching routine. This suggests that the limited use of mechanical ventilation is often correlated with a poor awareness of available air quality management tools [30,31].

Window opening occurred regularly throughout the school year, as will be discussed in the following sections. A survey administered to the teaching staff and students revealed that the primary reasons for opening windows were the perception of stale air and thermal discomfort due to elevated indoor temperatures. Conversely, the main factor discouraging sustained window opening—or prompting their closure shortly after opening—was the draught discomfort experienced by students seated in close proximity to the glazed façade. These students, who were also physically responsible for operating the windows, were directly exposed to incoming cold air, creating a conflict between their role as ventilation actuators and their personal thermal comfort. This configuration effectively limited the duration and frequency of natural ventilation episodes, even under outdoor conditions that would otherwise have permitted sustained air exchange.

4.2. Characteristic CO₂ Concentration Patterns

The daily CO₂ typical dynamics observed under uncontrolled conditions can be analyzed by the worst-case profile recorded during the monitoring campaign. On this day (28 April 2025), indoor CO₂ concentration reached a peak of 3156 ppm—the highest value recorded throughout the entire year. During the first two hours of the morning, in the complete absence of air exchange, concentration increased at a mean rate of approximately 22 ppm/min, following a nearly linear trend consistent with a constant occupant emission rate (Figure 11). A marked change in the concentration trajectory occurred around 10:00, coinciding with a lesson changeover. The entry of a new teacher into the classroom—whose olfactory perception of air quality had not been attenuated by continuous exposure—prompted an immediate reaction, leading students to open the windows. This pattern was observed recurrently throughout the monitoring year. When asked about their perception upon entering the classroom at lesson changeover, incoming teachers consistently reported noticing markedly stale and stuffy air.

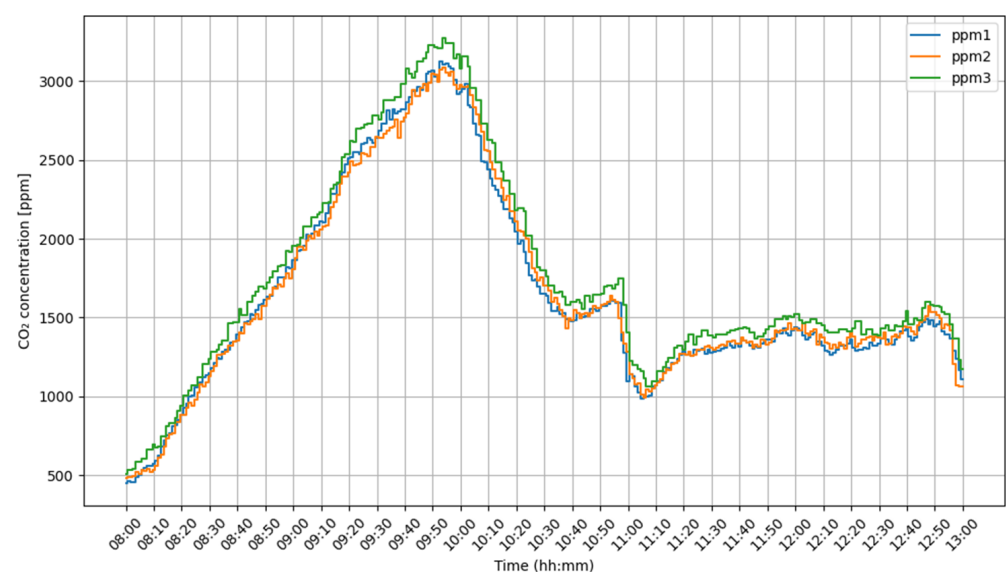


Figure 11. Daily CO₂ concentration profile (worst-case).

In contrast, students and teachers who had remained in the classroom throughout the lesson reported a significantly lower perception of air quality degradation, suggesting that prolonged exposure to elevated CO₂ concentrations progressively reduces occupants' sensitivity to indoor air quality conditions. As a result, ventilation responses tended to be delayed and concentrated around transition moments rather than distributed proactively across the lesson period.

The profile also shows that, in the absence of ventilation, CO₂ concentration continues to rise without any spontaneous saturation effect, exceeding 3000 ppm well before the end of the morning session. On this day, concentration remained above 2000 ppm for approximately 1 h and 40 min, corresponding to roughly 33% of total teaching time.

4.3. Seasonal Distribution of Critical CO₂ Events

The results obtained during the first monitoring year show that, in the winter season, Category IV conditions ($\Delta\text{CO}_2 > 1350$ ppm) were reached on more than 30% of school days, with a peak in January where this threshold was exceeded on 44.4% of monitored days (Figure 12).

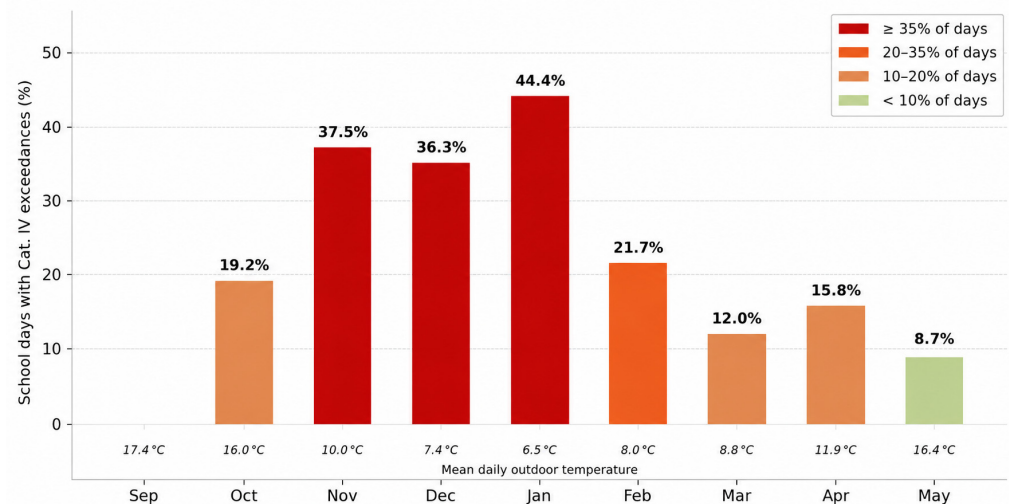


Figure 12. Percentage of school days per month with at least one Category IV exceedance ($\Delta\text{CO}_2 > 1350$ ppm above outdoor level) during the 2024–2025 school year.

The data reveal a pronounced seasonal pattern: during the winter months, Category IV thresholds were exceeded more than once in three school days on average, confirming that severely degraded air quality conditions were not isolated episodes but a recurrent feature of the coldest period of the school year.

Figure 13 reports the cumulative minutes spent under Category IV conditions for each monitored month on the y-axis, providing a complementary perspective on the duration of critical air quality exposure beyond its mere frequency.

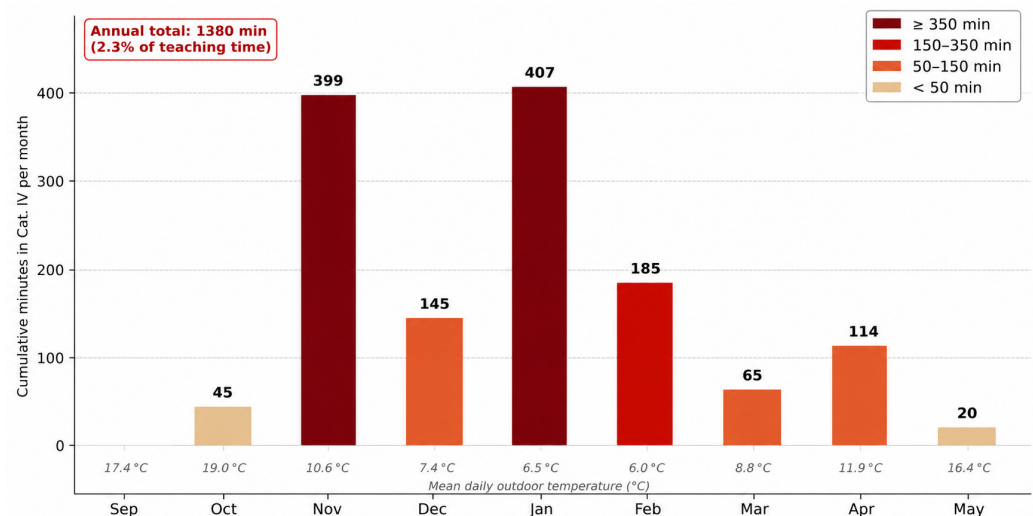


Figure 13. Cumulative minutes per month spent under Category IV air quality conditions ($\Delta\text{CO}_2 > 1350$ ppm above outdoor level) during the 2024–2025 school year.

The data reveal a pronounced seasonal pattern, with the frequency and duration of critical events peaking during the coldest months of the year. January recorded the highest incidence, with Category IV conditions occurring on 44.4% of school days and accounting for 407 min of cumulative exposure. November and January together account for over 58% of the total annual Category IV minutes, despite representing only two months of the nine-month monitoring period. The overall annual figures are significant: Category IV conditions occurred on 41 school days out of 190 monitored (21.6% of the year), with a total cumulative exposure of 1380 min, corresponding to 2.3% of total teaching time. While this percentage may appear modest in absolute terms, it represents nearly

23 h of severely degraded air quality distributed across the school year—a non-negligible burden on students who are expected to perform cognitively demanding tasks under these conditions.

It is worth noting that windows and doors were frequently kept closed during written tests and examinations—precisely the moments when students are expected to perform at their highest cognitive level. This behaviour, motivated by the need to minimise noise and maintain concentration, resulted in the most critical air quality conditions occurring during the periods of greatest cognitive demand.

4.4. Category III Exposure and Cognitive Implications

Beyond the most critical episodes, Figure 14 reports the monthly fraction of lesson time spent under Category III conditions ($\Delta\text{CO}_2 > 850$ ppm), which, while formally classified as acceptable under EN 16798-1 [8], is associated in the scientific literature with measurable reductions in cognitive performance and attention [11,12]. The seasonal pattern mirrors that observed for Category IV, with winter months consistently showing the highest values: December and January recorded 26.2% and 28.4% of lesson time above the Category III threshold, respectively, meaning that more than one quarter of teaching time during the coldest part of the year was spent under conditions potentially conducive to cognitive impairment. On an annual basis, 16.15% of total monitored teaching time exceeded the Category III threshold.

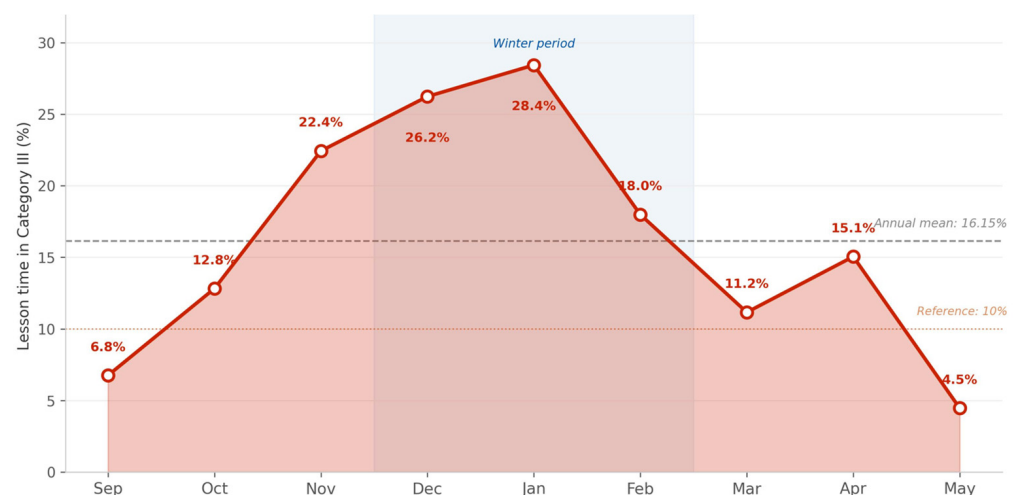


Figure 14. Monthly distribution of lesson time in Category III during the 2024–2025 school year.

4.5. Correlation Between Outdoor Temperature and Indoor CO_2 Concentration

As highlighted in the preceding sections, a progressive deterioration of indoor CO_2 conditions was observed as the school year moved into the winter season, driven by the occupants' tendency to keep windows closed to avoid exposure to cold incoming air.

To quantify this relationship, the correlation between mean indoor CO_2 concentration and mean outdoor temperature was investigated and is presented in the following figures. Figure 15 presents a dual-axis bar chart comparing monthly mean outdoor temperature with monthly mean indoor CO_2 concentration, while Figure 16 shows the corresponding scatter plot with linear regression fit.

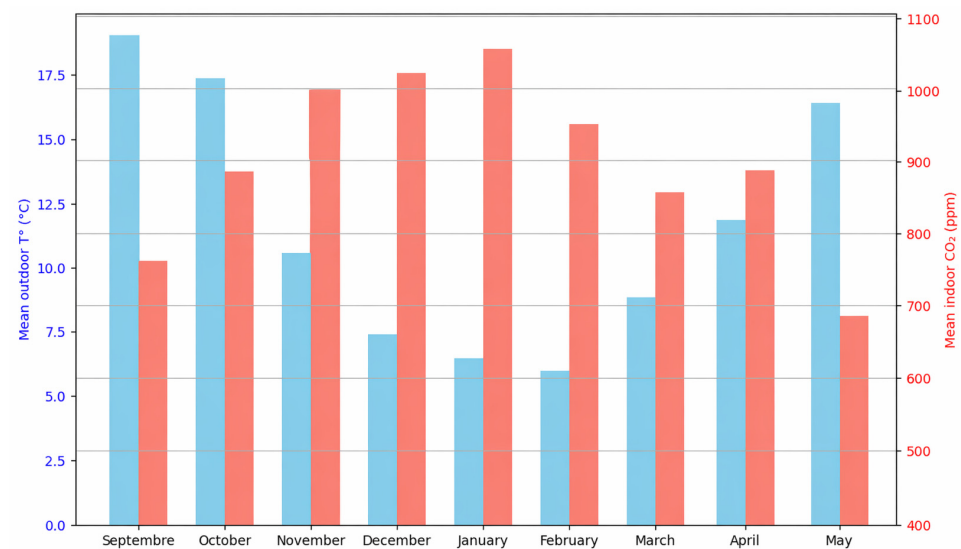


Figure 15. Dual-axis bar chart comparing monthly mean outdoor temperature.

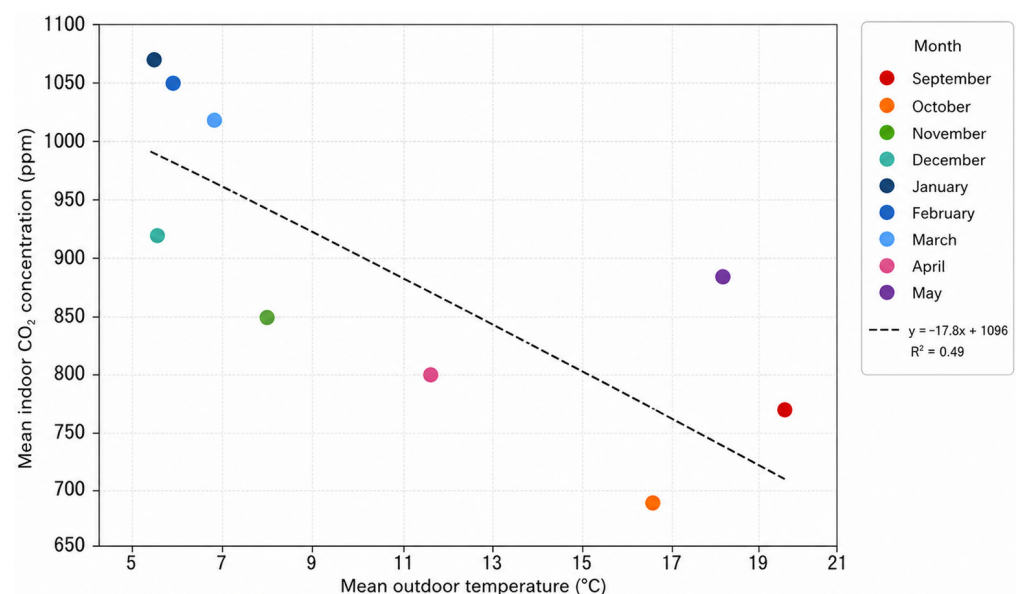


Figure 16. Scatter plot with linear regression fit (internal CO₂ vs. T_{out}).

The regression analysis yields the following relationship:

$$\bar{C}_{CO_2} = -17.8 \cdot T_{out} + 1096 \quad (R^2 = 0.49) \quad (5)$$

where $\bar{C}_{CO_2}$ is the monthly mean indoor CO₂ concentration (ppm) and T_{out} is the mean outdoor temperature during teaching hours (°C). The negative slope of -17.8 ppm/°C indicates that each 1 °C reduction in outdoor temperature is associated, on a monthly average basis, with an increase of approximately 18 ppm in mean indoor CO₂ concentration. This relationship reflects the behavioural mechanism described in Section 4.1: lower outdoor temperatures discourage window opening, reducing the frequency and duration of natural ventilation episodes and allowing CO₂ to accumulate to higher levels during occupied hours [17,18,25].

The practical implication of this finding is significant: in the absence of a structured ventilation control strategy, indoor air quality in the monitored classroom deteriorates predictably as outdoor temperatures decline, following a pattern that is foreseeable but not self-correcting.

5. Results: Automated HRV Control Strategy (2025–2026)

This section presents the results obtained during the second monitoring year, following the introduction of an automated HRV scheduling strategy. The design rationale and control system configuration are described first, followed by the progressive optimisation of the operating schedule, an acoustic assessment, an analysis of energy consumption, and a preliminary evaluation of absenteeism trends. The same methodology followed during the first monitoring year was used.

5.1. Design Rationale and Control System Configuration

The evidence highlighted during the 2024–2025 school year provided a clear empirical basis for the design of an improved ventilation strategy for the following academic year. The analysis of daily CO₂ profiles revealed that concentration accumulation was most pronounced during the first two hours of the morning (with a peak at 10:00 am) when occupants were least likely to open windows due to cold outdoor temperatures. This recurrent pattern informed the definition of targeted HRV activation intervals, designed to counteract CO₂ build-up during the most critical periods without requiring any manual intervention by occupants or teaching staff.

To implement the automated control strategy, a Shelly Plug S Gen3 smart plug was installed between the electrical outlet and the HRV unit. This device enabled remote on/off scheduling via a dedicated app, allowing pre-programmed daily operating windows to be defined and modified without physical access to the classroom. The solution required no modifications to the existing electrical or mechanical installation and represented a minimal-cost intervention fully compatible with standard school building management practices.

Outdoor temperature and CO₂ concentration data from the first year confirmed that the winter months—December through February—represented the period of greatest air quality risk, consistent with the seasonal pattern described in Section 4.5. Accordingly, the HRV was not activated during September and October 2025, and preliminary system tests were conducted during November 2025 to verify acoustic and operational performance under occupied conditions before committing to a fixed schedule.

5.2. Progressive Optimisation of the Control Strategy

The control strategy was implemented incrementally across three winter months, with operating parameters adjusted each month on the basis of the results obtained in the previous period. This iterative approach allowed the minimum effective operating duration to be identified progressively, rather than imposing a fixed schedule from the outset. The daily HRV operating schedules applied during each month are summarised in Figure 17.

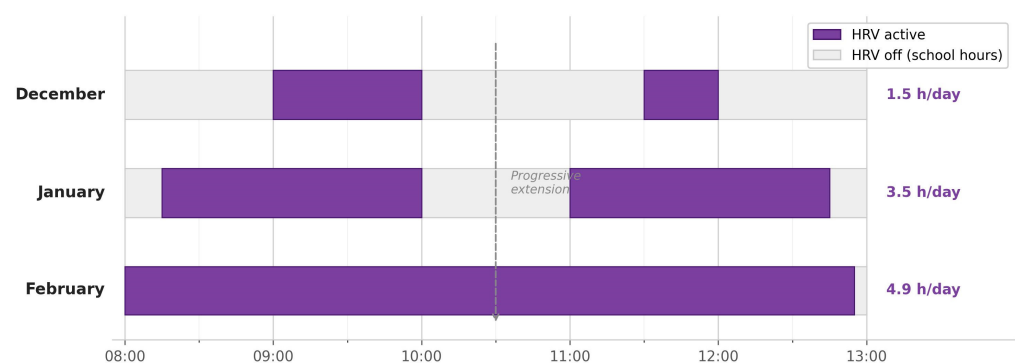


Figure 17. HRV daily operating schedule applied during the second monitoring year.

Table 5 shows the comparison of the mean daily indoor CO₂ concentration measured during the three winter months for the two monitored school years. Besides the reduction in the average CO₂ concentration observed in all months, a progressive decrease in the day-to-day variability can also be noted, as highlighted by the lower standard deviations during the second monitoring campaign. This indicates that the controlled operation of the HRV not only reduced the average CO₂ levels but also contributed to stabilizing indoor air quality over time. The most favourable conditions were achieved in February, when continuous HRV operation throughout the entire occupancy period limited the mean indoor CO₂ concentration to approximately 905 ppm.

Table 5. CO₂ mean comparison between 2024–2025 and 2025–2026.

Month	2024	2025	%
December	1027 ± 216	992 ± 188	−3.4%
January	1061 ± 254	977 ± 153	−7.9%
February	940 ± 201	905 ± 115	−3.7%

Table 6, instead, summarizes the percentage of occupied time spent in Category III. A progressive reduction was observed throughout the monitoring campaign, with the greatest improvement recorded in February, when Category III exposure decreased from 15.0% to 10.2%, corresponding to a 32% relative reduction. These results confirm that extending the daily operating time of the HRV effectively reduced the duration of moderate indoor air quality conditions.

Table 6. Monthly comparison of lesson time spent in Category III between 2024–2025 and 2025–2026.

Month	2024	2025	Relative Reduction (%)
December	23.0 ± 21.4	19.0 ± 18.2	17.4%
January	22.0 ± 16.5	18.0 ± 13.4	18.2%
February	15.0 ± 14.9	10.2 ± 8.9	32.0%

Table 7 reports the percentage of occupied time spent in Category IV, corresponding to the poorest indoor air quality conditions according to EN 16798-1. During December, the limited operating schedule produced almost no improvement compared with the reference year, confirming that the initial ventilation strategy was insufficient to control the highest CO₂ peaks. These findings motivated the progressive extension of the HRV operating schedule during the following months. As a consequence, Category IV exposure was reduced by 83.3% in January and by 76.7% in February, reaching only 0.7% of the occupied time under continuous HRV operation. This result demonstrates that an appropriately controlled decentralized mechanical ventilation system can virtually eliminate prolonged exposure to the most critical indoor air quality conditions.

Table 7. Monthly comparison of lesson time spent in Category IV between 2024–2025 and 2025–2026.

Month	2024	2025	Relative Reduction (%)
December	3.0 ± 6.0	3.1 ± 4.2	−3.3%
January	6.0 ± 13.4	1.0 ± 2.0	83.3%
February	3.0 ± 6.3	0.7 ± 2.2	76.7%

5.3. Acoustic Assessment

A key concern in the deployment of mechanical ventilation in school classrooms is the potential for noise disturbance during lessons, which could offset the cognitive benefits of

improved air quality with the cognitive costs of increased acoustic distraction. To assess this aspect, occupant perception was evaluated through direct feedback collected from students and teaching staff at the end of the February monitoring period. All respondents confirmed that HRV operation at speed level 1 was imperceptible during normal lesson activities, consistent with the manufacturer's declared sound pressure level of 33 dB(A) at 3 m distance—a value well below the threshold of 35 dB(A) typically recommended for teaching spaces [23]. This finding suggests that continuous HRV operation at the lowest speed setting is acoustically compatible with standard classroom use and does not represent a barrier to adoption.

5.4. Energy Consumption

Figure 18 reports the electrical energy consumption associated with HRV operation during the three monitored winter months. Consumption values were estimated on the basis of the nominal power draw declared in the manufacturer's technical specifications, corresponding to approximately 37.5 W at speed level 1. This declared value was independently verified through spot measurements carried out directly in the classroom using the integrated energy monitoring function of the Shelly Plug S Gen3 smart plug, confirming close consistency with the catalogue data. The recorded consumption values are remarkably low across all configurations tested. Even under the most intensive operating schedule applied in February—continuous operation throughout the full five-hour lesson period—daily energy consumption amounted to only 187.5 Wh, equivalent to less than 0.19 kWh per school day.

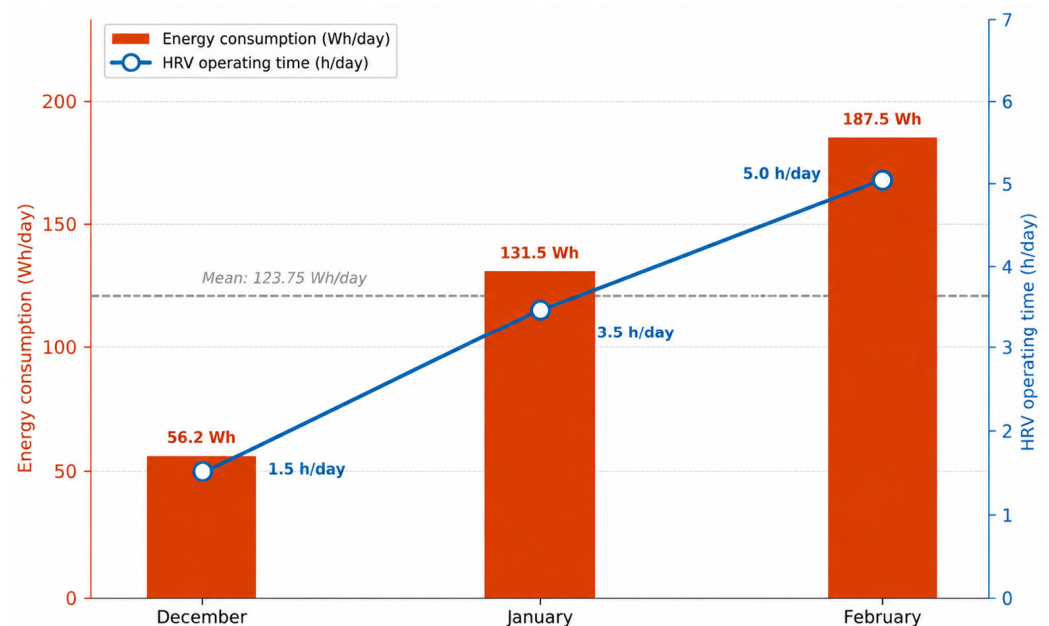


Figure 18. HRV energy consumption by month.

5.5. Absenteeism as a Complementary Indicator

Figure 19 presents a comparison of student absences recorded during the winter months of the two consecutive school years. A reduction of approximately 32% in total absences was observed between 2024–2025 and 2025–2026, from 223 to 151 recorded absences across the four monitored months. The most pronounced decrease occurred in January (−46.2%), coinciding with the month in which HRV daily operating time was extended to 3.5 h.

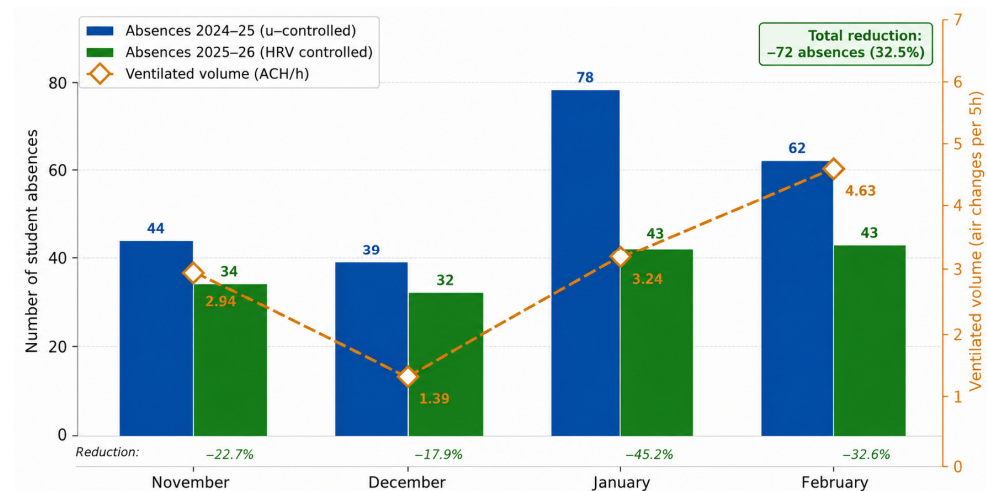


Figure 19. Monthly student absences and ventilated air volume during the 2024–2025 and 2025–2026.

It should be noted that the ventilated air volume reported in Figure 19 refers to the cumulative air changes occurring over the entire 5 h lesson period. For reference, the equivalent mean hourly ventilation rates are: November = 0.60 ACH, December = 0.28 ACH, January = 0.65 ACH, and February = 0.93 ACH. The weighted mean ventilation rate over the four monitored months amounted to 0.61 ACH, maintained continuously throughout the five-hour daily lesson period. The relatively low value recorded in December is consistent with the limited daily HRV operating time applied during that month (1.5 h/day), while the progressive increase observed through January and February reflects the extension of the automated control schedule.

6. Discussion

This section discusses the key findings of the study in a broader context and draws the main conclusions. The analysis begins with a critical assessment of indoor air quality under uncontrolled conditions, followed by a discussion of the outcomes of the automated control strategy, a scalability framework for practical interventions, the main limitations of the study, and the concluding remarks.

6.1. Indoor Air Quality in a Typical Secondary School Classroom: A Critical Assessment

The results of the first monitoring year reveal a situation that, while perhaps unsurprising to those familiar with the Italian school building inventory, is nonetheless concerning when examined quantitatively. During the 2024–2025 school year, Category IV air quality conditions—corresponding to CO₂ increments exceeding 1350 ppm above outdoor levels, the lowest quality class defined by EN 16798-1 [8]—were recorded on 21.6% of all monitored school days, with a cumulative exposure of 1380 min equivalent to 2.3% of total teaching time. During the winter months, more than one quarter of lesson time was spent under Category III conditions, a range that scientific literature associates with measurable reductions in cognitive performance and attention [11,12]. Peak concentrations reached 3156 ppm—more than six times the outdoor reference level—on the worst recorded day.

These results do not belong to a building without ventilation infrastructure. On the contrary, the monitored classroom was equipped with a functioning decentralised HRV unit, installed approximately three years prior to the start of this study. Yet the system was never activated throughout the entire school year—a finding confirmed by a survey of teaching staff. Informal observation extended to the remaining classrooms in the same school building revealed that none of the approximately ten HRV units installed across the building was regularly operated. This pattern points to a systemic issue that goes beyond

individual behaviour: in the absence of a structured operational framework, mechanical ventilation systems in school buildings tend to remain unused regardless of their technical availability, rendering the associated investment substantially ineffective.

6.2. Outcomes of the Automated HRV Control Strategy

The introduction of an automated operating strategy during the second monitoring year demonstrated that substantial improvements in indoor air quality can be achieved without modifying the existing ventilation hardware and without relying on occupants' behaviour. By progressively extending the daily operating time of the decentralized HRV unit (0.9 ACH) to cover almost the entire classroom occupancy period, the time spent under the poorest indoor air quality conditions (Category IV) was reduced by 83.3% in January and 76.7% in February, while Category III exposure decreased by 18.2% and 32.0%, respectively.

Beyond the reduction in the average indoor CO₂ concentration, the proposed control strategy also produced a marked decrease in the day-to-day variability of CO₂ levels. The standard deviation of the daily mean concentration decreased from 254 ppm to 153 ppm in January and from 201 ppm to 115 ppm in February, indicating a more stable and predictable indoor environment. Under continuous HRV operation, the average indoor CO₂ concentration was limited to approximately 905 ± 115 ppm, while the time spent in Category IV was reduced to only 0.7% of the occupied period.

The proposed strategy required no additional ventilation hardware, generated no perceptible acoustic discomfort at the lowest fan speed, and maintained extremely low energy consumption, remaining below 190 Wh per school day even under continuous operation. These findings demonstrate that a simple time-based control strategy can substantially improve both the average indoor air quality and its temporal stability in existing school buildings equipped with decentralized mechanical ventilation systems.

The choice of operating the HRV unit at its lowest speed level was motivated not only by the absence of acoustic disturbance, as discussed in Section 5.3, but also by the associated benefits in terms of ventilation efficiency and reduced energy consumption. Furthermore, it should be noted that the adoption of a mechanical ventilation unit equipped with an internal heat exchanger introduces an additional thermal advantage: unlike window opening, which introduces outdoor air directly at ambient temperature, the HRV unit supplies air that has been pre-heated through heat recovery, at a temperature considerably higher than that of the outdoor environment. Consequently, at equal ventilation flow rates, mechanical ventilation with heat recovery is thermally preferable to natural ventilation through windows, as it reduces the additional heating load required to maintain indoor comfort conditions. The electrical energy consumption associated with HRV operation may therefore be partially or fully offset by the thermal energy savings attributable to the heat recovery process, making the overall energy balance of the system particularly favourable in cold weather conditions.

A concurrent 32.3% reduction in student absenteeism was observed during the monitored winter period. Although this finding cannot be interpreted as direct evidence of a causal relationship, owing to the influence of epidemiological, environmental, and behavioural factors, it is consistent with the hypothesis that improved ventilation may contribute to reducing the transmission of airborne respiratory pathogens in school environments. It must be emphasised that this reduction cannot be causally attributed to the improvement in indoor air quality alone. Student absenteeism is influenced by a wide range of concurrent factors, including the seasonal incidence of influenza and other respiratory viruses, individual health conditions, year-to-year epidemiological variability, family and social factors, as well as school-related conditions that cannot be controlled

for within the present study design. The absence of a dedicated control group and the single-classroom scope of the monitoring campaign further preclude any definitive causal inference. Nevertheless, the observed trend is noteworthy and is consistent with the hypothesis that improved mechanical ventilation may contribute to reducing airborne transmission of respiratory pathogens in enclosed school environments, a mechanism supported by a growing body of epidemiological and experimental evidence [40–44]. The observed reduction in absenteeism should therefore be regarded as an encouraging finding that warrants further investigation through dedicated longitudinal studies involving larger samples and appropriate control groups.

7. Conclusions

This study investigated indoor air quality conditions in a real secondary school classroom over two consecutive school years, with the aim of characterising the limitations of unmanaged natural ventilation and quantifying the improvement achievable through a simple automated HRV control strategy. The findings suggest a graduated framework of ventilation improvement interventions, applicable across different levels of existing infrastructure and budget availability.

The simplest and most immediately accessible measure—applicable in any classroom regardless of mechanical ventilation availability—is the systematic opening of corridor doors during lesson periods. As demonstrated by the decay experiments presented in Section 3.3, open doors generate an equivalent ventilation flow rate to that of the HRV unit at its lowest speed setting. Although this measure is constrained by teachers' preferences for acoustic privacy, raising awareness of its ventilation potential could encourage more consistent adoption at zero cost.

A second measure, deployable at minimal expense in any classroom, is the installation of low-cost CO₂ sensors equipped with an audible alert function. Devices such as the HOBO MX1102A used in this study include a configurable alarm that activates when a user-defined CO₂ threshold is exceeded, providing occupants with an immediate prompt to take ventilation action—whether by opening windows, doors, or activating a mechanical unit.

For classrooms already equipped with HRV units, the addition of a programmable smart plug enables automated time-based scheduling without any modification to the existing hardware. As demonstrated by this study, this minimal intervention is sufficient to deliver reproducible and significant improvements in air quality, effectively activating the latent ventilation capacity of hardware that would otherwise remain unused. If scaled across the Italian school building inventory, where a significant number of decentralised HRV units were installed during post-pandemic air quality improvement programmes, this approach could deliver substantial public health benefits at negligible per-unit cost [45].

Finally, for new installations or future upgrades, demand-controlled ventilation (DCV) strategies represent the natural evolution of the time-based approach implemented in this study. In a DCV configuration, HRV activation and fan speed can be modulated according to real-time CO₂ measurements, ensuring that ventilation is continuously adapted to the actual occupancy and indoor air quality while minimizing unnecessary energy consumption. Beyond conventional sensor-based DCV, future developments could also investigate advanced adaptive control strategies, such as reinforcement learning algorithms, which have recently shown promising results in optimizing HVAC operation by continuously learning the optimal control policy under changing occupancy and environmental conditions [46].

The proposed control strategy is readily applicable to existing school buildings equipped with decentralized HRV units, as it does not require modifications to the ventilation hardware. In the present case, the automated operation was implemented through a commercially available smart plug, costing approximately 25 EUR per unit, allowing

the operating schedule of each HRV device to be remotely programmed with minimal installation effort. Routine maintenance requirements remain unchanged and are limited to the periodic cleaning or replacement of the ventilation filters, as recommended by the manufacturer. For school buildings not equipped with mechanical ventilation, a simple and cost-effective first step could consist of installing CO₂ sensors with visual or acoustic alarms to inform teachers when ventilation becomes necessary. Such solutions may increase occupants' awareness of indoor air quality and promote more effective natural ventilation practices until dedicated mechanical ventilation systems can be implemented.

Several limitations of the present study should be acknowledged. Firstly, the present study assessed indoor air quality exclusively through carbon dioxide (CO₂) concentration, which was adopted as a proxy for ventilation effectiveness in accordance with EN 16798-1. Other relevant indoor air quality indicators, such as particulate matter (PM_{2.5} and PM₁₀), volatile organic compounds (VOCs), and bioaerosols, were not monitored.

Secondly, the monitoring campaign was conducted in a single classroom within a single school building, which limits the generalisability of the present findings. Although the proposed control strategy proved effective under the investigated conditions, its optimal operating schedule cannot be considered universally applicable. Classroom geometry, occupancy density, occupancy patterns, climatic conditions, and the characteristics of the installed ventilation system may substantially influence both CO₂ dynamics and the required ventilation strategy. Therefore, while the general principle of adopting a structured control logic for decentralized mechanical ventilation is expected to be transferable to similar educational environments, the specific operating schedule should be adapted to the characteristics of each building. Additionally, the absenteeism data, while suggestive of a positive trend associated with improved ventilation, cannot be interpreted as causal evidence in the absence of a dedicated control group and a larger sample size.

Future research should extend the monitoring campaign to multiple classrooms, school buildings, and climatic regions, with the aim of validating the proposed approach under different operating conditions. Future developments should also investigate the effect of additional contaminants, demand-controlled ventilation and more advanced adaptive control strategies, including reinforcement learning algorithms, capable of optimizing both the activation and operating speed of decentralized mechanical ventilation systems according to real-time indoor CO₂ concentration, occupancy patterns, and outdoor environmental conditions.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ACH	Air changes per hour (h^{-1})
CO ₂	Carbon dioxide
CV	Coefficient of variation
DCV	Demand-controlled ventilation
HRV	Heat recovery ventilation
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
NDIR	Non-dispersive infrared
ppm	Parts per million ($\mu\text{mol}/\text{mol}$)
ΔCO_2	CO ₂ increment above outdoor concentration ($\mu\text{mol}/\text{mol}$)
RH	Relative humidity

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