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Translating CO_2 decay into ventilation and occupancy guidance using a low-cost IAQ monitor: Particulate matter and air quality in a university weight room

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Abstract
Indoor Air Quality (IAQ) in gyms is a concern for both athletic performance and for reducing airborne transmission of viruses, particularly during peak usage hours. To reduce the build-up of breath exhalate and other bodily emissions, facilities typically force outside fresh air through the indoor space, but building operators often limit this air flow to minimize air conditioning costs. Small enterprises and non-profits often lack affordable ways to test fresh air ventilation. Grounded in first principles, this study presents a low-cost monitoring approach for evaluating fresh air adequacy by using the carbon dioxide (CO_2) tracer gas decay method to estimate Air Change Rates (ACR), translate them into occupancy thresholds, and assess Particulate Matter (PM). Monitoring was performed in the American University of Beirut weight room over two weeks in July–August 2025. A low-cost sensor system was designed and built to measure CO_2 and particulate matter ($PM_{1.0}$, $PM_{2.5}$, PM_{10}). ACR was estimated by fitting nighttime CO_2 decay after gym closure to a mass-balance model. Compliance with the standards of the American Society for Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) was assessed, and CO_2–PM associations were tested with Spearman's correlation. Across 10 valid nights, ACR ranged from 1.00–1.94 h^{-1} (mean 1.51 ± 0.37 h^{-1}), a value that would accommodate ~17 occupants according to ASHRAE 62.1. The weight room frequently hosts more than double that number during the evening hours of the Fall and Spring semesters, indicating insufficient fresh air flow for the number of users. The mean indoor CO_2 during open hours was ~792 ppm and tracked gym occupancy patterns. PM concentrations did not correlate with occupancy, and peaked during the hours the gym was closed, indicating a different mechanism for PM build-up. This work demonstrates that public facilities can assess ventilation with inexpensive monitoring, offering a practical alternative to costly HVAC engineering services. The approach enables resource-constrained operators to identify ventilation gaps and pursue evidence-based improvements to IAQ without disrupting normal operations.

Keywords
Indoor air quality, Ventilation, Tracer gas method, CO_2 decay, Air change rate, Occupancy, Particulate matter, Low-cost monitoring, ASHRAE 62.1, Gym, Weight room

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1. Introduction

In recent years, Indoor Air Quality (IAQ) has increasingly become a subject of concern (1). The COVID-19 pandemic brought attention to the key role of ventilation, airborne particles, and indoor pollutants in disease transmission (2). Beyond infection, poor IAQ has been linked to Sick Building Syndrome (SBS), reduced productivity, and impaired cognitive performance (3–6).

Indoor gyms where people perform physical activity are especially prone to poor air quality. This vulnerability stems from several factors. Indeed, high occupant density leads to greater production of exhaled carbon dioxide (CO_2) (7,8) as well as higher humidity and bioaerosols (9,10). Increased respiratory activity during exercise further enhances pollutant uptake, since individuals inhale more deeply into their lungs (11).

In addition, gyms are characterized by the emission of secondary pollutants. Studies in sports facilities have reported elevated concentrations of Particulate Matter (PM) due to the resuspension of dust during physical activity (7,8,12,13). Fitness centers are also prone to high levels of Volatile Organic Compounds (VOCs), originating from cleaning agents (8,13), as well as from perspiration, exhaled breath, and personal care products (14,15). Furthermore, secondary oxidation reactions between ozone and human skin can generate additional indoor pollutants, including respiratory irritants (7,16).

A recent literature review found that many studies continuously monitored CO_2, PM, VOCs and formaldehyde, often reporting concentrations above safety standards during periods of peak occupancy (17). Another review also found CO_2 to be the most frequently measured parameter to assess indoor air quality (14). The reviewed literature confirms that while studies highlight potential exposure risks, they seldom quantify ventilation rates or air-exchange performance directly (7–9,18). These studies also use CO_2 concentration as an IAQ indicator. CO_2 is particularly useful because it is an inert gas, making it a reliable tracer for ventilation studies: after occupants leave a space, the decline in CO_2 reflects how quickly indoor air is being replaced (19). This tracer-gas decay approach is explicitly endorsed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (20) as a valid method to estimate Air Change Rates (ACR), which can then be compared to ventilation standards. In practice, this approach involves tracking the decrease in indoor CO_2 concentration that occurs after occupants leave a space, as fresh air entering the room displaces the exhaled, CO_2-rich air. By tracking this decline over time, ACR can be calculated and then compared to ventilation standards to assess whether the airflow is sufficient. When ACR falls below these standards, pollutant buildup and degraded air quality are likely to occur (21).

While earlier works predominantly documented such issues, they often stopped short of detailed remediation strategies. Many papers conclude by noting that ventilation needs improvement but do not always provide specific guidance. However, a 2014 investigation by Ramos *et al.* explicitly stated that it is *"crucial to optimize the HVAC systems, ventilation rates, and occupants' behavior"* to reduce pollutant exposure in fitness centers (12). Similarly, a 2024 review of fitness-center IAQ advised that future ventilation strategies should consider crowd density and exercise intensity, tailoring fresh-air supply to different areas and times of use (17). Furthermore, one study found that IAQ could be improved by limiting the number of simultaneous occupants in combination with source control and an efficient ventilation system (22). However, non-profits and small businesses do not commonly have access to engineering consultants and equipment needed to rigorously test ventilation adequacy. This study was performed in the weight room of the student center of the American University of Beirut to test the feasibility of building a low-cost analysis tool (under $100 for materials) that could be used to audit fresh air adequacy.

This makes the methodology especially relevant for countries such as Lebanon, where air quality monitoring is rarely enforced and accessible commercial solutions are limited. As such, the framework presented here offers facility managers a practical tool to improve ventilation, protect health, and enhance athletic performance in resource-constrained contexts.

The analysis was informed by the theoretical framework of ventilation and exposure assessment, which examines indoor pollutant concentrations as the outcome of the interplay between emission sources and air exchange. In this context, CO_2 decay was applied as a practical proxy for estimating ACR, providing a clear link between observed data and established standards for indoor air quality.

The study relied on field-based monitoring with low-cost sensors that continuously tracked CO_2 and PM over a two-week deployment. Decay analyses were performed during post-occupancy intervals to estimate ACR, enabling concentration data to be converted into ventilation performance metrics to address inadequate IAQ.

2. Materials and Methods

2.1 Study site

This study was performed in the American University of Beirut's gym, specifically in its weight room (Figure 1). The facility is located near a busy urban-traffic area, which may influence outdoor air quality (23). The monitored zone had a calculated floor area of $V = 169\,m^2$ (based on measured dimensions) and a volume of $V = 439\,m^3$. Ventilation was provided by a Heating, Ventilation, and Air Conditioning (HVAC) system using a displacement strategy, with low-level supply and high-level return diffusers. IAQ monitoring was performed during July-August 2025, a period of reduced occupancy since most university students—the primary users of the gym—were away for the summer break.

Figure 1. Photograph of the AUB weight room

2.2 Instrumentation

2.2.1 *Monitoring setup*
IAQ was continuously monitored over a 14-day period, operating 24 hours per day at a median 61-second sampling interval. Measurements included CO_2 and PM concentrations. The monitoring platform was assembled using off the shelf, low-cost and widely available sensors. These same sensors are often embedded in commercially marketed IAQ monitors sold for premium prices, such as in the PurpleAir Zen® air-quality monitor (PurpleAir LLC, Draper, UT, USA) which retails at USD 300 (24).

CO_2 levels were measured using an MH-Z14 NonDispersive InfraRed (NDIR) sensor with a stated Margin Of Error (MOE) of ±(50 ppm+5% reading value) for values between 0 ppm and 5000 ppm. Particulate matter was monitored using the Adafruit PM2.5 Air Quality Sensor, which reports $PM_{1.0}$, $PM_{2.5}$, and PM_{10} mass concentrations. The stated consistency error for $PM_{2.5}$ is ±10 µg/m³ for concentrations between 0–100 µg/m³ and ±10% for values between 100–500 µg/m³.

2.2.2 *Sensor calibration*
Calibration was performed against a GC-2028 CO_2 monitor (Lutron Electronics Co. Inc., Taiwan), hereafter referred to as the *reference instrument*. The stated MOE for the reference instrument was ±40 ppm for CO_2 concentrations ≤ 1000 ppm and ±5% of the reading for values between 1000 ppm and 3000 ppm.

Calibration was performed over a 50 minute period in a household kitchen, with CO_2 concentrations measured simultaneously by both the reference instrument and the custom device at 61-second intervals, to produce a controlled rise and decay in CO_2 levels. The experiment consisted of two phases: (i) CO_2 buildup induced by operating a gas stove, and

(ii) subsequent ventilation achieved by turning off the stove, activating the kitchen fan, and opening the windows.

A time-series comparison (Figure 2) found that both instruments captured nearly identical concentration trends during the buildup and decay phases.

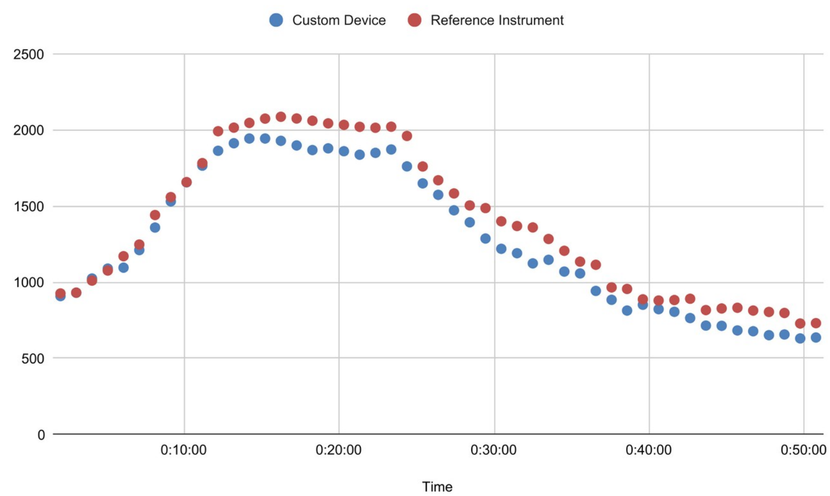

Figure 2. Time series comparison of custom CO_2 (ppm Y-axis) monitor and reference instrument

A linear regression between the custom monitor and the reference instrument yielded the equation, *Reference instrument = 1.03 × Custom monitor + 73.8 (*R^2 *= 0.984)* (Figure 3). The high R^2 indicated linear agreement, with the reference instrument reading on average 3 % higher than the reference across the measured range and a positive intercept of ~74 ppm, both of which were coherent with the stated MOE. In addition, the ACR calculated from the CO_2 decay curves was 2.52 h^{-1} for the reference instrument and 2.66 h^{-1} for the custom monitor. Thus, for the purposes at hand, the custom-built device provided data equivalent to the commercial reference instrument.

2.2.3 *Data acquisition and assembly*

The sensors were integrated with an ESP32 development board (30-pin) microcontroller. At each cycle, the microcontroller measured CO_2 concentration by timing the Pulse-Width Modulation (PWM) output of the MH-Z14A sensor. In parallel, particulate matter was recorded from the PMS5003 over a Universal Asynchronous Receiver–Transmitter (UART) serial connection. All valid readings were paired with a Real-Time Clock (RTC) timestamp, formatted as Comma-Separated Values (CSV), and written to a MicroSD card module via the Serial Peripheral Interface (SPI). To maintain uninterrupted operation, the firmware inserted "NA" entries for corrupted or missing values rather than halting the cycle.

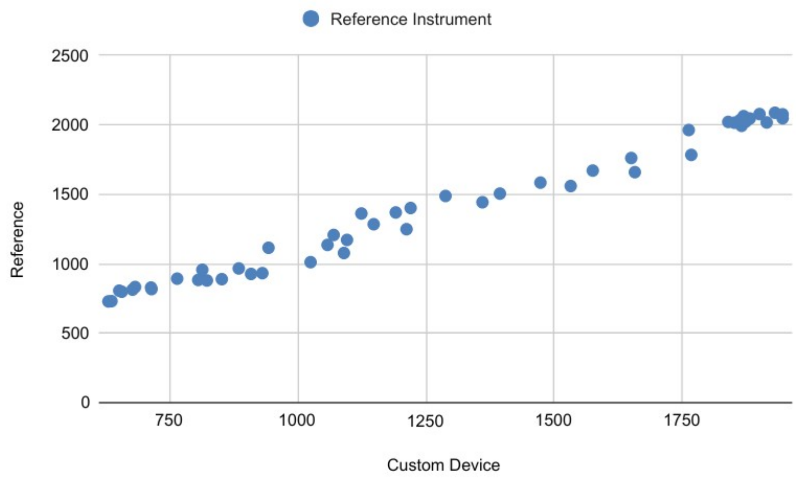

Figure 3. Comparison of Custom CO_2 Device and Reference Instrument (Both axes represent CO_2 concentrations in ppm)

Figure 4 shows the assembled device, while Figure 5 provides the wiring diagram.

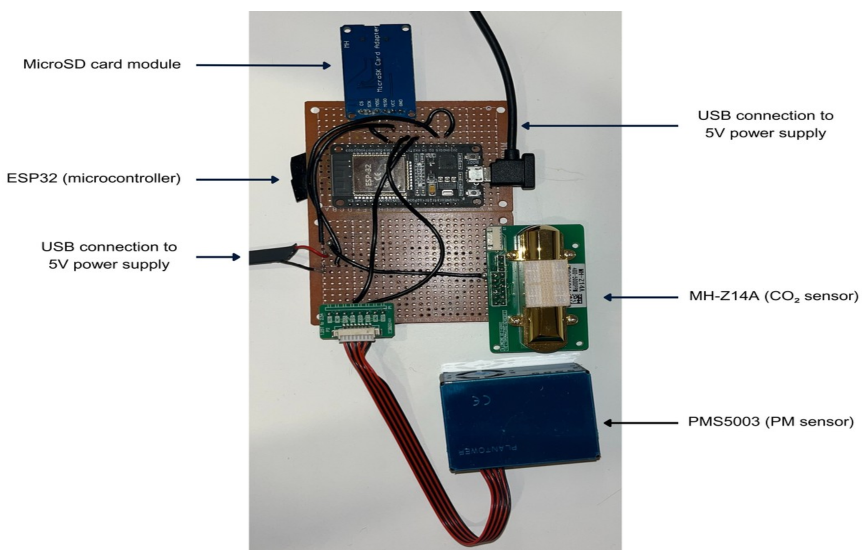

Figure 4. Photograph of the multi-sensor system developed for this study

The Arduino firmware used for acquisition and logging is provided in Supplementary file S1 for reproducibility, and a bill of materials including component prices is presented in Supplementary Table S2. The code, dataset, component list (including prices), wiring diagram, and step-by-step assembly guide are equally available in an open-source code and data repository on GitHub (https://github.com/laylashihadeh26-ctrl/esp32-air-quality-logger).

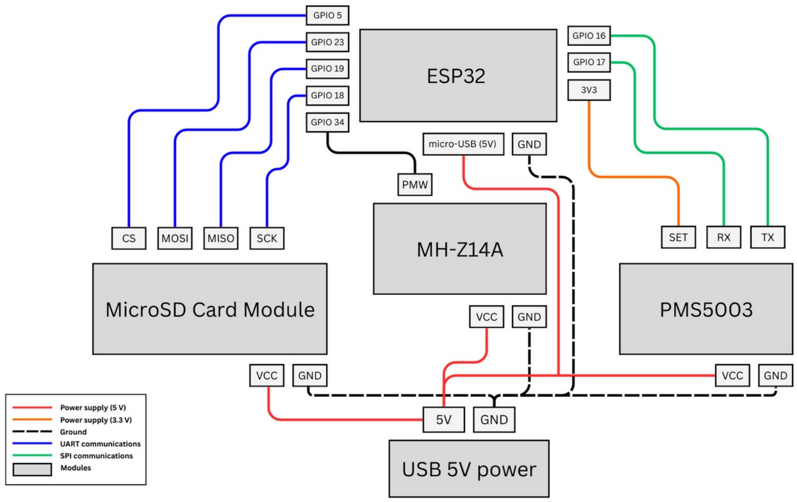

Figure 5. Wiring diagram of the IAQ monitor

2.2.4 *Sensor placement*

For optimal measurement accuracy, the air quality monitor was positioned ~ 1.8 m above the floor, in the middle of the room and on the opposite wall of the air conditioning ducts, following ASHRAE recommendations (20). To ensure that CO_2 decay readings reflected the well-mixed bulk air rather than localized airflow patterns, the sensor was deliberately placed away from supply vents and inlet streams, where concentrations could be artificially diluted. Since the air return area provided the most representative sampling of room air, placement was selected to approximate this location. The multi-sensor unit was housed in a ventilated project enclosure with multiple side openings to promote cross-airflow and ensure accurate, responsive measurements.

2.3 Air Change Rate measurements

ACR was estimated using the CO_2 tracer gas concentration decay method (19), for which a multi-point regression approach has been shown to achieve an uncertainty of ~ 5% under optimal conditions (25). Each night, following gym closure, a period of uninterrupted CO_2 decline was identified by locating the time of peak CO_2 concentration.

The concentration of CO_2 in the room was calculated using a mass balance, assuming that the room of volume V was uniformly mixed, $\frac{d}{dt\left(VC(t)\right)} = QC_{amb} - QC(t) + S$ (eq0), where $C(t)$ is the indoor concentration at time t , C_{amb} is the ambient (baseline) concentration, Q the volumetric airflow rate, and S is the internal source term representing CO_2 emitted by all occupants.

This balance is illustrated in Figure 6.

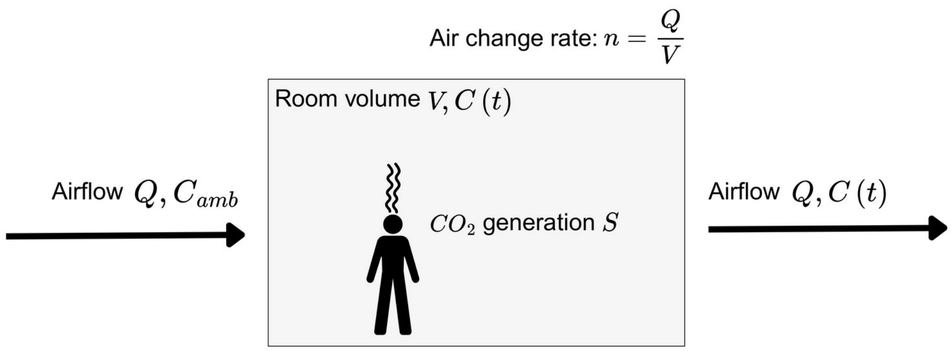

Figure 6. Conceptual diagram of CO_2 mass balance in a well-mixed volume

Since the volume V is constant, Eq. (0) reduces to, $\frac{dC}{dt} = \frac{Q}{V(C_{amb} - C(t))} + \frac{S}{V}$ (eq1) . After closing hours, people exit the room so that $S=0$. With concentrations expressed relative to ambient concentrations,$(C^* = C - C_{amb})$, Eq. (1) becomes $\frac{dC^*}{dt} = \frac{-Q}{V} C^*(t)$ (eq2). This first-order differential equation has the solution $C^*(t) = C_0^* e^{\frac{-Q}{V}t}$ (eq3), where C_0 is the concentration at $t(0)$. Defining the ACR as $n = \frac{Q}{V}$ (eq4), yields the standard exponential decay model $C^*(t) = C_0^* e^{-nt}$ (eq5). From eq5, the ACR, n was obtained as the exponent of the regression line of an exponential equation, calculated using Microsoft Excel. The data was filtered for spikes exceeding a deviation of 150 ppm from the neighboring points. To convert ACR into volumetric fresh airflow($L s^{-1}$), the measured room volume was used $Q = \frac{ACR \times V}{3.6}$ (eq6), where Q is the volumetric fresh airflow rate ($L s^{-1}$), ACR is in (h^{-1}), and V is the room volume (m^3). The divisor 3.6 converts cubic meters per hour to liters per second, aligning units with ASHRAE 62.1 ventilation requirements. The volumetric fresh airflow rate Q, was assumed to represent the zone outdoor airflow V_{oz} as defined in ASHRAE 62.1, allowing direct comparison with ventilation requirements.

2.4 Uncertainty analysis of ACR estimates

Monte Carlo simulation (10,000 runs) was used to quantify how measurement noise and data truncation could affect the calculated air change rate (ACR). In each run, the CO_2 readings were randomly perturbed within the sensor's stated accuracy bounds of ±(5 % of reading + 50 ppm), with the errors treated as independent, uniformly distributed (bounded) noise consistent with the manufacturer's tolerance specification. To capture sensitivity to the selected fitting window, each simulation also randomly trimmed up to three points from the beginning and end of the decay curve before refitting. Since the background CO_2 level was measured during the same session as the decay data, any uniform offset in the sensor's baseline (e.g., ±50 ppm) canceled out and did not influence the ACR. The resulting distribution of fitted ACR values exhibited a standard deviation of 0.19 h^{-1}, corresponding to a 95 % confidence interval (CI) of ±0.37 h^{-1}. This interval represented the combined uncertainty due to point-to-point sensor noise and the limited sensitivity of the ACR estimate to modest changes in the fitted time window. In the Results section, the larger uncertainty interval (±0.37 h^{-1}) from the per-day Monte Carlo analysis is reported, rather than the narrower across-day mean interval (±0.18 h^{-1}), to provide a more conservative estimate of ventilation precision.

2.5 Compliance with ASHRAE 62.1 (20)

For fitness spaces, ASHRAE 62.1 (20) specifies the breathing-zone outdoor airflow as $V_{bz}=(R_p \times P)+(R_a \times A_z)$ (eq7), where, $R_p=10\,L\,s^{-1}\,person^{-1}$ is the people-based outdoor air rate, P is the number of occupants and $R_a=0.3\,L\,s^{-1}\,m^{-2}$ is the area-based outdoor air rate. These values are specified by ASHRAE Standard 62.1 for weight rooms and represent mean design values. Actual conditions within the studied gym may differ, potentially resulting in ventilation needs above this nominal rate. A_z is the zone floor area. The zone outdoor airflow V_{oz} was then adjusted for air distribution effectiveness as $V_{oz}=\frac{V_{bz}}{E_z}$ (eq8), where $E_z=1.2$ corresponded to displacement ventilation (low supply, high return). The occupancy supported under ASHRAE 62.1. was then deduced by solving $P_z=\frac{V_{oz}E_z-R_aA_z}{R_p}$ (eq9).

2.6 Baseline estimation

To calculate the daily baseline for accurate ACR measurements, the average CO_2 concentration during the 5:00–6:30 AM period of the following morning was used when both the Standard Deviation (SD) and slope were within 20 ppm and ±5 ppm·h^{-1}, respectively. If those checks failed, 15-min 'FLAT' windows within 05:00–06:30 defined by SD ≤ 15 ppm and |slope| ≤ 6 ppm·h^{-1} were identified and the baseline was set to the lowest 15-min mean among those FLAT windows.

2.7 Statistical analysis

Descriptive analyses, including calculation of means, peaks, and daily/hourly averages, were performed using Microsoft Excel and Google Sheets. Statistical analyses were performed using Python 3.11. Differences in mean PM_{10} concentrations between weekdays and weekends were assessed using Welch's *t*-test for unequal variances, with 95 % CIs derived via the Welch–Satterthwaite approximation. A Mann–Whitney *U* test was additionally applied as a non-parametric verification.

Effect sizes were computed to quantify the magnitude of the difference, including Hedges' *g* (bias-corrected Cohen's *d*) and the rank-biserial correlation (equivalent to Cliff's δ). A two-tailed significance level of $p < 0.05$ was used for all tests.

Associations between CO_2 and particulate matter ($PM_{2.5}$, PM_{10}), as well as among particulate fractions (PM_1, $PM_{2.5}$, PM_{10}), were assessed with Spearman's rank correlation (ρ), a nonparametric method that does not require normality or linear relationships. Since the three particle size fractions were perfectly correlated across the monitoring period ($\rho = 1.00$, $p < 0.0001$, $n = 19{,}777$), subsequent inferential analyses were performed only on PM_{10} as a representative size fraction, thereby avoiding redundancy while retaining full interpretive value. Residual analyses were also performed for all ten daily decay experiments to verify model assumptions.

2.8 Ethics statement
This study involved environmental monitoring of IAQ in a gymnasium setting. No human subjects were directly recruited, and no personal or identifying information was collected. Measurements were limited to physical parameters obtained from fixed-location sensors.

Since the study took place in an occupied space, signage was provided to inform users of the monitoring activity. Data were not linked to specific individuals, classes, or activities.
If IAQ levels were found to exceed health or comfort guidelines, results were communicated to facility managers to promote safe and informed decision-making. All procedures were performed in accordance with widely accepted standards for indoor air quality research (20,21).

3. Results

3.1 CO_2 and PM concentration patterns

Two representative 24-hour profiles of indoor CO_2 and particulate matter (PM) concentrations in the weight room are first presented (Figures 7 and 8). These profiles captured gym opening and closing periods, the buildup of CO_2 during occupancy, the post-closure decay segment used to estimate daily ACR, and PM fluctuations linked to HVAC operation, including the nighttime rise when the system was turned off.

3.1.1 *Particulate matter and CO_2 concentration*
Across the full monitoring period, CO_2 and PM showed weak to moderate negative correlations.

On weekdays, Spearman coefficients were –0.43 for both $PM_{2.5}$ and PM_{10} ($p<0.0001$, $n=14,126$ for each PM type). On Saturdays, correlations were slightly stronger but still negative (for both $PM_{2.5}$ and PM_{10}, $\rho = –0.58$, $p<0.001$, $n=2,825$). These results suggest that PM dynamics were largely independent of occupancy-driven CO_2 patterns.

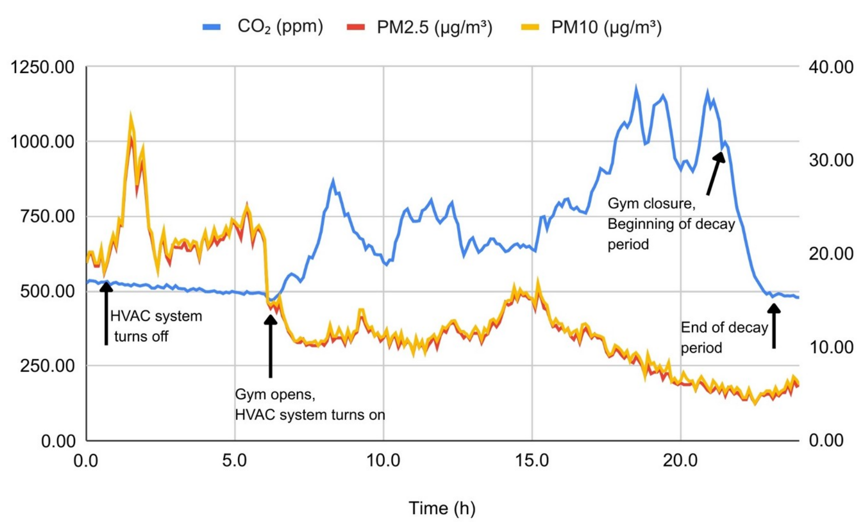

Figure 7. PM (Right Y-axis) and CO_2 (Left Y-axis) concentrations on Tuesday, July 29, 2025, averaged over 0.1h intervals

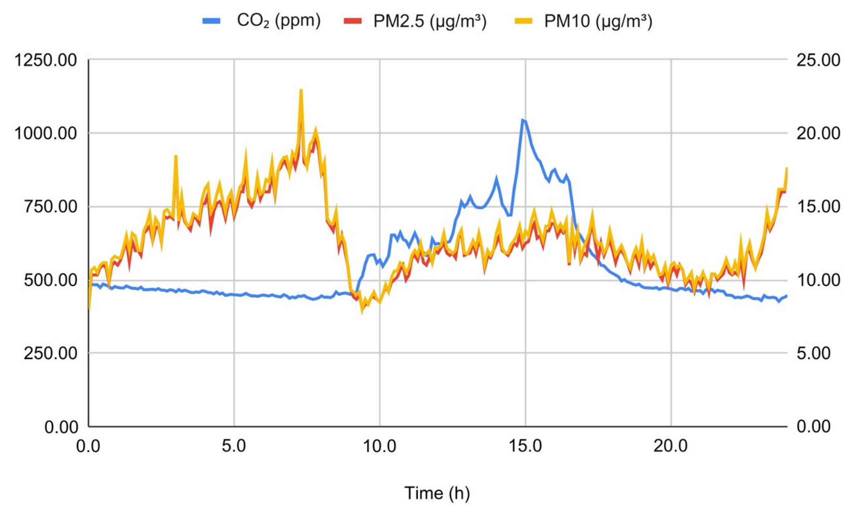

Figure 8. PM (Right Y-axis) and CO_2 (Left-Y-axis) concentrations on Saturday, August 2, 2025, averaged over 0.1h intervals

3.1.2 *CO_2 concentrations*

Building on this overview, Figures 9 and 10 present hourly average CO_2 concentrations on a representative weekday (July 30) and a Saturday (August 2), showing how levels closely track gym occupancy patterns, rising after opening and decaying after closure. CO_2 concentrations consistently peaked near closing hours, which the facility manager confirmed corresponded to the period of highest occupancy. Figure 11 shows the contrasting Sunday profile, when the facility was closed and concentrations remained steady throughout the day.

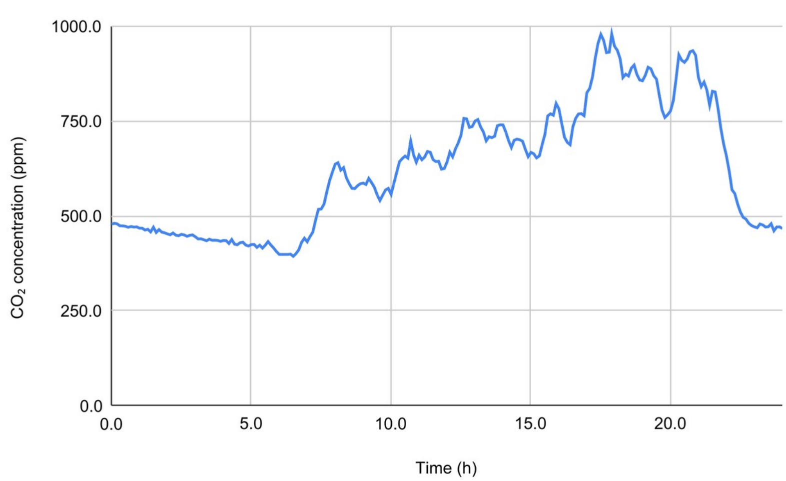

Figure 9. CO_2 concentrations on Wednesday, July 30, 2025, averaged over 0.1h intervals. (open hours 6:30-21:30)

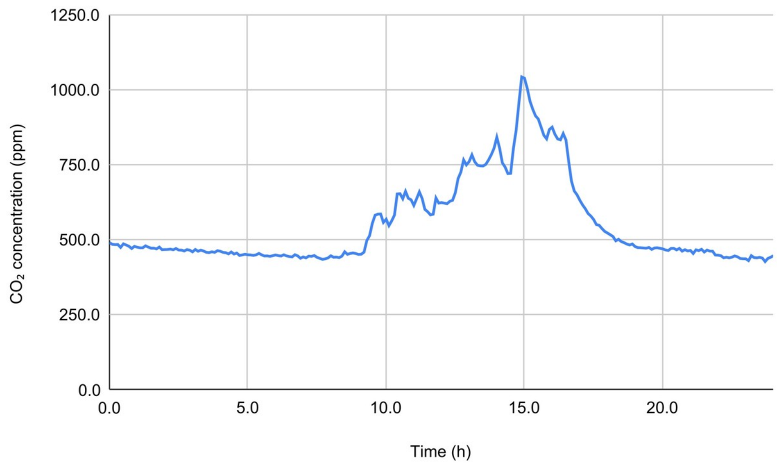

Figure 10. CO_2 concentrations on Saturday, August 2, 2025, averaged over 0.1h intervals. (open hours 9-16:30)

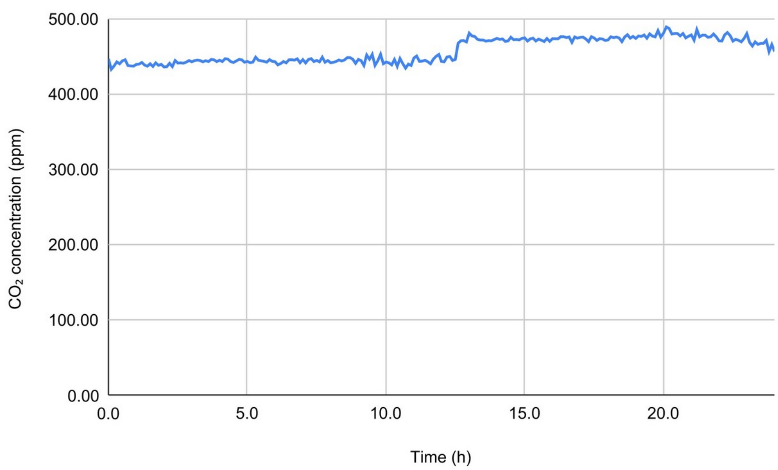

Figure 11. CO_2 concentrations on Sunday, August 8, 2025, averaged over 0.1h intervals. No significant rise in concentration was observed because the weight-room is closed on Sundays.

3.1.3 *Particulate matter concentrations*

Table 1 summarizes PM_{10} concentrations during open hours for weekdays and Saturday. Average weekday concentrations were 9.2 ± 5.0 µg m^{-3}, while Saturday values were significantly higher at 15.7 ± 5.1 µg m^{-3}, representing an increase of approximately 6.5 µg m^{-3}. Peak PM_{10} levels reached 56 µg m^{-3} on weekdays and 60 µg m^{-3} on Saturday.

The difference between weekdays and weekends was statistically significant (Welch's t = –35.5, $p<10^{-180}$; Mann–Whitney U = 954,827, $p<10^{-250}$). The mean difference (95 %

CI = 6.15–6.87 µg m^{-3}) corresponded to a large effect (Hedges' g = 1.30; rank-biserial = 0.71), indicating that weekend PM_{10} concentrations were significantly and consistently higher than weekday levels.

Table 1. Mean and peak PM_{10} concentrations during open hours

Period	Samples	Days	PM_{10} Mean (µg/m³)	PM_{10} Peak (µg/m³)
Weekdays (6:30-21:30)	7,602	9	9.2	56
Saturday (9-4:30)	886	2	15.7	60

PM_1, $PM_{2.5}$, and PM_{10} were strongly correlated across the monitoring period. Spearman's rank coefficients were 1.00 for all pairwise comparisons (p<0.0001, n=19,777), indicating that the three particle fractions varied in near-perfect synchrony.

3.2 Compliance with health guidelines

Compared with the WHO 24-h guideline at 15 µg/m³ for $PM_{2.5}$ (26), exceedances were observed in the Monday, Saturday, and Sunday daily averages (See Table 2). When considering only opening-hour means, exceedances occurred on Saturdays. PM_{10} concentrations remained well below the WHO 24-h guideline of 45 µg/m³ throughout the week.

Table 2. Mean 24-h PM concentrations

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Total
PM2.5	17.99	11.22	12.15	10.19	10.76	19.72	22.34	14.66
PM10	18.64	11.60	12.70	10.65	11.29	20.87	23.76	15.40

3.3 Ventilation

Ventilation rates across 10 nights of post-closure monitoring (excluding July 25 and August 4), ACR ranged from 1.00 to 1.94 h^{-1}. All studied decay curves were well captured by the exponential model (eq 5), with R^2 values between 0.95 and 0.99 and residuals symmetrically distributed around 0, confirming the adequacy of the fit. A representative decay curve and fit are shown for a single night (Figure 12). The distribution of nightly ACR values (Figure 13) yielded a mean of 1.51 ± 0.37 h^{-1} (95% CI: 0.96–1.88), where the uncertainty range reflects results from a 10000-run Monte Carlo analysis that accounted for sensor noise and fitting-window variability (see section 2.3 of Methods).

The volumetric outdoor airflow was calculated to be 184 $L s^{-1}$. $Q = \frac{1.51 \times 43}{3.6} \approx 184\, L s^{-1}$, where $V_{oz} = 184\, L s^{-1}$ corresponding to an ACR of 1.5 $h^{-1}$for $V = 439\, m^3$). The area component was calculated as $R_a A_z = 0.30 \times 168.84 = 50.7\, L s^{-1}$. Occupancy supported under ASHRAE 62.1. Solving $P_z = \frac{V_{oz} E_z - R_a A_z}{R_p}$, as $P_z = \frac{(1.2 \times 184) - 50.7}{10} = 17.0 \Rightarrow 17$ persons.

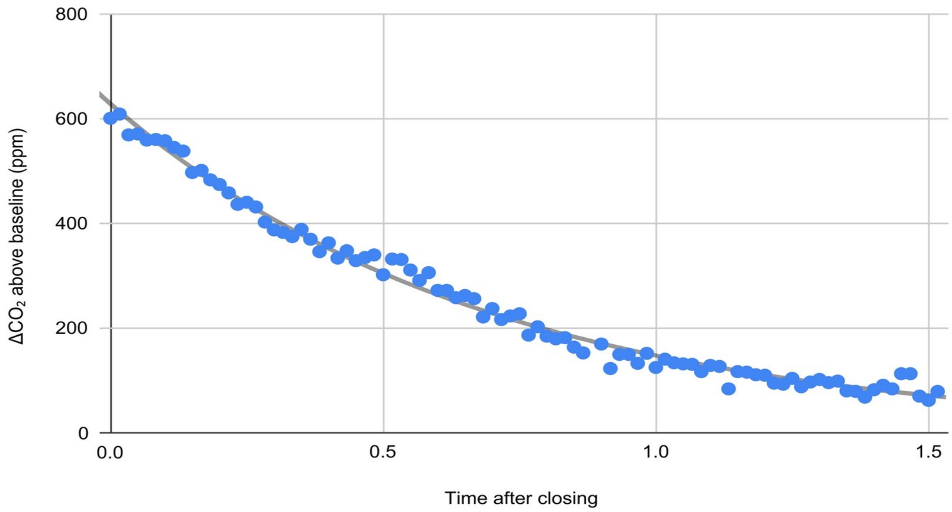

Figure 12. ΔCO_2 vs. time after closing. The decay curve is fitted with an exponential model

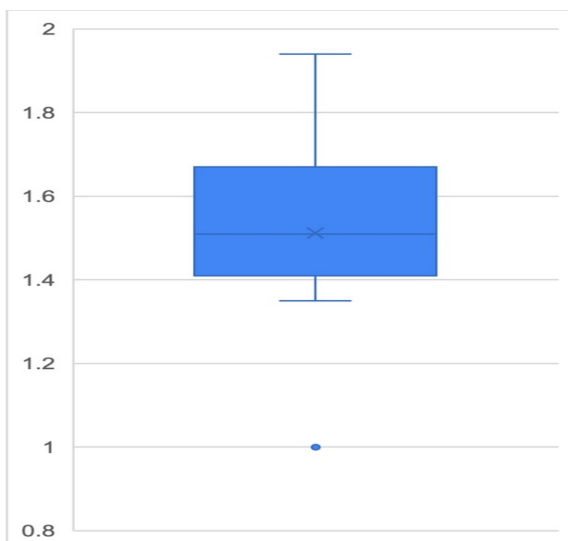

Figure 13. Distribution of ACR values (h^{-1}, Y-axis) across nights,

With a measured outdoor airflow of 184 $L \cdot s^{-1}$, the room met the ASHRAE 62.1 minimum ventilation at ~ 17 occupants under displacement-style distribution. These counts already included the area-based requirement (50.7 $L \cdot s^{-1}$). Occupancies beyond these values would require proportionally greater outdoor air delivery or reduced density to maintain compliance. It is important to note that this study was performed in the summer, which is a relatively low occupancy period for the university gym. Thus, the current measured outdoor airflow may not be sufficient in periods with higher occupancy (n>17).

3.4 Baseline CO_2

Outdoor baseline CO_2 concentrations averaged 453 ppm (median = 451 ppm), with daily values ranging from 400 to 503 ppm (Table 3). The standard deviation was 31.9 ppm, which is within the sensor's stated accuracy of ±(50 ppm+5% of readings). Across the monitoring period, baseline values varied by 103 ppm, a range that was comparable to the typical outdoor background fluctuations (±50–100 ppm) and ~ twice the instrument's margin of error. This indicated that outdoor conditions were relatively stable across days. The typical indoor-outdoor difference during open hours was about +349 ppm above baseline. As shown in Table 3, baseline values fluctuated modestly from day to day but showed no consistent upward or downward trend.

Table 3. Daily baseline CO_2 concentrations (averaged from 5:00–6:30 am)

Date	July 25	July 26	July 27	July 28	July 29	July 30	July 31	Aug 1	Aug 2	Aug 3	Aug 4	Aug 5	Aug 6	Aug 7
Baseline CO2 (ppm)	420	439	462	493	402	400	454	447	444	468	503	444	476	490

4. Discussion

This study quantified ventilation in a weight room using the CO_2 decay method, yielding an average ACR of 1.5 h^{-1}. This corresponds to a maximum recommended occupancy of ~ 17 people. Average indoor CO_2 concentration was 792 ppm during open hours, which generally tracked occupancy patterns. In contrast, PM concentrations did not consistently follow changes in occupancy. $PM_{2.5}$ levels showed mild exceedances during opening hours, with Saturday values (15.3 µg/m³) slightly surpassing the WHO 24-hour guideline of 15 µg/m³.

The objective of this study was to demonstrate a low-cost method for assessing ventilation using an inexpensive monitoring device, providing an alternative to costly consultant services. The monitoring device proved effective as a ventilation diagnostic, offering a replicable framework for mitigating pollutant buildup, ensuring compliance with ASHRAE standards, and guiding facility management, at a fraction of the cost of commercial systems. This accessibility highlights its potential for wider adoption, particularly in regions where IAQ monitoring is not routinely mandated.

Although CO_2 is not itself a pollutant of concern, elevated indoor concentrations provide a practical proxy for ventilation adequacy. Under current conditions, limiting occupancy to ~ 17 people would keep the room compliant with ASHRAE standards. These standards were developed to assure sufficient ventilation for a healthy environment and represent a good tradeoff point between energy expenditures and health outcomes (27).

The build-up of PM in the late night/early morning hours, opposite to CO_2, was intriguing. As shown in Figures 7 and 8, the PM decreased when the HVAC system turned on in the morning, and then increased when it was turned off in the evening. The off-hours aerosol source could be related to chemical processes related to cleaning compounds or volatile organic materials in the recycled rubber flooring (8,9).

Similar observations have been reported in previous studies, which found weak or absent CO_2–PM correlations. For instance, Ramalho et al. reported weak but significant positive correlations between CO_2 and PM,($r = 0.21$ for PM_{10}; $r = 0.12$ for $PM_{2.5}$), which were strongest during the heating season and absent in non-heating months (28), while Wang et al. found strong correlations on a university campus attributed to its urban location (29). These variations suggest that CO_2–PM relationships are context-dependent, reflecting differences in ventilation regimes and outdoor pollution rather than occupancy. In fact, particulate matter concentrations are influenced by outdoor sources (30,31), suggesting that PM dynamics in indoor spaces are frequently dominated by exterior conditions rather than internal activity. The indoor concentration changes could equally be driven by changes in the particle formation inside the gym and hygroscopic growth and shrinkage. Further investigation is needed to clarify the PM concentration changes observed.

This study's short duration (two weeks) and relatively low occupancy period limit the generalizability of the findings. It should also be emphasized that the CO_2 decay–derived ACR represents total air exchange, including both mechanical ventilation and uncontrolled infiltration. Because ASHRAE's zone outdoor airflow (V_{oz}) represents only the intentional mechanical supply, the decay results are indicators of effective dilution performance rather than adequate design compliance. Unless natural air infiltration is part of the design, the decay method should be applied only with windows and other openings closed to assess design compliance.

Finally, a key assumption of the ACR analysis was that the mechanical ventilation system operated identically during the 1.5-hour decay period as it did during normal business hours. In reality, the absence of occupants reduces the thermal load, potentially lowering the frequency of cooling cycles and leading to an underestimation of the effective ACR. The building operator confirmed that the fresh air change was constant in the hours after closure, however because the fresh air flow was not measured directly, further verification of this information could not be performed. Furthermore, it was assumed that the baseline was steady during the 1.5 hour window used for ACR calculations, a more robust approach would include a second CO_2 sensor placed outside to account for these potential shifts. These limitations should be considered when interpreting the results.

Translating ACR into occupancy limits provides facility managers with a practical tool for safeguarding both health and performance. Incorporating ventilation diagnostics into routine monitoring represents a critical step toward healthier, safer, and more sustainable athletic environments.

5. Conclusion

This study applied CO_2 decay analysis to evaluate ventilation in a university gym, demonstrating that ACR can be translated into practical occupancy thresholds. The measured average ACR of 1.5 h^{-1} supported a maximum of ~17 occupants under ASHRAE 62.1, offering a clear benchmark for facility management. Current occupancy rates at the facility studied, routinely exceeded this value. Indoor CO_2 concentrations reliably tracked occupancy, confirming its role as a robust proxy for ventilation adequacy. By contrast, particulate matter concentrations showed weaker associations with occupancy and occasional exceedances of the WHO 24-h $PM_{2.5}$ guideline, indicating that PM levels are influenced by multiple factors, including outdoor conditions and system dynamics.

Using a low-cost sensor system, this work demonstrated that ventilation diagnostics could be performed affordably and effectively. Incorporating such methods into routine monitoring provides a replicable framework for maintaining compliance, mitigating disease, and safeguarding health in public indoor environments.

6. References

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