Peer-Review

Shihadeh, Layla. 2025. "Translating CO2 Decay into Ventilation and Occupancy Guidance Using a Low-Cost IAQ Monitor: Particulate Matter and Air Quality in a University Weight Room." *Journal of High School Science* 9 (4): 109–28. https://doi.org/10.64336/001c.146444

The experimental design and device construction is generally well conceived. The paper is well written and well presented. However, there are certain implicit assumptions and estimations that need justification; calibration, monitoring and statistical inadequacies that need explanation and discussion; and omission of controls, normalization, model uncertainty propagation and model sensitivity analsyses that need inclusion in the manuscript. Specific comments appear below.

1.equating decay-derived total outdoor air + infiltration directly to ASHRAE's zone outdoor airflow (Voz) is an assumption that may overstate compliance for design purposes; clarify limits.

2.The low-cost-to-occupancy translation is practical but not novel; consider adding: (1) co-location calibration against reference instruments; (2) multi-point spatial sampling; (3) direct HVAC outdoor air fraction measurements; (4) model-based uncertainty propagation; (5) occupancy counting and intensity (metabolic rate) adjustments; (6) humidity correction for PM sensors; (7) open-source code/data repository.

3.States well-mixed room, S=0 post-closure, and treats decay-derived Q as Voz; mixing and displacement ventilation nuances, infiltration contributions, and sensor accuracy/ drift are only partially justified; discuss potential biases and bounds.

4.Two-week, single-room, single-sensor deployment during low-occupancy season limits generalizability; lacks sensitivity analyses (e.g., to mixing, baseline selection, spike filtering thresholds) and redundancy (replicate sensors). No deliberate variation of ventilation setpoints to explore response.

5.Reports Spearman correlations and ACR 95% CI; however, lacks p-values, sample sizes, residual analyses for decay fits, and formal uncertainty propagation; no multiple-comparison or assumption checks reported.

6.No explicit positive/negative controls, calibration checks, or duplicate sensors; no outdoor reference monitor to separate infiltration from indoor sources; add calibration gases or co-location with reference instruments.

7.CO2 baseline estimation is described, but no correction for PM hygroscopic growth (RH), instrument drift, or HVAC schedules; occupancy and outdoor PM influences not partialed out; consider mixed models or partial correlations.

8.Data normalization not described (e.g., PM for RH, occupancy intensity, or time-of-day effects); clarify whether any normalization was applied or justify omission.

1.equating decay-derived total outdoor air + infiltration directly to ASHRAE's zone outdoor airflow (Voz) is an assumption that may overstate compliance for design purposes; clarify limits.

Thank you for bringing my attention to this important point. I have now clarified in the Discussion Section that the CO_2 decay–derived air change rate reflects total air exchange (mechanical ventilation and uncontrolled infiltration) and thus the decay results are indicators of effective dilution performance rather than strict design compliance. The revised Discussion section also mentions that 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.

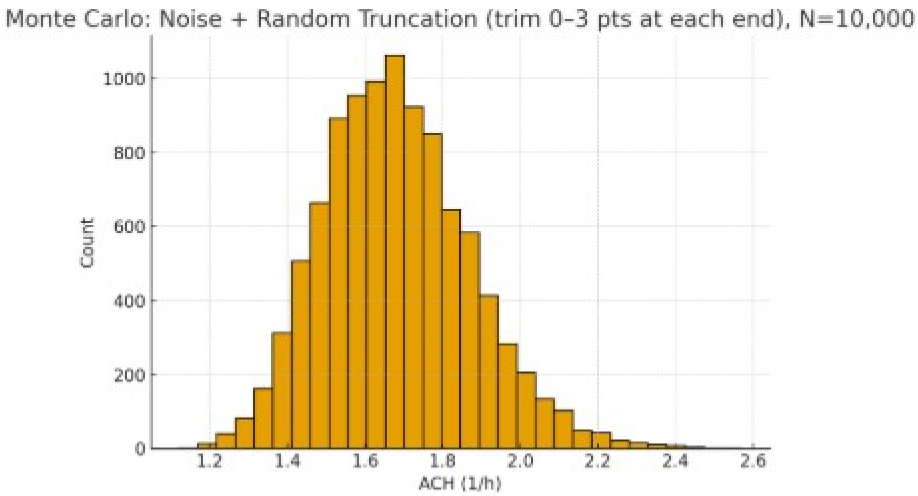
2.The low-cost-to-occupancy translation is practical but not novel; consider adding: (1) co-location calibration against reference instruments; (2) multi-point spatial sampling; (3) direct HVAC outdoor air fraction measurements; (4) model-based uncertainty propagation; (5) occupancy counting and intensity (metabolic rate) adjustments; (6) humidity correction for PM sensors; (7) open-source code/data repository.

(1) The reviewer raises an important question on the accuracy of the device. In response, I conducted a co-location calibration experiment using a reference-grade instrument, the GC-2028 CO_2 monitor. The experiment was performed in a household kitchen environment: the stove was turned on to allow CO_2 concentrations to rise, followed by ventilation through window opening and fan operation to observe the decay phase. Measurements from both devices were recorded at 61-second intervals throughout the experiment. The comparative results have been added as a new section (*Section 2.2.2: Sensor Calibration*). The observed differences between the two instruments were within their respective margins of error, demonstrating that the custom-built sensor provided measurements corresponding to those of the reference instrument.

(2) I appreciate the reviewer's suggestion, and I have clarified this concern in the Methods Section. The sensor was located in the middle of the room on a wall at breathing level. Air conditioning ducts were located on the opposite wall. The sensor location therefore is not biased by being in a fresh air stream flow. I have clarified this in the methods section.

(3) While I agree that direct measurement would be ideal, it was not feasible to measure this directly because the fresh air is drawn through a mixing box that combines recirculated air with fresh air. The box and ducting are not accessible to the public.

(4) In accordance with model-based uncertainty propagation, additional statistical tests were conducted. The plot below shows the results for August 1st, and the following paragraph was added to the Methods Section (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. Because 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) cancels out and does not influence the ACR. The resulting distribution of fitted ACR values had a standard deviation of 0.19 h^{-1}, corresponding to a 95 % confidence interval of ±0.37 h^{-1}. This interval represents 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.

(5) The reviewer's feedback helped clarify this aspect, as detailed below. The value $R_p = 10\, L\, s^{-1}\, person^{-1}$ is specific to weight rooms thus other values specified by ASHRAE for different fitness rooms are not applicable in this context. I've clarified that this ASHRAE standard value is a mean value which may or may not fully represent the gym users on a given day. For example, when the gym is being used by the varsity team for intensive supervised training, the value may be higher. However, ASHRAE recommends this value for ordinary recreational gym use. This caveat was added to section *2.5 Compliance with ASHRAE*.

(6) The reviewer raises an important point. The PMS5003 readings were collected without concurrent RH measurements; therefore, humidity-induced positive bias could not be corrected. However, because PM variability can also result from several secondary factors independent of occupancy—including outdoor pollution infiltration, hygroscopic particle growth under humid conditions, and other indoor aerosol sources—it was noted in the Discussion that no definitive conclusions were drawn, and that further extensive research is required to quantify sources.

(7) The code, dataset, component list (including prices), wiring diagram, and step-by-step assembly guide were made publicly available in an open-source code and data repository on GitHub (https://github.com/laylashihadeh26-ctrl/esp32-air-quality-logger). This is also now mentioned in section 2.2.3 of the paper.

3. States well-mixed room, S=0 post-closure, and treats decay-derived Q as Voz; mixing and displacement ventilation nuances, infiltration contributions, and sensor accuracy/ drift are only partially justified; discuss potential biases and bounds.

Thank you for this helpful comment, I have revised the text accordingly by adding additional material to the Methods Section that clarifies the potential biases. In brief, I added that to ensure CO_2 decay measurements were representative of the bulk room air, sensor placement was selected to avoid proximity to any supply or inlet air stream, where concentrations would be artificially diluted. The ideal location for CO_2 monitoring is near the air return, which provides a well-mixed average of the indoor air. In this study, the sensor was positioned accordingly to minimize local bias in ACR estimation.

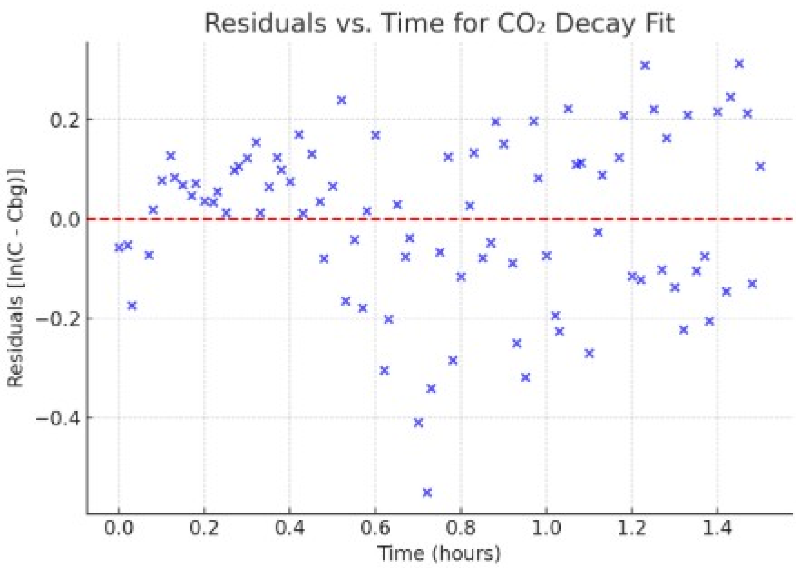
A limitation of the study is that I assumed that the mechanical ventilation system is unaffected by the closure of the facility for the 1.5 hours of the decay measurements. In reality, the absence of occupants reduces the thermal load, potentially lowering the frequency of cooling cycles and leading 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, I could not independently verify the information provided. These limitations have been added to the discussion section.

4. Two-week, single-room, single-sensor deployment during low-occupancy season limits generalizability; lacks sensitivity analyses (e.g., to mixing, baseline selection, spike filtering thresholds) and redundancy (replicate sensors). No deliberate variation of ventilation setpoints to explore response.

I acknowledge that the two-week, single-room, single-sensor deployment conducted during a low-occupancy period limits generalizability; this limitation is noted in the Discussion. Regarding sensitivity and redundancy, measurements were cross calibrated with a reference instrument as mentioned above, and sensitivity to baseline selection and spike filtering thresholds was explored through the Monte Carlo simulation described above. Deliberate variation of ventilation setpoints was not feasible, as the study site was an institutional facility where HVAC controls could not be altered.

5. Reports Spearman correlations and ACR 95% CI; however, lacks p-values, sample sizes, residual analyses for decay fits, and formal uncertainty propagation; no multiple-comparison or assumption checks reported.

The reviewer raises a valuable point. To address this and improve the thoroughness of our analysis, the following has been added to the *Statistical Analysis* subsection (2.7) and subsection 3.3 of the Results (*Ventilation*). "Residual analyses were conducted for all ten daily decay experiments. In each case, residuals were symmetrically distributed around zero with no discernible temporal structure, supporting the assumption of exponential decay. The fits yielded coefficients of determination (R^2) between 0.95 and 0.99, indicating that the model explained more than 95 % of the variance in the log-transformed data." Representative residual plots are provided in the figure below for one of the days.



I have also included p-values as well as sample sizes in the *particle-size correlation* and *PM–CO_2 correlation* subsections. Formal uncertainty propagation was addressed through the Monte Carlo–based simulation as mentioned above.

Additionally, I've added a new paragraph in Section 2.7 detailing the comparative tests used for PM_{10} and specified the values in results. Specifically, it now states that differences in mean PM_{10} concentrations between weekdays and weekends were evaluated using Welch's *t*-test with 95 % confidence intervals (Welch–Satterthwaite approximation) and verified with the Mann–Whitney *U* test. Effect sizes (Hedges' *g* and rank-biserial correlation) and a significance threshold of $p < 0.05$ were also reported.

We now distinguish two uncertainties in ACR: (i) the confidence interval for the mean ACR across days (n = 10), which quantifies day-to-day variability in the space, and (ii) the per-day measurement uncertainty from Monte Carlo simulation, which quantifies precision of a single decay fit given sensor noise and truncation sensitivity. For our dataset, the across-day 95% CI for the mean ACR was ±0.18 h^{-1} (n = 10), whereas the per-day measurement uncertainty was ±0.37 h^{-1} (95% CI, n=10,000). Reporting the larger interval provides a more conservative value. This has been clarified in Methods Section 2.4 *"Uncertainty Analysis of ACR Estimates"*.

6. No explicit positive/negative controls, calibration checks, or duplicate sensors; no outdoor reference monitor to separate infiltration from indoor sources; add calibration gases or co-location with reference instruments.

The reviewer points out the lack of explicit controls and external validation. Likewise, no external validation was available to confirm that the computed ACR values matched the true ACR. Nonetheless, the tracer gas decay approach used here represents the established gold standard for estimating air change rates. The primary contribution of this work lies in demonstrating the feasibility of building and deploying a low-cost monitoring system that can be implemented by non-experts without the need for costly consultancy services to rapidly check the adequacy of the ventilation. This method may not be sufficient on its own to assess the design compliance of the HVAC system with ASHRAE. A calibration subsection has been added, as noted above.

7. CO2 baseline estimation is described, but no correction for PM hygroscopic growth (RH), instrument drift, or HVAC schedules; occupancy and outdoor PM influences not partialed out; consider mixed models or partial correlations.

I agree with the reviewer that PM is influenced by hygroscopic growth and particularly in environments like Beirut which is dominated by secondary organic aerosols that are hygroscopic. The set up does not distinguish the water portion of the PM and determining the composition of the PM was not an aim of this study nor was it used in the analysis. That said, hygroscopic growth cannot be ruled out as one of the factors driving the PM concentration changes observed. I have added a clarification in the Discussion.

The HVAC schedule was confirmed with the building manager to remain active for approximately two hours after facility closure, aligning with the ACR measurement window.

8. Data normalization not described (e.g., PM for RH, occupancy intensity, or time-of-day effects); clarify whether any normalization was applied or justify omission.

Thank you for noting this. The raw CO2 values were baseline corrected as described in the methods section. CO_2 levels above baseline reflect occupancy as explained in the introduction. We did not normalize for occupancy when computing ACR because the occupancy was always zero for the time window analyzed (i.e. after closure). Regarding CO_2 baseline shifts during the decay period used to analyze ACR, it was assumed that the shift was negligible. A more robust method would employ a second CO2 sensor to adjust for any shift; however, I did have access to a second sensor. Nonetheless, on the days in which the gym was closed we saw that the baseline CO_2 level was steady for far longer than the 1.5-hour window (See Figure 11). We have acknowledged this limitation in the Discussion Section of the revised manuscript.

Author Note: Table 1 from the original manuscript has been removed, as it did not contribute substantially to the interpretation of the results. The current Table 1 (previously Table 2) has been revised to exclude $PM_{2.5}$ values. Because the particle size fractions were perfectly correlated across the monitoring period ($\rho = 1.00$, $p < 0.0001$, $n = 19\ 777$), subsequent analyses focused on PM_{10} as a representative measure to avoid redundancy while retaining full interpretive value. In the revised manuscript, changes and additions are marked in blue.

Thank you for addressing my comments. Accepted.