Journal of
Petroleum Gas & Chemical Engineering

Research Article

ISSN: 3069-2075

Dynamic Analysis of Indoor Carbon Dioxide Concentrations on a Campus

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Received: 2025 November 08 **Accepted:** 2025 November 27 **Published:** 2025, December 06

Abstract

Indoor air quality (IAQ) has become an emerging public health concern, particularly in densely occupied educational environments. This study investigated the temporal dynamics of indoor carbon dioxide (CO_2) concentrations in a university classroom and quantified ventilation conditions and human CO_2 emission rates under controlled and real occupancy scenarios. Continuous CO_2 monitoring was performed in three controlled experiments and five actual class sessions. The controlled experiments were conducted with seven occupants under fixed ventilation conditions, in which air conditioning was operating, windows were slightly opened, and the door was closed. Background CO_2 levels ranged from 430 to 450 ppm. After the occupants entered the facility, the indoor CO_2 concentrations increased to 610–720 ppm (1,117–1,318 mg/m^3) and returned to baseline when the room was vacated. Air exchange rates (a) were calculated from the decay phase of CO_2 time-series data, yielding values between 1.60 and 1.79 h^{-1} (mean: 1.69 ± 0.09 h^{-1}). Total CO_2 emission rates (S) were derived from the rising segment of the time-series data, resulting in values of 162–208 g/h, corresponding to per-person emission rates (SPs) of 23.1–29.5 g/h/person (mean: 25.9 ± 3.3 g/h/person), consistent with light-intensity activity. During the five monitored lectures (42–52 occupants), background CO_2 levels ranged from 440 to 470 ppm, while peak CO_2 concentrations reached 1,000–1,450 ppm (1,830–2,653 mg/m^3), exceeding the regulatory limit of 1,000 ppm. The average air exchange rate during teaching sessions was 2.45 ± 0.78 h^{-1}, comparable to that in the controlled scenarios. The mean per-person CO_2 emission rate during actual classes was 20.38 ± 4.42 g/h/person, corresponding to mild activity such as sitting and listening. These findings demonstrate inadequate ventilation performance in the evaluated classroom and highlight the need for improved IAQ management in higher education institutions. This work provides actionable guidance for improving IAQ management in higher education environments.

Keywords: Carbon Dioxide, Indoor Air Quality, Air Exchange Rate, Co_2 Emission Factor, Classroom Ventilation

1. Introduction

Indoor air quality (IAQ) has gained increasing public and scientific attention due to its direct impact on human health, cognitive performance, and overall well-being. Individuals spend approximately 80–90% of their time in indoor environments, such as homes, offices, and educational institutions, where pollutant exposure may be significantly greater than that outdoors. Poor IAQ has been associated with adverse health effects, including discomfort, respiratory irritation, reduced cognitive function, and decreased productivity [1]. Major sources of indoor air pollution can be categorized into eight groups: infiltration of outdoor pollutants, indoor combustion, paints and coatings, office equipment, cleaning agents, biological contaminants, human respiration and activities, and other miscellaneous sources [2]. Cigarette smoke generates nicotine, carbon monoxide (CO), CO_2, tar, and other harmful substances. Additionally, allergens such as pollen, pet dander, and shed skin particles contribute to indoor particulate matter. Common IAQ pollutants include CO_2, CO, particulate matter ($PM_{2.5}$ and PM_{10}), ozone (O_3), and volatile organic compounds (VOCs), which may cause dizziness, eye and respiratory irritation, and reduced cognitive performance. In environments with limited ventilation, indoor pollutant concentrations frequently exceed outdoor levels [3].

2. Materials and Methods

This section outlines the study site characteristics, instrumentation, monitoring design, and analytical methods used to quantify the indoor CO_2 dynamics, air exchange rates, and human CO_2 emission factors. A mass-balance modeling approach was applied to evaluate ventilation performance under both controlled experimental conditions and actual classroom occupancy.

2.1. Study Site

The investigation was conducted at National Chung Cheng University (CCU), located in Minxiong Township, Chiayi County, Taiwan. The campus lies within the Yun-Chia-Nan Air Quality Region and is characterized by a subtropical monsoon climate with distinct seasonal variabilities in temperature, humidity, and prevailing wind patterns. The university occupies an area of approximately 134.23 hectares and accommodates nearly 11,000 students and faculty. Indoor CO_2 monitoring was performed in Classroom 102 of the Earth Sciences Building (referred to as the "Seismology Hall") within the College of Science. The classroom was selected because it represents a typical university lecture environment with common ventilation conditions. The room is equipped with ceiling-mounted split-type air-conditioning units and has limited natural ventilation, except for a single entrance door and windows along one side of the room. This enclosed setting provides a suitable environment for assessing CO_2 accumulation and ventilation performance during teaching activities.

2.2. Instrumentation

Indoor CO_2 concentrations were measured using a calibrated nondispersive infrared (NDIR) CO_2 analyzler (Model HPC-AN15AD-TM, Han-Ping Corp., Taiwan). The instrument has a measurement range of 0–5,000 ppm (0–9,150 mg/m^3), an accuracy of ±30 ppm or ±3% of the reading (whichever is greater), and a resolution of 1 ppm. The analysis was factory-calibrated prior to the campaign, and a two-point field calibration check was performed using zero air and a certified standard span gas (1,000 ppm). Air samples were drawn through a 5 m polytetrafluoroethylene (PTFE) sampling tube to minimize adsorption or chemical interaction. The sampling inlet was positioned approximately 1.1 m above the floor to represent the human breathing zone and to avoid stratification biases. Indoor temperature and relative humidity were simultaneously recorded using a HOBO data logger (Onset Computer Corporation, USA) to support interpretation of CO_2 variations under different thermal conditions. For reference, outdoor CO_2 concentrations were periodically measured near the building entrance.

2.3. Monitoring Design

Indoor CO_2 concentrations were monitored under two distinct scenarios.

- controlled experiments with a fixed number of occupants and ventilation settings and
- real classroom teaching sessions with naturally varying occupancies.

The monitoring period consisted of three controlled experiments, each lasting approximately 60–90 min, and five classroom sessions lasting 100–150 min. All monitoring was performed on weekdays during regular academic schedules. In the controlled setting, seven volunteer participants remained seated and refrained from unnecessary movement to standardize metabolic CO_2 output. The classroom door remained closed, windows were slightly opened (~3–5 cm), and the air conditioning system was operated continuously at a constant fan speed. During actual teaching sessions, the instructor conducted the class under routine conditions, and no restrictions were imposed on student movement or behavior. Occupancy ranged from 42 to 52 individuals. Entry and exit times, door opening frequency, and noticeable changes in ventilation conditions were recorded throughout the sessions. Indoor CO_2 concentrations were logged at 10-second intervals (0.1 Hz) to capture short-term variations. The temporal resolution allowed accurate analysis of the CO_2 build-up and decay phases, ensuring reliable estimation of air exchange and emission rates.

2.4. Mass-Balance Model for CO_2 Dynamics

Changes in the indoor CO_2 concentration were analyzed using a standard mass-balance model, which assumes that CO_2 within the classroom is well mixed. The temporal variation in the CO_2 concentration is governed by the following differential equation.

$$\frac{dC(t)}{dt} = a[C_{\text{out}} - C(t)] + \frac{S}{V} \quad (1)$$

where
C(t)= indoor CO_2 concentration at time t(ppm)
C_{out} = outdoor CO_2 concentration (ppm)
a= air exchange rate (h^{-1})
S= total indoor CO_2 emission rate (mg/h)
V= volume of the classroom (m^3)

To accommodate regulatory reporting conventions, CO_2 concentrations are presented primarily in ppm, with equivalent values in mg/m^3 given in parentheses. The conversion was performed as follows.

$$CO_2\ (\text{mg/m}^3) = CO_2\ (\text{ppm}) \times 1.83 \quad (2)$$

assuming 25°C and 1 atm pressure.

Decay Phase (Calculation of the Air Exchange Rate)

During the decay phase—after occupants exited the classroom—the emission term becomes negligible, and Equation (1) simplifies to.

$$\frac{dC(t)}{dt} = a[C_{\text{out}} - C(t)] \quad (3)$$

The solution yields.

$$\ln(C(t) - C_{\text{out}}) = -at + \ln(C_0 - C_{\text{out}}) \quad (4)$$

For each experiment, S was computed over 5-min intervals during the build-up phase to reduce noise and improve the stability of the estimates.

The per-person emission rate (SP) was then derived as follows.

$$S = V[\frac{dC(t)}{dt} + a(C(t) - C_{\text{out}})] \quad (5)$$

where *Nis* the number of occupants.

2.5. Data Processing and Quality Control

All CO_2 time-series data were screened to remove anomalous spikes caused by sudden door opening, instrument disturbance, or sensor resetting. Outliers exceeding three standard deviations from local running means were inspected and removed only when attributable to nonrepresentative events. The data were then smoothed using a 30-second moving average to reduce high-frequency noise while retaining short-term dynamic responses. For each experiment and class session, the following procedures were applied.

- **Identification of Key Time Intervals.**

background period,
build-up phase,
steady-state (if reached), and
decay phase.

- **Estimation of Parameters.**

Air exchange rates aware estimated from the decay phase.
CO_2 emission rates Sand SPwere computed from the build-up phase.

- **Cross-Validation.**

The calculated aand Svalues were cross-validated using multiple time windows to ensure consistency. Results differing by >15% were re-evaluated for data noise or unrecorded ventilation events.

Instrument calibration records and environmental metadata were archived to ensure reproducibility.

2.6. Ethical Considerations

All participants involved in the controlled experiments were adult volunteers recruited from the university and provided informed consent. No personal data were collected, and no physiological measurements were taken. The study exclusively monitored indoor CO_2 levels and general environmental parameters; therefore, it did not involve human subject research requiring institutional review board (IRB) approval. Nonetheless, ethical guidelines on privacy and voluntary participation were strictly followed.

2.7. Summary of Methods

This study combined continuous CO_2 monitoring with mass-balance modeling to evaluate the indoor ventilation performance and human CO_2 emissions in a university classroom.

Symbol	Definition	Unit
$C(t)$	Indoor CO_2 concentration at timet	ppm (mg/m^3)
C_{out}	Outdoor CO_2 concentration	ppm (mg/m^3)
a	Air exchange rate	h^{-1}
S	Total CO_2 emission rate	mg/h
SP	Per-person CO_2 emission rate	mg/h/person
N	Number of occupants	persons
V	Indoor volume of classroom	m^3

Table 1: Summarizes the Key Parameters and Variables Adopted in This Study.

The methodological framework enabled quantitative assessment of CO_2 accumulation and removal under both controlled and real classroom occupancy conditions, providing a robust basis for identifying ventilation inefficiencies and informing IAQ improvement strategies.

3. Results and Discussion – Part A

3.1. Background CO_2 Levels and Initial Conditions

Prior to each measurement, background CO_2 concentrations were recorded to establish reference conditions. Outdoor CO_2 concentrations ranged from 430 to 470 ppm (788–860 mg/m^3) throughout the monitoring period, consistent with typical suburban background concentrations in Taiwan. The indoor preoccupancy CO_2 concentrations were similar to the outdoor concentrations, indicating that the classroom was well ventilated before use or had sufficient time to return to baseline between sessions. Slight variations in background CO_2 levels between days may be attributed to meteorological conditions, including atmospheric mixing height, wind speed, and ventilation events occurring before monitoring (such as janitorial room access or air conditioner precooling). These initial conditions established a reliable baseline for evaluating CO_2 accumulation during occupancy.

3.2. CO_2 Dynamics in Controlled Experiments

Three controlled experiments were conducted to characterize the relationship between occupancy and the indoor CO_2 concentration under fixed ventilation conditions. Each experiment involved seven seated participants with the air conditioning system operating, windows slightly open (approximately 3–5 cm), and doors closed. This configuration simulated a minimally ventilated but commonly observed university classroom condition.

3.2.1. CO_2 Build-Up Patterns

Upon occupancy, the indoor CO_2 concentrations increased steadily from 430–450 ppm (788–860 mg/m^3) to 610–720 ppm (1,117–1,318 mg/m^3) within 40–55 minutes. The rate of increase ranged between 5.1 and 6.4 ppm/min, depending on the initial airflow and minor variability in participant metabolic activity. The observed build-up patterns demonstrated a nearly linear trend during the early phase of occupancy, gradually transitioning into a sublinear approach toward a quasisteady state. This behavior is consistent with the expected exponential model of indoor pollutant accumulation when emission and removal processes occur simultaneously. The moderate increase observed in the controlled setting relative to real class sessions reflects the low number of occupants. These findings align with studies indicating that CO_2 concentrations increase proportionally with the number of occupants and their metabolic activity under limited ventilation [4].

3.2.2. CO_2 Decay Patterns and Air Exchange Rates

Following the departure of occupants, CO_2 concentrations decreased toward outdoor levels. The decay curves exhibited strong exponential behavior, with R^2 values exceeding 0.95 for all three experiments, confirming that the indoor air was reasonably well mixed and suitable for mass-balance modeling.

The air exchange rates calculated from the decay phase ranged from.

• 1.60 to 1.79 $h/^1$, with a mean of 1.69 ± 0.09 $h/^1$

This rate is lower than the commonly recommended 3–6 h^{-1} for classrooms to maintain adequate IAQ, indicating insufficient ventilation. Similarly, low air exchange rates have been reported in university classrooms in East Asia, where reliance on air conditioning often leads to reduced natural air renewal [5]. The results demonstrated that even with windows slightly open, ventilation performance remained suboptimal due to limited airflow pathways and insufficient pressure differentials to promote exchange.

3.2.3. CO_2 Emission Rates Per Person

The total CO_2 emission rates (S) estimated from the build-up phase ranged from 162 to 208 g/h, translating to per-person emission rates (SP) of.

• 23.1–29.5 g/h/person, with a mean of 25.9 ± 3.3 g/h/person

These values correspond to light-intensity sedentary activity, consistent with metabolic CO_2 production during seated rest or quiet reading, and fall within previously documented ranges of 18–30 g/h/person for adults [3]. The controlled environment allowed for a stable estimation of human respiration-driven CO_2 emissions, establishing a baseline for comparison with real classroom conditions.

3.3. CO_2 Dynamics During Real Classroom Sessions

Five regular teaching sessions were monitored to examine CO_2 variations under realistic occupancy and natural classroom activities. The class duration ranged from 100 to 150 minutes, with 42–52 occupants present. Compared with those in the control experiments, the CO_2 concentrations increased more rapidly and reached substantially greater peak values. Indoor CO_2 concentrations during lectures rose from background levels of 440–470 ppm (805–860 mg/m^3) to peak concentrations of 1,000–1,450 ppm (1,830–2,653 mg/m^3). In four out of five sessions, CO_2 levels exceeded the Taiwan IAQ regulatory limit of 1,000 ppm, indicating poor ventilation and potential discomfort or reduced cognitive function for occupants et.al. The rate of increase in CO_2 during the first 30–40 minutes was significantly greater. Than that under controlled conditions (11.2–14.8 ppm/min) due to the higher occupancy density. Subsequent fluctuations during the mid-to-late session corresponded with door-opening events, window adjustments, and intermittent air conditioner fan speed changes. These observations highlight that actual teaching activities introduce unstructured ventilation patterns, resulting in dynamic CO_2 variations. Similar exceedances of classroom CO_2 during active teaching hours have been reported internationally, such as in the U.S. and European schools lacking mechanical ventilation systems [6].

3.3.1. Air Exchange Rates Under Real-Classroom Use

Air exchange rates during regular teaching sessions ranged from.

• 1.72 to 3.46 h/1, with a mean of 2.45 ± 0.78 h/1

Despite exceeding the controlled-condition average (1.69 h^{-1}), these values remain below the optimal range of ≥5 h^{-1} recommended for classrooms to maintain high IAQ and reduce airborne exposure risks in dense learning environments. Air exchange increased during real class sessions due to more frequent door openings, occasional window adjustments, and occupant movements.

Although higher than that in controlled scenarios, the ventilation rate was insufficient to counterbalance the substantially greater emission load generated by 42–52 occupants. A ventilation shortfall caused CO_2 accumulation to exceed the recommended level, demonstrating the importance of active ventilation management.

3.3.2. Comparison of Emission Rates Between Controlled and Real Use

The estimated per-person CO_2 emission rates during regular classes ranged from.

• 15.96 to 26.42 g/h/person, with a mean of 20.38 ± 4.42 g/h/person

These values were lower than those obtained in the controlled setting (25.9 ± 3.3 g/h/person). The reduction is attributed to.

- A lower metabolic load during passive lecture attendance than during controlled tasks requiring consistent seated status.
- Reduced physical movement and lower engagement intensity for most people.
- Fluctuations in ventilation altered the shape of the CO_2 curve and affected estimation.

Overall, the comparison confirms that human emission factors vary with activity type and may be overestimated if controlled experiments do not reflect real behavior patterns.

3.4. Implications for Ventilation and IAQ Management at Universities

The findings demonstrate that naturally ventilated or air-conditioned university classrooms are prone to CO_2 accumulation and frequent exceedance of regulatory limits, particularly under high occupancy conditions. The key implications of this study include the following.

- Current ventilation conditions are inadequate for maintaining CO_2 concentrations less than 1,000 ppm in most sessions.
- Mechanical ventilation or enhanced air circulation is needed, particularly in large classrooms with dense seating.
- CO_2 monitoring can serve as an IAQ management tool, enabling instructors or facility managers to adjust

ventilation in real time.

- Occupant behavior strongly influences IAQ, suggesting that ventilation strategies should incorporate behavioral components such as scheduled doors/might's.

These results are consistent with global campaigns advocating for improved school and university ventilation as a low-cost means of protecting cognitive performance and health [6,7].

4. Conclusion

This study investigated the temporal dynamics of indoor CO_2 concentrations and evaluated ventilation performance in a university classroom under both controlled and real teaching conditions. The results demonstrated that indoor CO_2 levels increased rapidly during occupancy, frequently surpassing the regulatory threshold of 1,000 ppm (1,830 mg/m^3), particularly during regular teaching sessions with 42–52 occupants. Although air exchange rates during actual classes (mean: 2.45 ± 0.78 h^{-1}) were higher than those observed in controlled experiments (1.69 ± 0.09 h^{-1}), they remained insufficient to offset the substantially greater CO_2 emission load associated with higher occupancy. Human CO_2 emission factors derived from both experimental scenarios provided realistic benchmarks for sedentary academic activities, with mean values of 25.9 ± 3.3 g/h/person under controlled conditions and 20.38 ± 4.42 g/h/person during teaching sessions. These findings highlight the strong influence of occupancy density, ventilation behavior, and teaching practices on indoor air quality outcomes. The study confirmed that prevailing ventilation practices in higher education classrooms are generally inadequate to maintain acceptable IAQ levels and suggested that improved ventilation strategies are needed. Practical implications include the adoption of CO_2-based IAQ monitoring for real-time ventilation management, the incorporation of scheduled ventilation interventions, and the consideration of mechanical or hybrid ventilation systems in large or densely occupied classrooms. The findings provide a scientific basis for evidence-driven IAQ improvement and support future policy and infrastructure enhancements aimed at creating healthier learning environments in universities.

Contributions to the Study

This study makes several notable contributions to the understanding and management of indoor CO_2 dynamics and ventilation performance in higher education settings.

• This Study Provides Empirical Evidence of Co_2 Accumulation in University Classrooms.

Continuous monitoring under both controlled and real classroom conditions revealed frequent exceedances of the 1,000-ppm regulatory threshold, emphasizing the need for improved ventilation management in tertiary education environments.

• Quantifying Air Exchange Rates Using a Mass-Balance Modeling Framework.

This study applied CO_2 decay analysis to estimate the air exchange rate and demonstrated that ventilation performance remained below recommended levels even when windows were slightly open or natural leakage pathways were present.

• Driving Realistic Human Co_2 Emission Factors Under Classroom Conditions.

Emission rates estimated from controlled and actual teaching sessions provide valuable human-based CO_2 emission factors for sedentary academic activities, filling empirical gaps in IAQ research in subtropical university settings.

• This Study Highlights the Influence of Occupant Behavior on IAQ Outcomes.

This study illustrates how door-opening frequency, window adjustment, movement, and class routines directly modulate CO_2 dynamics, demonstrating the importance of behavioral and administrative interventions beyond engineering controls.

• These Findings Provide Actionable Insights for IAQ Monitoring and Ventilation Strategies.

These findings support the use of CO_2 as a rapid diagnostic proxy for ventilation adequacy and provide a basis for data-driven IAQ improvement strategies that universities can readily implement at low cost.

Limitations and Future Work

This research is subject to several limitations that should be considered when interpreting the findings and designing subsequent studies.

Single-Room Focus.

Measurements were taken in one classroom within a single university, which may limit generalizability across different building designs, volumes, or climates. Future studies should examine a wider range of classroom typologies and institutions.

Assumption of Well-Mixed Indoor Air.

The mass-balance model assumes homogeneous mixing of indoor air, which may not fully hold in rooms with ventilation dead zones or strong thermal gradients. Incorporating computational fluid dynamics (CFD) simulations or multisensory monitoring could refine spatial representativeness.

Limited Activity Diversity.

CO_2 emission estimates were based on seated lecture-related activities. Future work could explore different teaching modes (e.g., group work, laboratory sessions, active learning formats) to establish activity-specific emission factors.

Uncontrolled Behavioral Variables During Actual Classes.

Real classroom settings introduced variability in student behavior, door opening patterns, and air conditioning adjustments. Integrating environmental sensors for air velocity or CO_2-controlled ventilation systems could provide more precise cause–effect attribution.

Future research may also investigate long-term IAQ management interventions, such as demand-controlled ventilation based on CO_2 thresholds or hybrid mechanical–natural ventilation strategies tailored to subtropical university environments.

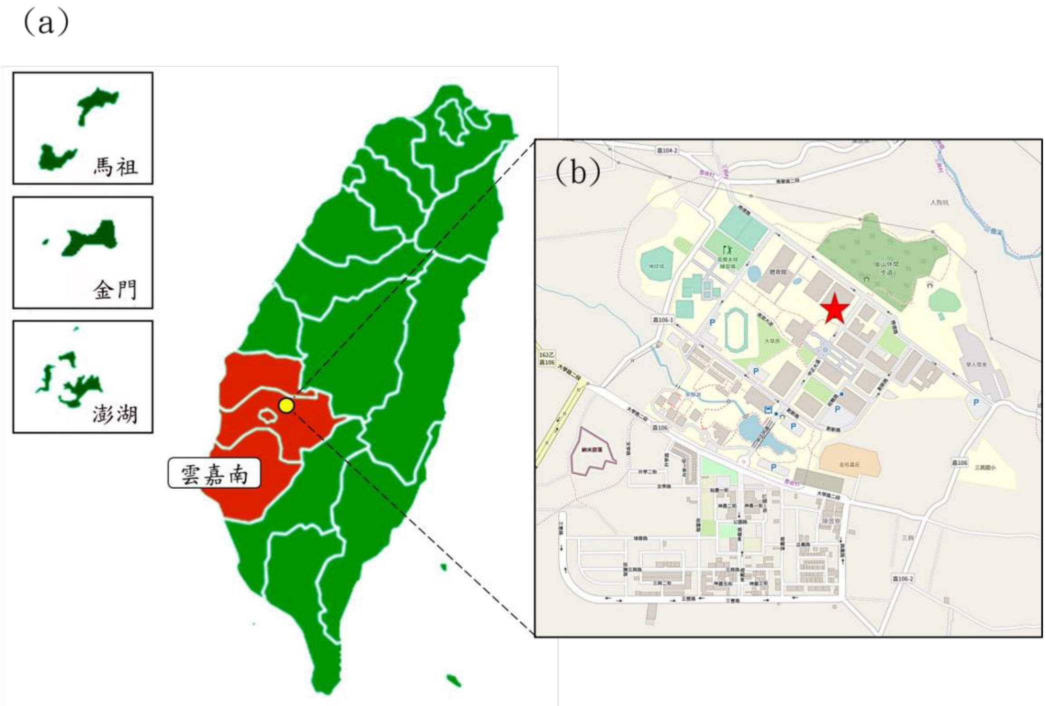

Figure 1: Location of National Chung Cheng University within the Yun-Chia-Nan Air Quality Region in Taiwan.

Figure 2: Floor Plan of the Monitored Classroom in the Earth Sciences Building Showing the Sampling Inlet and Instrument Placement.

國立中正大學空氣品質即時資訊

通識教育中心製作

各月分鐘圖表連結
即時圖表請點選下方偵測項目

台北標準時間 (GMT+8)
2023/5/26 星期五 上午9:57:37

[redacted]
參訪人數 (自107/03/29)

測點位置	地環系頂樓 (戶外)	活動中心 (小吃街)	共同教室大樓 (106 教室)	普化實驗室 (203)
CO_2 (ppm)	450.0	778.0	870.0	510.0
$PM_{2.5}$ (μg/m^3)	18.6	23.9	3.5	6.0
PM_{10} (μg/m^3)	50.4	44.5		
CO (ppm)		3.9		1.0
O_3 (ppb)	18.0			
VOC (ppm)			0.12	0.18
溫度 (°C)	---	28.3	23.3	26.5
濕度 (RH%)	---	79.8	55.8	72.5

空氣品質指標

	單位	良好	普通	對敏感族群不健康	對所有族群不健康	非常不健康
CO_2	ppm	依照室內空氣品質管理法，大於1000為超標				
$PM_{2.5}$	μg/m^3	0~15.4	15.5~35.4	35.5~54.4	54.5~150.4	> 150.5
PM_{10}	μg/m^3	0~54	55~125	126~254	255~354	> 355.0
O_3	ppb	-	-	125~164	165~204	> 205.0
CO	ppm	0~4.4	4.5~9.4	9.5~12.4	12.5~15.4	> 15.5
VOCs	ppm	0~0.065	0.065~0.220	0.221~0.660	0.661~2.200	> 2.201

資料來源：行政院環境保護署空氣品質監測網 揮發性有機物空氣污染管制及排放標準 室內空氣品質標準

緣起

近年來空汙議題愈來愈受到大眾的重視，也漸漸讓大家注意到空氣品質的重要性，為了讓師生可以更好的了解學校即時的空氣品質，在中正大學的補助下，經由通識教育中心與地球與環境科學系合作，發展了一套校園環境即時監測系統，提供學校各個位置的空氣汙染指數，透過通識教育中心製作的「國立中正大學空氣品質即時資訊網」，可以讓全校師生即時的掌握學校各個位置的空汙資訊，利用網頁上各數值的顏色變化可以很容易的判別目前是否適合進行戶外活動，網頁下方的空氣品質指標也可以幫助大家去了解這些數字所包含的資訊。

特別感謝

瀚平顧問有限公司
通識中心 胡維平主任
地球與環境科學系 范誠偉副教授
地球與環境科學系 吳政諭專任助理
化學暨生物化學系 蔡承成博士
化學暨生物化學系 李宗倫兼任助理

Figure 3: Indoor CO_2 Concentration Time Series for the Three Controlled Experiments, Showing Build-Up and Decay Patterns.

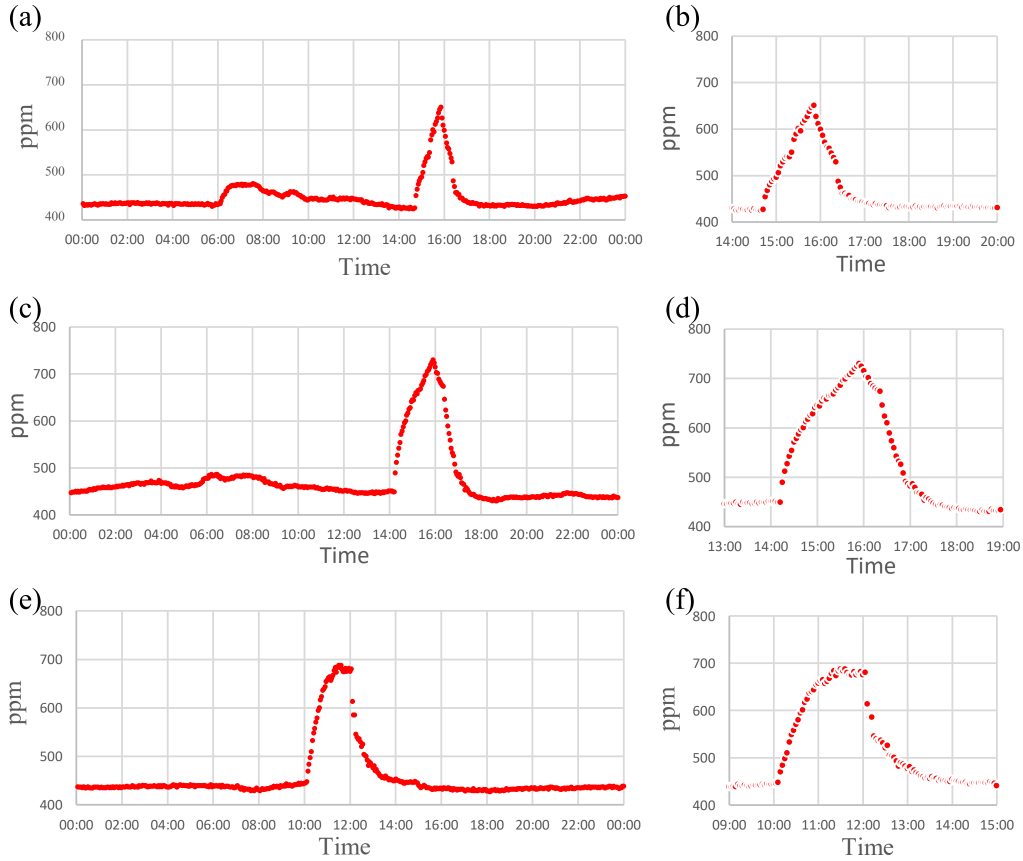

Figure 4: Linear Regression of Ln(C(T) – Cout) Versus Time for Decay Analysis to Determine Air Exchange Rates (a).

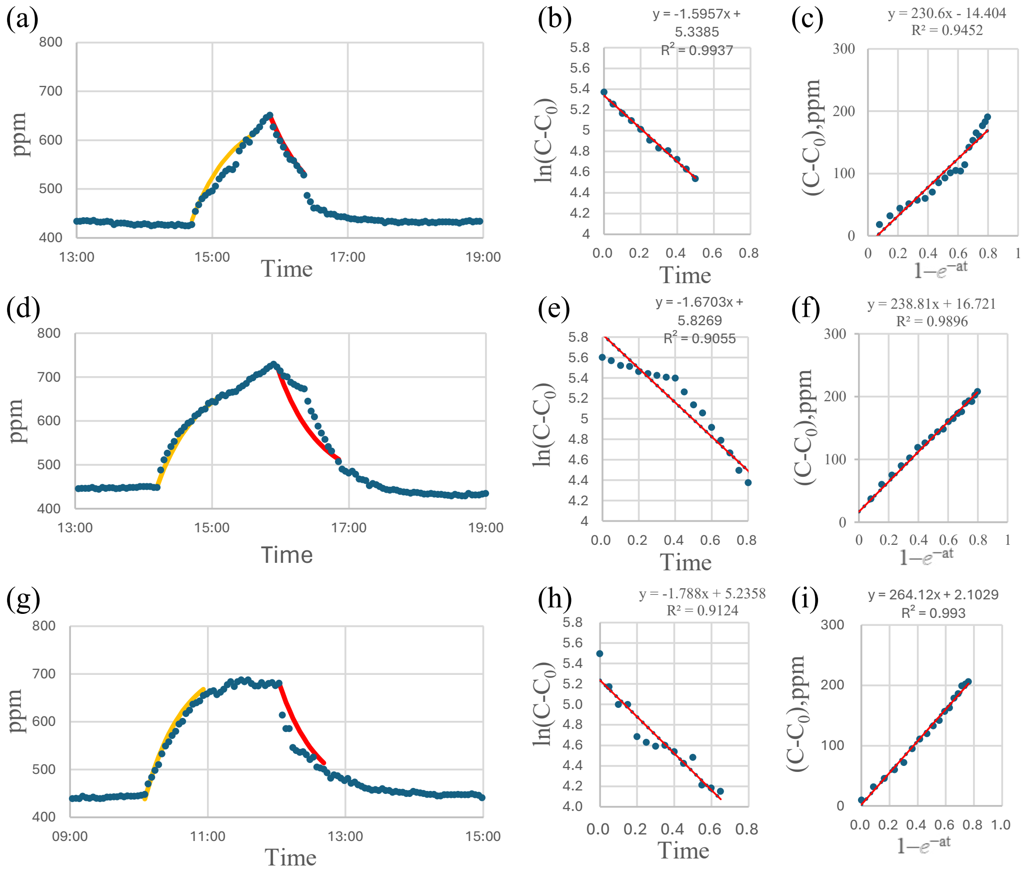

Figure 5: CO_2 Concentration Profiles During Five Regular Teaching Sessions, Indicating Peak Values and Exceedances of the 1,000-Ppm Threshold.

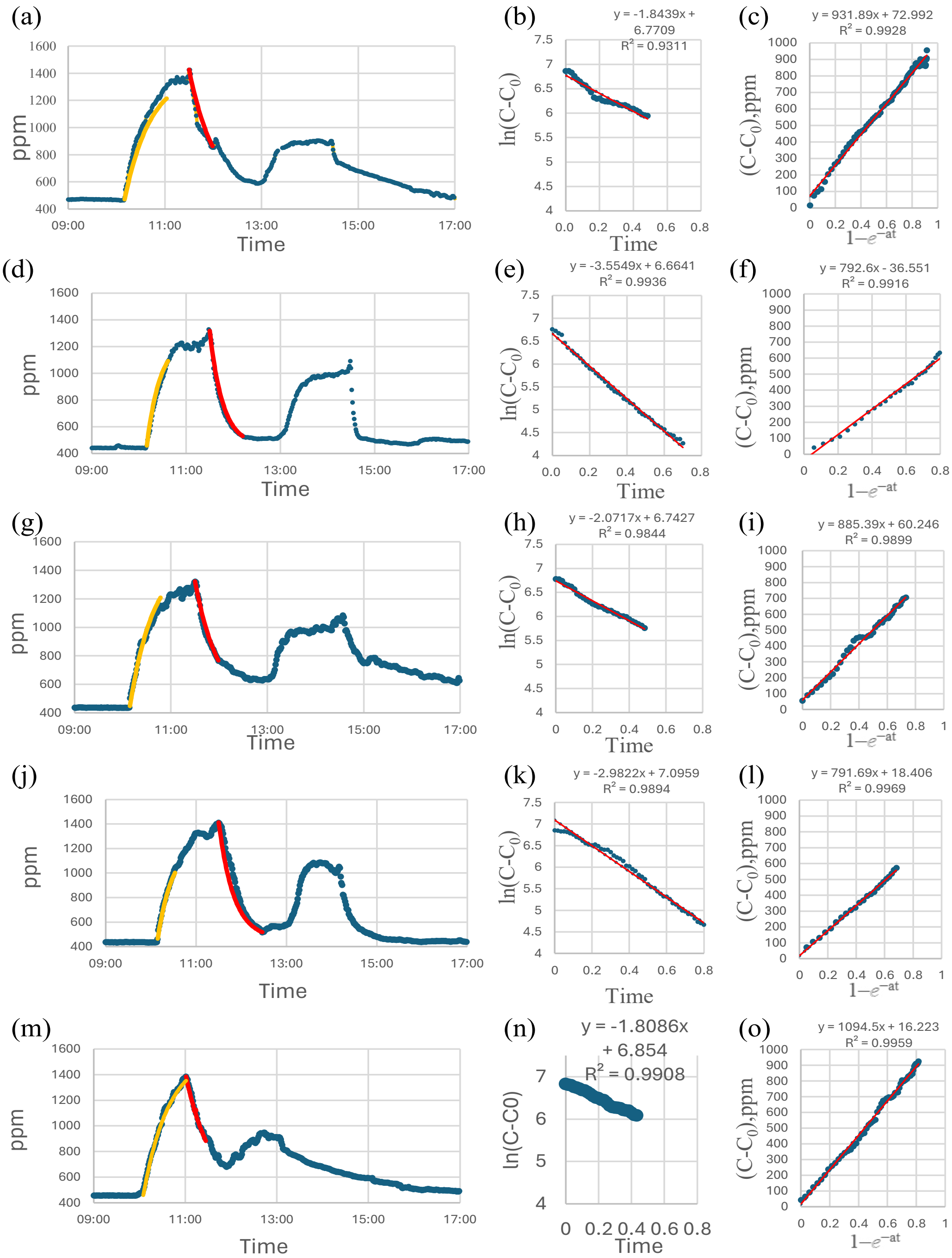

Figure 6: Comparison of Air Exchange Rates Between Controlled Experiments and Actual Classroom Sessions.

Item	Standard Value Period	Standard Averaging	Unit
Carbon dioxide (CO_2)	8-hour average	1000	ppm (parts per million by volume)
Carbon monoxide (CO)	8-hour average	9	ppm (parts per million by volume)
Formaldehyde (HCHO)	1-hour average	0.08	ppm (parts per million by volume)
Total volatile organic compounds (TVOC, including the sum of 12 volatile organic compounds)	1-hour average	0.56	ppm (parts per million by volume)

Ozone (O_3)	8-hour average	0.06	ppm (parts per million by volume)
Bacteria	Maximum value	1500	CFU/m^3 (colony-forming units per cubic meter)
FungiSS	Maximum value	1000	CFU/m^3 (colony-forming units per cubic meter)
Particulate matter ≤10 µm (PM_{10}))	24-hour average	75	µg/m^3 (micrograms per cubic meter)

Table 2: Summary of Key Variables and Symbols Used in the Co_2 Mass-Balance Model.

Notes

- 1-hour average: Refers to the arithmetic means of measurements obtained within one hour or the value from cumulative sampling over one hour.
- 8-hour average: Refers to the arithmetic means of measurements obtained continuously over eight hours or the value from cumulative sampling over eight hours.
- 24-hour average: Refers to the arithmetic means of measurements obtained continuously over twenty-four hours or the value from cumulative sampling over twenty-four hours.
- Maximum value: Refers to the sampling and analytical value obtained following the sampling methods specified by the central competent authority.
- Total volatile organic compounds (TVOCs): The TVOC standard is based on the total concentration of twelve volatile organic compounds, including benzene, carbon tetrachloride, chloroform (trichloromethane), 1,2-dichlorobenzene,1,4-dichlorobenzene, dichloromethane, ethylbenzene, styrene, tetrachloroethylene, trichloroethylene, toluene, and xylene (para-, meta-, and ortho-isomers).
- The indoor-to-outdoor fungal concentration ratio was defined as the ratio of the indoor fungal concentration to the outdoor fungal concentration. The relative sampling positions for the indoor and outdoor sites complied with the Regulations for Indoor Air Quality Inspection and Determination Methods issued by the Environmental Protection Administration (EPA) of Taiwan.
- Source: Environmental Protection Administration, Executive Yuan, Taiwan.

S. No	Event Number	Date	Member	Laboratory Time	*a Value* Initial Time	*S Value* Initial Time
1	200813 (Th)	2020/8/13	7	14:39~ 16:20	15:51~16:21	14:42~15:42
2	200818 (Tu)	2020/8/18	7	14:10~ 16::45	15:57~16:51	14:12~15:09
3	200820 (Th)	2020/8/20	7	10:05~ 13:00	12:03~12:42	10:06~10:51

Table 3: Background Indoor and Outdoor CO_2 Concentrations Prior to Each Experiment and Class Session.

S. No	Event Number	C_0 0ppm	C_f 0ppm	a h^{-1}	R^2	*n*
1	200813 (Th)	436	651	1.60	0.9937	11
2	200818 (Tu)	452	724	1.67	0.9055	19
3	200820 (Th)	438	681	1.79	0.9124	14
	Average value	442±9	685±37	1.69±0.09		

Table 4: Summary of CO_2 Build-Up Characteristics and Per-Person Emission Rates for Controlled Experiments.

S. No	Event Number	C_o	*n*	*S/V/a* (ppm)	R^2	*S* g/h	Member	*Sp*
1	200813 (Th)	436	21	231	0.9495	162	7	23.1
2	200818 (Tu)	452	20	239	0.9896	176	7	25.1
3	20020 (Th)	438	16	263	0.9923	208	7	29.5
	Average value	442 ±9		244 ±17		182 ±24		25.9 ±3.3

Table 5: Air Exchange Rates Derived from Decay-Phase Analysis for Controlled Experiments and Classroom Sessions.

S. No	Event Number	C_0 ppm	Cf ppm	*a* h^{-1}	R^2	*n*
1	220907 (wed)	471	1426	1.84	0.9311	30
2	220914 (wed)	459	1318	3.55	0.9936	43
3	220919 (mom)	447	1322	2.07	0.9844	30
4	220921 (wed)	464	1413	2.98	0.9894	59
5	220928 (wed)	460	1385	1.80	0.9908	27
	Average value	460±9	1373±50	2.45±0.78	Average value	

Table 6: Peak CO_2 Concentrations and Exceedance Duration for Each Monitored Classroom Session.

S. No	Event Number	CO	n	S/V/a (ppm)	R^2	*S* g/h	Member	*Sp*
1	220907 (wed)	471	53	952	0.9948	774	42	18.4
2	220914 (wed)	459	28	793	0.9916	1242	46	27.0
3	220919 (mom)	447	39	885	0.9899	808	52	18.3
4	220921 (wed)	464	24	792	0.9869	1041	52	20.0
5	220928 (wed)	460	57	1095	0.9959	872	49	17.8
	Average value	460 ±9		909 ±127		947. ±194		20.4 ±4.4

Table 7: Peak CO_2 Concentrations and Exceedance Duration for Each Monitored Classroom Session.

Declarations

Ethics Approval and Consent to Participate

This study was exempt from ethical review. Consent to participate was not required.

Consent for Publication

Yes. A publication agreement was submitted through Research Square.

Availability of Data and Materials

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing Interests

The author declares that he has no competing interests.

Funding

This research received no external funding.

Author's Contributions

WANG HAN SHENG is the sole author of this study and contributed to all aspects of the research, including.

- Conceptualization
- Methodology
- Data curation and analysis
- Writing – original draft
- Writing – review & editing

- Visualization
- Supervision
- Project administration

He also serves as the corresponding author.

Acknowledgements

No acknowledgements to declare.

Highlights

- Continuous indoor CO_2 monitoring was conducted under both controlled and real classroom occupancy conditions.
- Air exchange rates were quantified using a mass-balance model based on the temporal variation in CO_2 concentrations.
- CO_2 emission factors per person were estimated and compared between controlled experiments and actual teaching sessions.
- Indoor CO_2 frequently exceeded 1,000 ppm (1,830 mg/m^3), surpassing regulatory limits and indicating insufficient ventilation.
- These findings provide evidence-based implications for IAQ assessment in higher education learning environments.

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