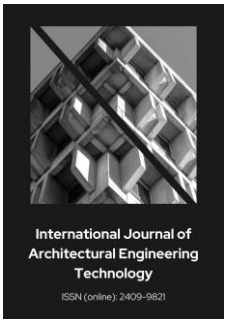
Published by Avanti Publishers

International Journal of Architectural Engineering Technology

ISSN (online): 2409-9821



Beyond Certification: A Multi-Quantitative Post-Occupancy Evaluation of Indoor Environmental Quality in a Platinum-Certified Subtropical University Building

Danyang Du[1], Xiaoqiang Gong[1], Kaimin Chen[2] and Yahong Dong[1,3,*]

[1]*Department of Environmental Science and Engineering, Faculty of Innovation Engineering, Macau University of Science and Technology, Macau, China*

[2]*Guangdong Provincial Academy of Building Research Group Co., Ltd., Guangzhou, China*

[3]*Macao Institute of Green and Net-Zero Technology, Macau University of Science and Technology, Macau, China*

ARTICLE INFO

Article Type: Research Article

Academic Editor: Biao Wang

Keywords:
Climate change
Occupant satisfaction
BEAM Plus certification
Subtropical green buildings
Post-occupancy evaluation (POE)
Indoor environmental quality (IEQ)

Timeline:
Received: August 03, 2026
Accepted: November 01, 2026
Published: November 14, 2026

Citation: Du D, Gong X, Chen K, Dong Y. Beyond certification: A multi-quantitative post-occupancy evaluation of indoor environmental quality in a platinum-certified subtropical university building. Int J Archit Eng Technol. 2026; 13(3): 284-311.

DOI: https://doi.org/10.15377/2409-9821.2026.13.14

ABSTRACT

Green building certification formally evaluates building performance, while it may not fully capture occupants' experiences of indoor environmental quality (IEQ) during post-occupancy use. This study presents a post-occupancy evaluation (POE) of a BEAM Plus Platinum-certified academic building at the Macau University of Science and Technology (MUST), using a quantitative evaluation approach that combines a questionnaire survey of occupant satisfaction (n = 108, 90.0% valid response rate) with in-situ physical measurements of key IEQ parameters, including carbon dioxide (CO_2), total volatile organic compounds (TVOC), formaldehyde (HCHO), PM_{10}, thermal conditions, and operational sound level, supplemented by DIALux simulation of artificial-lighting performance. The survey and field measurements were conducted in three classrooms on three days between March 28 and April 11, 2025, during the transition period between classes in a Spring semester. The results indicated that the five IEQ categories received mean scores ranging from 3.65 to 3.94 on a five-point scale, with visual environmental quality being the best while ventilation effectiveness being the worst. In terms of the specific items, natural ventilation adequacy and local overheating/overcooling received the lowest mean scores of 3.47 and 3.14, respectively. Short-term classroom CO_2 concentrations peaked at 897 ppm, and TVOC ranged between 0.001 and 0.008 mg/m³. Thermal measurements showed inter-room variation, with mean temperatures ranging from 23.99 °C to 25.23 °C (a differential of 1.24 °C). Operational sound levels ranged from 46.3 to 57.2 dB(A) in the monitored classrooms. Interpreting occupant feedback with in-situ measurements offers practical, user-centered evidence that bridges the gap between green building certification and actual building performance. The findings provide actionable guidance for follow-up IEQ monitoring and operational optimization in university classrooms.

*Corresponding Author

Email: yhdong@must.edu.mo

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1. Introduction

Indoor Environmental Quality (IEQ) constitutes a foundational dimension in building science, architectural engineering, and human habitat assessment [1, 2]. Epidemiological and environmental behavior studies indicate that individuals spend over 90% of their daily lives indoors; consequently, the physical and chemical attributes of indoor microclimates directly modulate human immune load, physiological well-being, and cognitive capacity [2, 3]. Integrating IEQ into holistic assessment frameworks to quantify and safeguard occupant health has become a core aspect of the contemporary green building promotion [4]. Within educational settings, the indoor environment of learning spaces acts as a critical determinant of students' physiological health, psychological states, and academic productivity [4]. Among the multiple dimensions of IEQ, indoor air quality (IAQ) specifically concerns ventilation conditions and occupants' exposure to airborne contaminants. In educational settings, IAQ has been associated with cognitive function and learning performance. Evidence from higher-education settings indicates that classroom IEQ can influence short-term academic performance, although the magnitude and mechanisms of these effects vary across environmental parameters and tasks [5, 6].

Among diverse institutional building typologies, higher education facilities represent highly complex, high-density public spaces with distinct environmental and operational attributes [7]. University teaching spaces are uniquely characterized by elevated occupant densities, highly variable schedules, and prolonged, continuous user exposure [8]. Environmental degradation within these dense settings can trigger Sick Building Syndrome (SBS), manifesting as physiological discomforts, such as dizziness, lethargy, and respiratory tightness, which severely inhibit cognitive processing and academic performance [9-11]. Furthermore, a persistent misalignment between dynamic, transient occupancy loads and static, centralized environmental control strategies frequently drives systemic operational performance degradation. Therefore, a systematic, rigorous evaluation of the actual operational environmental performance of educational buildings is essential to optimize institutional facility management, close the performance gap, and maximize spatial educational efficiency.

Post-Occupancy Evaluation (POE) has emerged as an invaluable diagnostic methodology to identify operational barriers, performance deviations, and underlying design flaws by comprehensively scrutinizing green building performance during the occupancy phase [12, 13]. By prioritizing the user perspective, POE bridges the gap between design-stage simulations and actual operational realities [14]. In the context of green campus research [15], empirical POE studies have extensively investigated educational facilities, primarily focusing on the correlation between classroom environmental parameters and student satisfaction [16, 17]. Traditional literature extensively utilizes Likert scales to capture subjective feedback and correlate it with physical environmental variables [18]. Such evaluations can help diagnose operational shortcomings and provide feedback for subsequent building management and performance improvement [19, 20]. Within this domain, thermal comfort remains a major focus in educational-building IEQ research, with field studies frequently comparing occupants' thermal responses with Predicted Mean Vote (PMV), Predicted Percentage of Dissatisfied (PPD) or adaptive-comfort models [21]. In addition, the scope of inquiry has expanded to address IAQ and ventilation effectiveness, including occupancy-related CO_2 accumulation as an indicator of ventilation conditions [22-24]. Visual environmental quality has likewise received growing attention, particularly regarding daylight availability, illuminance, glare, and occupant preferences [25, 26].

Research in comparable hot-humid Asian contexts has demonstrated that IEQ performance is strongly shaped by local climate, building operation, and occupant experience. Studies of university teaching spaces in Hong Kong have combined occupant surveys with physical measurements and identified thermal, acoustic, air-quality, and visual conditions as important components of perceived IEQ, with the relative importance of individual dimensions varying among studies [27, 28]. In Singapore, post-occupancy surveys of Green Mark-certified air-conditioned buildings found generally favorable overall satisfaction but identified temperature, air movement, personal control, and acoustic privacy as persistent sources of dissatisfaction [29]. Research on classroom buildings in hot-humid Guangzhou has likewise documented thermal-performance challenges associated with summer conditions and cooling demand [30]. These regional findings establish the importance of climate- and operation-specific POE, yet evidence remains comparatively limited for certified university buildings in Macau that have been evaluated through concurrent occupant assessment and multi-dimensional environmental

measurement. The building performance gap commonly refers to discrepancies between expected building performance and the performance observed after occupancy [31]. In green buildings, this gap may extend beyond energy use, as certification outcomes and design intentions do not necessarily translate into equivalent operational IEQ or occupant satisfaction [7, 32]. In this study, certification provides the case-study context for examining occupant-reported IEQ and short-term environmental conditions during building use. Related studies have integrated occupant evaluations with physical IEQ measurements in tropical green-campus and higher-education settings across different climatic contexts [33, 34]. In Macau, campus sustainability research has also examined stakeholder-integrated carbon management in local higher education institution [35]. However, comparable evidence remains limited for certified university buildings in subtropical cities, like Macau, particularly studies that combine occupant evaluations with multi-dimensional environmental measurements under actual teaching conditions.

To address these gaps, this study conducts a POE of the Block R Academic Complex at the Macau University of Science and Technology (MUST), the first BEAM Plus (Existing Buildings) Platinum-certified building in Macau. The primary aim of this study is to evaluate the occupant-reported IEQ and short-term environmental conditions in three classrooms of the Platinum-certified subtropical university building during the spring transition period through post-occupancy assessment. Occupant questionnaire surveys are combined with in-situ environmental measurements to characterize thermal comfort, IAQ, ventilation effectiveness, acoustic comfort, and visual environmental quality under actual teaching conditions. The study contributes case-specific evidence on the coexistence of favorable overall IEQ evaluations and less favorable assessments of particular thermal, ventilation, and visual attributes in Block R. Short-term measurements and lighting simulation provide complementary context for identifying priorities for further assessment under the documented classroom-use conditions.

2. Methods

The methods used in this study included case study, questionnaire survey, on-site environmental measurements, lighting simulation, and statistical analyses. The questionnaire assessed occupant evaluations of five IEQ categories, while field measurements and lighting simulation were used to characterize the corresponding indoor environmental conditions. The collected data were subsequently analyzed to evaluate the operational IEQ performance of the case building and the associations between the five IEQ categories and overall satisfaction.

2.1. Study Case

Macau University of Science and Technology (MUST) is located in Taipa, Macau, and encompasses a total site area of approximately 210,000 m² across 18 campus buildings (Blocks A through R). In September 2024, a field survey was conducted to evaluate the campus portfolio based on building typology, construction year, regulatory compliance, HVAC configuration, and geographic location. Four primary academic buildings, Blocks B, C, O, and R, were initially screened for green building evaluation. Blocks B and C were subsequently excluded due to structural aging and suboptimal facility conditions, while Block O was omitted owing to its irregular architectural geometry. Consequently, Block R was selected as the representative case study.

Completed in October 2019, Block R (Fig. **1**) occupies a footprint of 9,469.57 m² with a total gross floor area (GFA) of 30,293.62 m². The facility comprises seven above-ground stories, a roof terrace, and a two-level underground parking garage. To ensure energy-efficient operations, the building is equipped with low-energy LED lighting networks integrated into a centralized Building Management System (BMS). Designed to satisfy modern pedagogical demands, the multi-functional program includes classrooms, administrative offices, film studios, multi-purpose halls, and conference spaces. In October 2025, MUST Block R was officially awarded the BEAM Plus Existing Buildings (Global Version) Platinum certification, marking it as the inaugural structure in Macau to attain this distinction.

Macau is situated within a low-latitude, subtropical monsoon region characterized by protracted periods of elevated ambient temperatures and high relative humidity. These localized climatic conditions severely constrain the efficacy of natural ventilation strategies, as incoming outdoor air introduces significant sensible and latent

heat loads to the interior. Consequently, educational facilities in this region predominantly utilize highly airtight envelopes and rely heavily on centralized mechanical ventilation systems to safeguard indoor environmental stability.



Figure 1: Exterior view and architectural envelope of Block R (Source: provided by the University).

Block R at the university exemplifies these high-performance, climate-adapted institutional structures. The classrooms are served by Daikin variable refrigerant volume (VRV) air-conditioning systems. Temperature set-points are centrally controlled, while local wall-mounted control panels allow users to switch the system on or off and adjust fan speed. As a core academic hub on campus, the floor plan and primary functional zones of a typical floor (Level 5) are illustrated in Fig. (**2**). Levels 3–7 have broadly comparable spatial configurations and constitute the principal general-teaching zone of Block R.

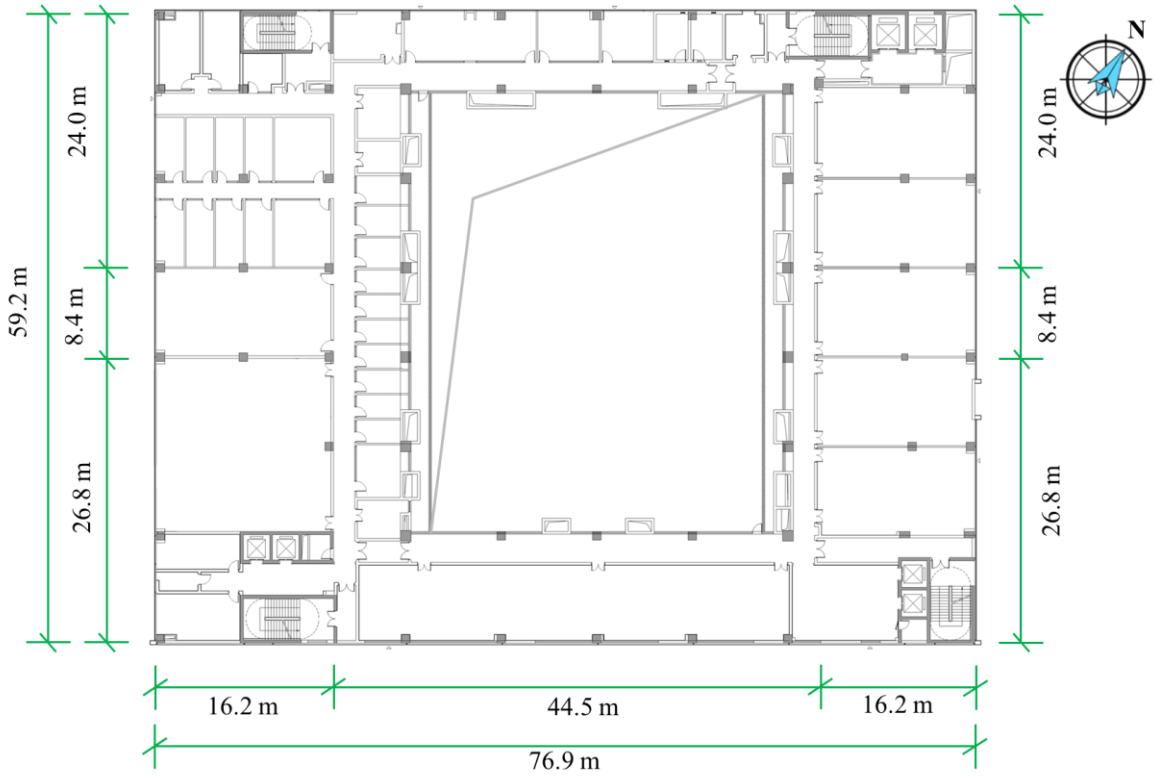


Figure 2: Floor plan of Level 5 of Block R (Source: generated from Autodesk).

2.2. POE Categories

IEQ is one of the primary dimensions of POE systems, directly influencing occupant health, psychological states, and cognitive performance. Modern building science emphasizes that the correlation between physical environmental variables and subjective user feedback provides the objective basis for verifying design and operational performance [36]. Based on building physics and environmental behavioral theories, these environmental factors are categorized into five core areas (Fig. **3**): thermal comfort, indoor air quality, ventilation effectiveness, acoustics, and visual environmental quality [17, 37].

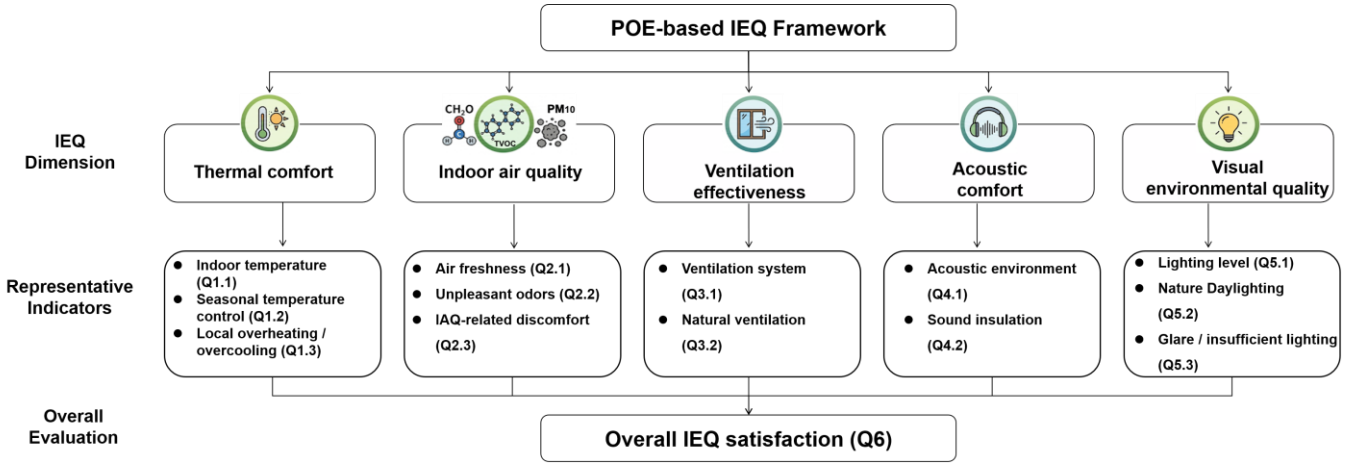


Figure 3: Five IEQ dimensions and representative indicators in the POE (Q1.1 refers to the question number in the questionnaire).

1). Thermal Comfort

This dimension reflects the psychological and physiological state of satisfaction with the thermal environment, serving as a primary determinant of overall spatial satisfaction and cognitive performance [37]. It is governed by a complex nexus of physical environmental variables (dry-bulb temperature, relative humidity, and mean radiant temperature) and human-centric factors (metabolic rates, clothing insulation, and behavioral adaptation mechanisms). Within empirical POE frameworks, the scrutiny of thermal comfort centers on the dynamic regulatory responsiveness of HVAC configurations and architectural envelopes under transient meteorological loads, alongside the system's efficacy in deploying adaptive controls to mitigate localized microclimatic imbalances [17].

2). Indoor Air Quality (IAQ)

This dimension correlates directly with the concentrations of chemical pollutants and airborne particulate matter, acting as the primary etiological factor for Sick Building Syndrome (SBS) and related respiratory pathologies [36]. Within high-density institutional buildings, the prolonged accumulation of CO_2, TVOC, and associated trace pollutants severely compromises central nervous system functions and cognitive efficacy. Consequently, IAQ post-occupancy evaluations must scrutinize not only absolute physical pollutant thresholds but also subjective user perceptions regarding air freshness, ambient odors, and acute physiological discomfort under conditions of continuous exposure [37].

3). Ventilation Effectiveness

Ventilation effectiveness index characterizes the systemic capability of a built environment to introduce fresh air vectors that dilute, exhaust, and replace internal stagnant air volumes, heavily modulating both chemical air quality and latent-sensible thermal loads [37]. Efficient airflow distribution profiles are critical to suppressing indoor aerosol transmission risks and maintaining room environmental quality. Consequently, post-occupancy diagnostic evaluations prioritize the fluid mixing efficiency of mechanical systems and natural design interfaces under actual occupant densities, focusing specifically on how effectively centralized systems

match spatial ventilation demands in real-time [17]. In this study, the ventilation dimension is assessed through ventilation-system satisfaction (Q3.1) and natural ventilation adequacy (Q3.2), representing perceived ventilation conditions rather than a directly measured ventilation-effectiveness index.

4). Acoustics

This dimension encompasses ambient background noise levels and cross-spatial sound attenuation capabilities, both of which are critical to mitigating occupant psychological stress and sustaining cognitive focus [36]. Extraneous acoustic disruptions typically stem from a triad of sources: outdoor transportation noise, indoor mechanical and HVAC equipment operations, and transient occupant activities in adjacent zones. Consequently, building envelope sound isolation, the configuration of interior sound-absorbing materials, and strategic soundscape planning constitute the core technical determinants of localized auditory privacy and acoustic resilience [17].

5). Visual Environmental Quality

Visual environmental quality encompasses the adequacy, distribution, and perceived psychological and physiological comfort of both natural and artificial illumination. Its evaluation focuses on whether indoor lighting provides sufficient illuminance to support cognitive and pedagogical activities while mitigating glare, sub-optimal lighting, excessive luminance contrast, and spatial non-uniformity. For POE, visual environmental quality can be quantified via occupant satisfaction regarding indoor illuminance levels, the perceived efficacy of daylighting integration, and subjective experiences of visual discomfort or insufficient illumination [37].

2.3. Questionnaire Design

Questionnaires are widely recognized as a foundational component of POE research, offering an empirical mechanism to capture the dynamic performance feedback loops between building occupants and facility management [38]. Existing research demonstrates that even when physical microclimate parameters comply with regulatory thresholds, a failure to align with human-centric requirements compromises overall operational efficacy [39]. Therefore, occupant satisfaction serves as a critical diagnostic metric within contemporary POE frameworks to identify and resolve systemic operational latent vulnerabilities [40].

To align with the explicit spatial and operational characteristics of the case building, this study deployed a customized psychometric instrument. The questionnaire comprises 14 items, including 13 items assessing five IEQ dimensions, i.e., thermal comfort, indoor air quality, ventilation effectiveness, acoustic comfort, and visual environmental quality, as well as one additional item evaluating overall IEQ satisfaction (Q6) (Supplementary Material S1). The survey results were mapped to the post-evaluation indexing criteria outlined in the “Assessment Standard for Green Campus” [41], translating abstract environmental variables into quantifiable subjective metrics to support structured comparison with objective physical measurements. The items were evaluated utilizing a five-point Likert scale ranging from 1 (representing the lowest level of satisfaction or poorest perceived performance) to 5 (denoting the highest level of satisfaction or optimal performance).

2.4. Data Collection

Data collection included a questionnaire survey, on-site environmental measurements, and a lighting simulation. The questionnaire survey and environmental measurements were conducted during the comparable scheduled classroom-use periods to obtain occupant evaluations and corresponding indoor environmental data. The lighting simulation was used to examine illuminance distribution in a representative classroom. Details of data collection are provided below.

2.4.1. Questionnaire Survey

Data collection through a questionnaire survey was conducted at the MUST Block R academic building on three separate days (March 28, April 1, and April 11, 2025). On each investigation day, one classroom was selected for assessment, and questionnaires were administered during scheduled class breaks, concurrently with the

corresponding indoor environmental measurements. Concurrent data collection provided contextual information for interpreting the survey results.

Based on administrative entry records and respondent background information from the 2024-2025 academic year, the average daily building traffic was approximately 197.8 entries, reflecting the typical usage intensity of Block R. The target respondents were undergraduate students, representing the primary occupant group of the investigated teaching spaces. The classrooms in Block R function as general teaching spaces and are not only assigned to specific classes or student groups; therefore, occupant composition varies across scheduled classes. The investigated teaching sessions were scheduled from 12:30 to 15:20, each including one 20-min class break from 14:00 to 14:20. Questionnaires were administered during this break to students attending the corresponding class. To avoid disrupting normal teaching activities, the questionnaires were administered during the scheduled breaks, when participating students were available to complete the survey. The respondents were students attending the corresponding scheduled class and had therefore experienced the classroom environment during the teaching session before completing the questionnaire. The surveyed students typically attended classes in Block R on at least three days per week, generally one class per day, while the highest reported use frequency was six classes per week, distributed from Monday to Friday.

A total of 120 questionnaires were distributed during the three investigation periods, and all questionnaires were returned. After screening responses for completeness and consistency, 12 invalid questionnaires were excluded, resulting in 108 valid responses and a valid response rate of 90.0%. The questionnaire evaluated occupants' perceptions across multiple IEQ dimensions, including thermal comfort, indoor air quality, ventilation conditions, acoustic environment, and visual environmental quality.

Questionnaire responses and environmental measurements were synchronized at the classroom-session level. Physical measurements were aggregated to room-level summaries corresponding to each survey session, while occupant responses represented evaluations of the same classroom environment during that session. Perceived and measured IEQ conditions were subsequently examined on this spatial and temporal basis.

The respondent-level response matrix in Table **S1** contains the 14 IEQ items and respondent IDs, but no demographic variables or classroom identifiers. The reported undergraduate status and use-frequency information therefore describe the recruitment context. These distributions and classroom-specific questionnaire scores could not be quantified from this matrix.

2.4.2. On-site Environmental Measurements

To interpret the survey results, we conducted measurements of the environmental metrics across three representative classrooms: R319 (on March 28, 2025), R505 (on April 1, 2025), and R742 (on April 11, 2025) (Fig. **4**). The investigations were conducted during scheduled afternoon teaching sessions (12:30–15:20), with indoor environmental measurements performed during the 20-min class break from 14:00 to 14:20 (Macau local time, UTC+8). Teaching classrooms are located across Levels 3–7, which share a typical floor configuration (Fig. **2**). R319, R505, and R742, located on Levels 3, 5, and 7, respectively, were selected as representative examples. The three classrooms were selected because they: (i) represent a dominant teaching-space typology; (ii) provide vertical representativeness across different floors; and (iii) demonstrate comparable functional characteristics (i.e., spatial layouts, occupancy patterns, lighting systems, and air-conditioning configurations).

Although the three classrooms differ in façade orientation, they were monitored under similar operating conditions, with windows closed, air-conditioning systems in operation, and artificial lighting in use. In addition, the three monitored classrooms share the same interior construction and environmental-control configuration. The classrooms are equipped with operable windows, while the local VRV control panels permit on/off operation and fan-speed adjustment; temperature set-points are centrally controlled. Artificial lighting is operated through conventional wall-mounted switches accessible within the classrooms. The interior finishes follow the standard classroom specification, including mold-resistant painted wall surfaces and 600 × 600 mm perforated aluminum ceiling panels. The standard classroom ceiling construction does not incorporate a dedicated sound-absorbing layer, and no additional purpose-designed acoustic treatment was specified for the monitored classrooms. The selected classrooms represent typical teaching spaces under normal operational conditions and enable

synchronous collection of occupant perceptions and indoor environmental measurements. The monitored parameters comprised indoor temperature, carbon dioxide (CO_2), formaldehyde (HCHO), total volatile organic compounds (TVOC), particulate matter (PM_{10}), and operational sound level. Within each classroom, measurements were collected simultaneously at three stationary points positioned at desk height, as shown in Fig. (**4**). Readings were recorded at 1-min intervals during the 20-min class break. To characterize room-level environmental conditions, the arithmetic mean across these three spatial points was computed for each sampling interval, yielding 21 room-averaged records per classroom during the monitoring session. The actual number of occupants present during the monitoring breaks was not recorded. HVAC operation was centrally controlled during monitoring. All instruments used for the field measurements were factory-calibrated by their respective manufacturers. Complete technical specifications for the instrumentation deployment are detailed in Table **1**.

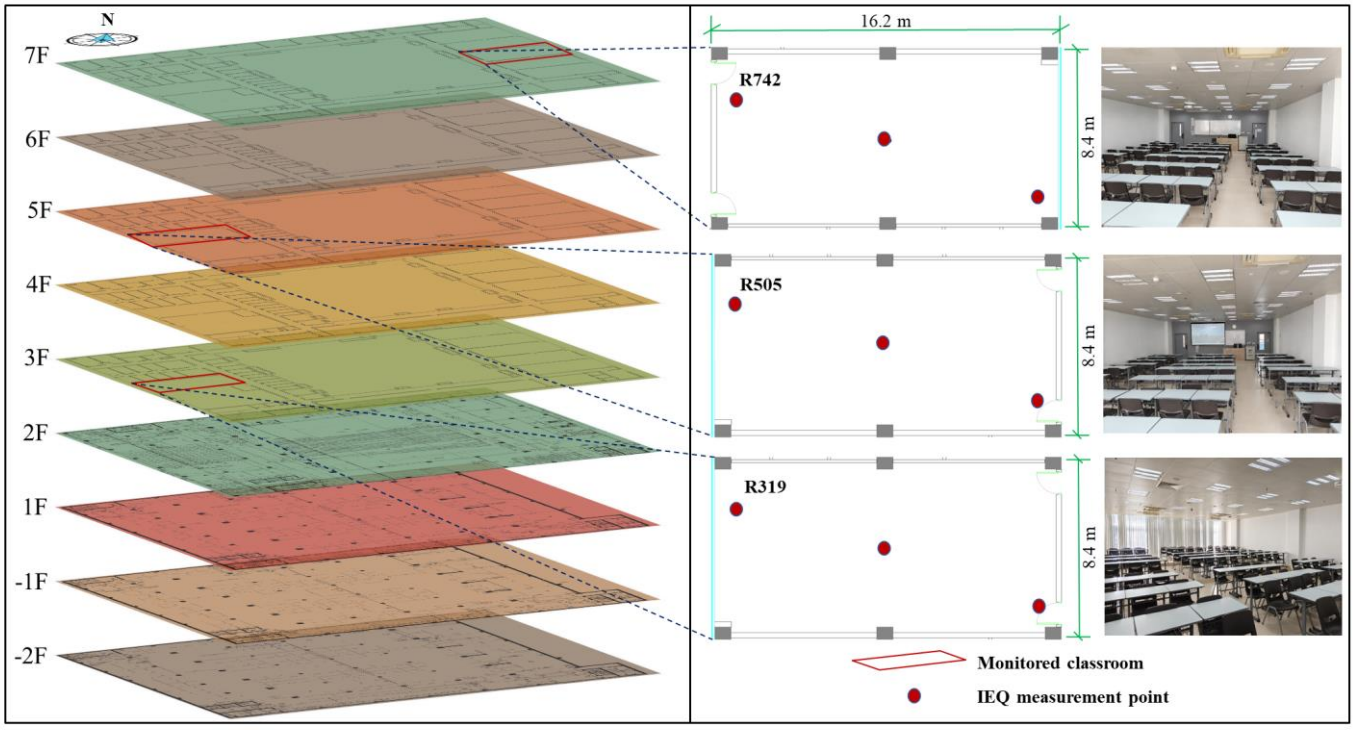


Figure 4: Locations and orientations of the three monitored classrooms in Block R, with the representative IEQ measurement-point layout (Photo source: taken by the authors on September 19, 2026).

Table 1: Specifications of the instruments used for on-site environmental measurements.

Variable	Instrument	Measurement Range	Precision
Noise	SMART SENSOR AR844	30 - 130 dB(A)	±1.5 dB(A)
CO_2	SMART SENSOR AR8200	350 - 9,999 ppm	±(30 ppm + 5% of reading)
Temperature		−10 – 50 °C	±5%
PM_{10}	Sensology MEF-550	0 - 0.999 mg/m^3	±5%
TVOC		0 - 9.999 mg/m^3	
HCHO		0 - 2.5 mg/m^3	

Note: The measurement ranges and precisions were obtained from the respective instrument manuals. The HCHO and TVOC sensors of the Sensology MEF-550 each have a limit of detection (LOD) and a resolution of 0.001 mg/m³, as confirmed by the supplier.

Outdoor meteorological conditions during the field investigations were characterized using historical observations from Macau International Airport (VMMC), located near the study building. Meteorological records at 14:00 local time, corresponding to the beginning of the indoor monitoring sessions, were retrieved from the Iowa

Environmental Mesonet (IEM) archive [42]. The recorded parameters included outdoor air temperature, relative humidity, wind direction, and wind speed (Table **2**).

Table 2: Outdoor meteorological conditions at the beginning of the classroom monitoring sessions.

Parameter	R319	R505	R742
Date	March 28, 2025	April 1, 2025	April 11, 2025
Outdoor temperature (°C)	28	17	26
Relative humidity (%)	78.9	63.4	88.8
Wind direction (°)	180	20	190
Wind speed (km/h)	16.7	25.9	16.7

Note: Meteorological observations were obtained from Macau International Airport (VMMC) at 14:00 local time (UTC+8). Relative humidity was calculated from air temperature and dew-point temperature.

2.4.3. Lighting Performance Simulation

To characterize the artificial-lighting conditions associated with the visual-environment assessment, a representative classroom model was established in DIALux evo based on the standard geometry and installed lighting configuration shared by the three monitored classrooms (R319, R505, and R742). The model represented a floor area of 141.12 m^2 (16.800 m × 8.400 m), a room and luminaire installation height of 3.250 m, and 36 LEDVANCE PanelLED Value 600 luminaires (40 W; 3,600 lm per luminaire) arranged in a 9 × 4 ceiling grid. During the classroom investigations, curtains were observed to remain closed for much of the teaching time to facilitate the use of projected teaching materials. Accordingly, the simulations were restricted to artificial lighting, without daylight contributions. Illuminance was evaluated on a horizontal working plane 0.750 m above floor level with a 0.500 m perimeter zone. The analysis quantified average, minimum, and maximum illuminance, illuminance uniformity, and the DIALux-reported Unified Glare Rating (UGR). Details of input parameters and simulation outputs are provided in Supplementary Material S4.

2.5. Data Analysis

Statistical analyses were performed using IBM SPSS Statistics (Version 22.0). For the items assessing the frequency of adverse conditions (Q1.3, Q2.2, Q2.3, and Q5.3), responses were coded from 1 = very frequent to 5 = never, so that higher scores indicated more favorable evaluations. Descriptive statistics were calculated for the individual questionnaire items, the five composite IEQ dimension scores, and overall satisfaction (Q6). The distribution of overall satisfaction was further examined using response frequencies, the median, interquartile range, and skewness to assess the concentration of responses at the upper end of the five-point scale.

Composite scores were calculated for each respondent as the arithmetic mean of Q1.1–Q1.3 (thermal comfort), Q2.1–Q2.3 (IAQ), Q3.1–Q3.2 (ventilation effectiveness), Q4.1–Q4.2 (acoustic comfort), and Q5.1–Q5.3 (visual environmental quality). Q6 was analyzed separately. Item-level summaries comprise the mean, sample standard deviation, median, interquartile interval, range, and frequencies in all five response categories. Positive item responses were defined as scores of 4 or 5; for adverse-condition items, this means rare or never rather than satisfied or very satisfied.

For each measured parameter, descriptive summaries were calculated separately for the 21 room-averaged records in each classroom. Standard deviations describe variation among these consecutive records, rather than variation among respondents or the three original measurement points. Concentration-to-reference ratios were used for contextual comparison. The local IAQ reference values are based on 8-h averages [43]; the available records do not establish an equivalent continuous or guideline-compliant intermittent monitoring period. These comparisons therefore do not constitute formal compliance tests. Because each classroom was measured on a different date, room and session effects cannot be separated. The 21 records were not treated as independent classroom replicates, and no measurement-to-questionnaire correlation was estimated without respondent-to-classroom linkage.

Given the ordinal measurement of overall satisfaction (Q6) and its concentration at the upper end of the response scale, bivariate associations between the five IEQ dimensions and overall satisfaction were examined using Spearman's rank correlation coefficient (ρ). Kendall's τ-b was additionally calculated as a non-parametric sensitivity analysis because it explicitly accounts for tied ranks.

Multiple linear regression (MLR) was then used to estimate the standardized partial associations between the five IEQ dimensions and overall satisfaction. All variables were standardized before model estimation, and HC3 heteroscedasticity-consistent standard errors were used for statistical inference. Variance inflation factors (VIFs) were examined to assess multicollinearity among the predictors. Because Q6 was measured on a five-level ordinal scale and showed substantial concentration in the upper response categories, ordinal logistic regression was additionally conducted as a sensitivity analysis.

3. Results

The results comprise descriptive analysis of the questionnaire data, assessment of the five IEQ categories based on occupant evaluations and corresponding environmental measurements or lighting simulation, and analysis of their associations with overall satisfaction. Correlation and regression analyses were further conducted to examine the relationships between the five composite IEQ scores and overall satisfaction.

3.1. Descriptive Analysis

A total of 120 questionnaires were distributed during the three investigation periods, of which 108 valid responses were retained, corresponding to a valid response rate of 90.0%. The questionnaire comprised 13 items representing five IEQ dimensions, together with Q6 assessing overall IEQ satisfaction. The investigated items were coded on five-point scales, with higher scores indicating more favorable evaluations. Details of the collected questionnaire responses are provided in Supplementary Material **S1** and Table **S1**.

Fig. (**5**) presents the response distributions for the 13 IEQ items and overall satisfaction (Q6). Overall satisfaction with IEQ in Block R was high (Q6: 4.30 ± 0.70). Specifically, 38.9% of respondents gave a score of 5 and 55.6% gave a score of 4, resulting in 94.4% favorable responses (scores 4 and 5); only 2.8% selected a score of 1 or 2. However, this concentration of favorable overall evaluations contrasted with the greater variation observed across specific IEQ attributes.

The five dimension-level means ranked as visual environmental quality (3.94), indoor air quality (3.89), acoustic comfort (3.87), thermal comfort (3.79), and ventilation effectiveness (3.65). For these dimensions, the respective percentages at scores 5, 4, 1, and 2 were 31.2%, 45.1%, 3.7%, and 5.6% for visual quality; 37.0%, 32.4%, 4.9%, and 7.7% for indoor air quality; 25.9%, 46.3%, 2.8%, and 6.0% for acoustics; 27.2%, 41.4%, 4.3%, and 8.3% for thermal comfort; and 21.8%, 40.3%, 6.0%, and 6.5% for ventilation. These percentages represent pooled item responses within each dimension. Visual quality had the highest combined proportion of scores 4–5 (76.2%), whereas ventilation had the lowest (62.0%). Indoor air quality recorded the largest proportion of score-5 responses (37.0%), despite a lower mean than visual quality. The relatively narrow range of dimension means (3.65–3.94) was accompanied by more pronounced differences among individual items.

Within visual quality, indoor lighting adequacy (Q5.1) recorded the highest item mean (4.33), with 95.4% favorable responses, compared with lower means for daylighting (Q5.2: 3.82) and glare or insufficient lighting (Q5.3: 3.68). For Q5.3, 13.9% reported frequent or very frequent visual discomfort. Thermal comfort exhibited the largest difference among its constituent item means: general temperature satisfaction (Q1.1: 4.18) and seasonal temperature control (Q1.2: 4.05) were evaluated more favorably than localized overheating or overcooling (Q1.3: 3.14). For Q1.3, 12.0% reported very frequent and 22.2% reported frequent occurrences. Within indoor air quality, item means ranged from 3.79 (Q2.2, unpleasant odors) to 4.00 (Q2.3, IAQ-related discomfort), with Q2.1 (air freshness) averaging 3.88; 16.7% reported frequent or very frequent unpleasant odors. Natural ventilation adequacy (Q3.2: 3.47) was rated less favorably than ventilation-system satisfaction (Q3.1: 3.83), with 10.2% selecting each of scores 1 and 2 for Q3.2. Acoustic evaluations were comparatively similar between overall acoustic comfort (Q4.1: 3.82) and sound-insulation effectiveness (Q4.2: 3.91).

The highest dimension-level mean in Block R was associated with particularly favorable assessments of general lighting adequacy, although the lower ratings for daylighting and glare-related conditions indicate differences among visual attributes. In contrast, the lowest dimension-level mean was associated with the comparatively unfavorable assessment of natural ventilation, rather than ventilation-system satisfaction. This distinction is relevant to the investigated classrooms, which operated with air-conditioning and closed windows during the survey sessions. Localized thermal conditions represented a separate concern: among the 102 respondents who rated overall IEQ satisfaction at 4 or 5, 32 (31.4%) also reported frequent or very frequent localized overheating or overcooling. The survey thus identifies specific differences in thermal, ventilation, and visual evaluations within the generally favorable indoor environment of Block R, providing a basis for the subsequent analysis of measured and simulated IEQ conditions.

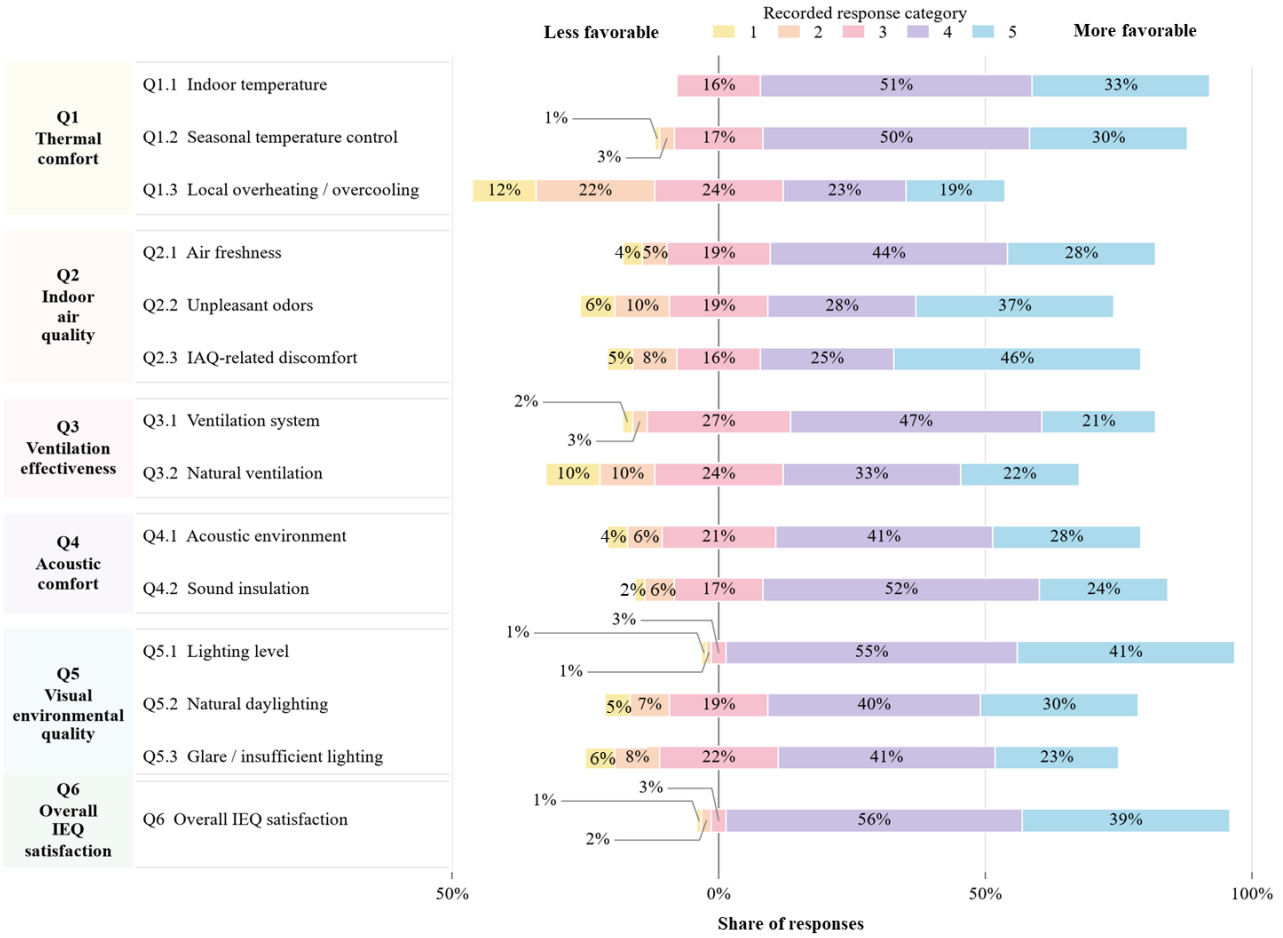


Figure 5: Distribution of occupant responses across the 13 IEQ items and overall IEQ satisfaction (Q6). Percentages indicate the proportion of responses in each five-point response category; higher response categories represent more favorable evaluations (n = 108).

3.2. Thermal Comfort

The thermal comfort dimension received a mean score of 3.79 ± 0.72. Questionnaire responses showed favorable evaluations of overall indoor temperature and seasonal temperature control, whereas localized overheating or overcooling received less favorable ratings (Fig. **6a**). During the monitored class breaks, all room-averaged temperature observations from the three air-conditioned classrooms fell within the 22–28 °C reference range specified in the Macau Guidelines for Indoor Air Quality in General Public Places [43] (Fig. **6b**).

Among the three thermal comfort items, overall satisfaction with indoor temperature (Q1.1) received the highest mean score (4.18 ± 0.68), with 84.3% of respondents selecting scores of 4 or 5, followed by seasonal

temperature control (Q1.2: 4.05 ± 0.81; 79.6%). In contrast, localized overheating or overcooling (Q1.3) received the lowest mean score (3.14 ± 1.29), with 12.0% and 22.2% reporting very frequent and frequent occurrences, respectively, whereas 41.7% reported rare or no occurrences. Q1.3 also exhibited greater response variability than Q1.1 and Q1.2. The measured mean temperatures in R505, R319, and R742 were 23.99 ± 0.33 °C, 25.23 ± 0.05 °C, and 25.03 ± 0.34 °C, respectively. Their corresponding ranges were 23.0–24.2 °C, 25.2–25.3 °C, and 24.6–25.5 °C, with R319 exhibiting the smallest within-session variation. Detailed monitoring statistics are provided in Supplementary Table **S2**.

Across the three monitoring dates, outdoor temperatures ranged from 17 °C to 28 °C (Table **2**), while the corresponding classroom mean temperatures under air-conditioned operation varied within a narrower range of 23.99–25.23 °C. This relatively limited variation in indoor mean temperatures, together with all monitored room-average values falling within the reference range, was consistent at the aggregate level with the favorable evaluation of overall indoor temperature (Q1.1). However, the comparatively low mean and greater response dispersion of Q1.3, together with the 34.3% reporting frequent or very frequent localized overheating or overcooling, showed that favorable general temperature evaluations coexisted with less favorable localized thermal experiences. The measured temperature distributions characterized short-term room-average conditions, whereas Q1.3 captured the reported occurrence of localized thermal discomfort, distinguishing two aspects of the thermal environment in Block R.

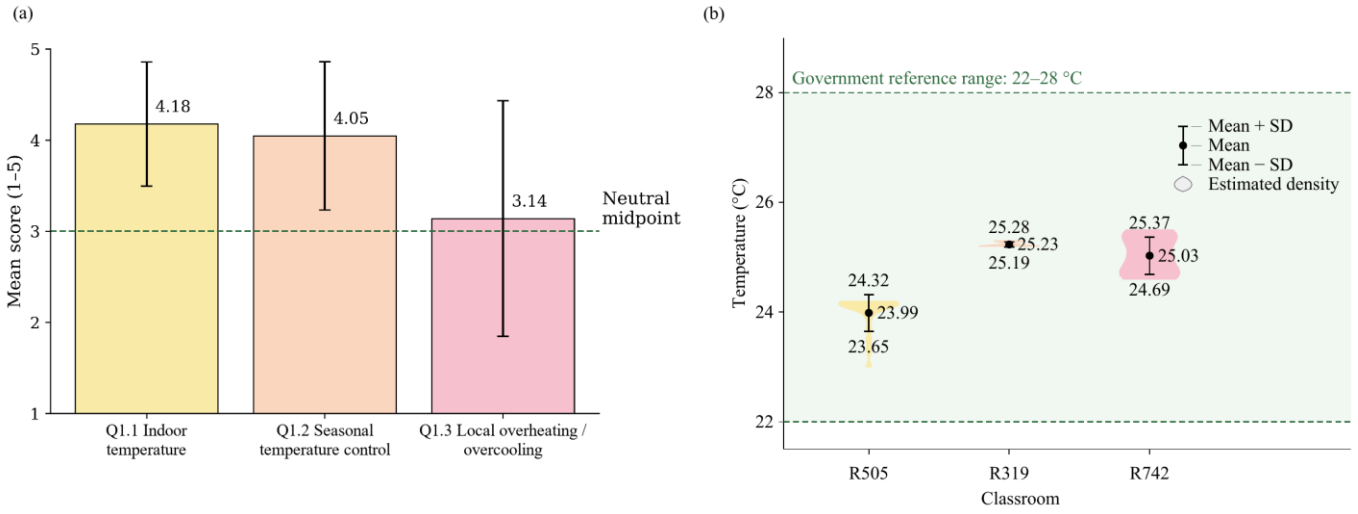


Figure 6: Thermal comfort evaluations and measured classroom temperatures. In (a), error bars indicate standard deviations (n = 108). (**a**) Questionnaire scores for Q1.1–Q1.3. (**b**) Distributions of room-averaged temperature observations for R505, R319, and R742 (21 observations per classroom). Points and error bars indicate means ± standard deviations, while violin shapes represent estimated distributions. Dashed boundaries and shading indicate the 22–28 °C government reference range [43].

3.3. Indoor Air Quality

The indoor air quality (IAQ) dimension received a mean score of 3.89 ± 0.95, with all three questionnaire items scoring above the neutral midpoint (Fig. **7a**). Occupant evaluations were generally favorable, although responses concerning unpleasant odors and IAQ-related discomfort showed greater variability than those concerning air freshness. On-site monitoring in the three representative classrooms recorded room-averaged HCHO, TVOC, and PM_{10} concentrations below the corresponding reference values specified in the Macau Guidelines for Indoor Air Quality in General Public Places during the monitored periods (Fig. **7b-d**).

Among the three IAQ items, infrequent IAQ-related discomfort (Q2.3) received the highest mean score (4.00 ± 1.18), with 71.3% of respondents selecting scores of 4 or 5. Satisfaction with indoor air freshness (Q2.1) averaged 3.88 ± 0.99, with 72.2% favorable responses, whereas infrequent unpleasant odors (Q2.2) received the lowest mean score (3.79 ± 1.23), with 64.8% favorable responses. Frequent or very frequent unpleasant odors and IAQ-related discomfort were reported by 16.7% and 13.0% of respondents, respectively. For the monitored pollutants,

mean HCHO concentrations ranged from 0.0031 mg/m³ in R742 to 0.0056 mg/m³ in R505, while mean TVOC concentrations ranged from 0.0036 mg/m³ in R319 to 0.0052 mg/m³ in R742. Mean PM_{10} concentrations were highest in R319 (24.10 ± 4.84 μg/m³), followed by R742 (23.62 ± 5.89 μg/m³) and R505 (19.05 ± 4.50 μg/m³). Detailed monitoring results are provided in Supplementary Table **S2**.

The highest mean evaluation for Q2.3 was associated with a greater proportion of respondents selecting the most favorable response category (46.3%) than for Q2.1 (27.8%), despite Q2.1 having a slightly higher combined proportion of scores 4 and 5. In contrast, Q2.2 exhibited both the lowest favorable-response proportion and the greatest response dispersion, identifying unpleasant odors as the relatively less favorably evaluated aspect of perceived IAQ. The pollutant measurements showed a different pattern of variation: the highest mean HCHO, TVOC, and PM_{10} concentrations occurred in R505, R742, and R319, respectively, without a consistent ranking across the classrooms. The maximum recorded HCHO, TVOC, and PM_{10} concentrations represented only 10.0%, 1.3%, and 21.3% of their respective local reference concentrations [43]. These short-term measurements were broadly consistent with the favorable overall IAQ evaluations, while the reported occurrences of unpleasant odors and IAQ-related discomfort represented aspects of occupant experience not directly characterized by the monitored pollutant concentrations.

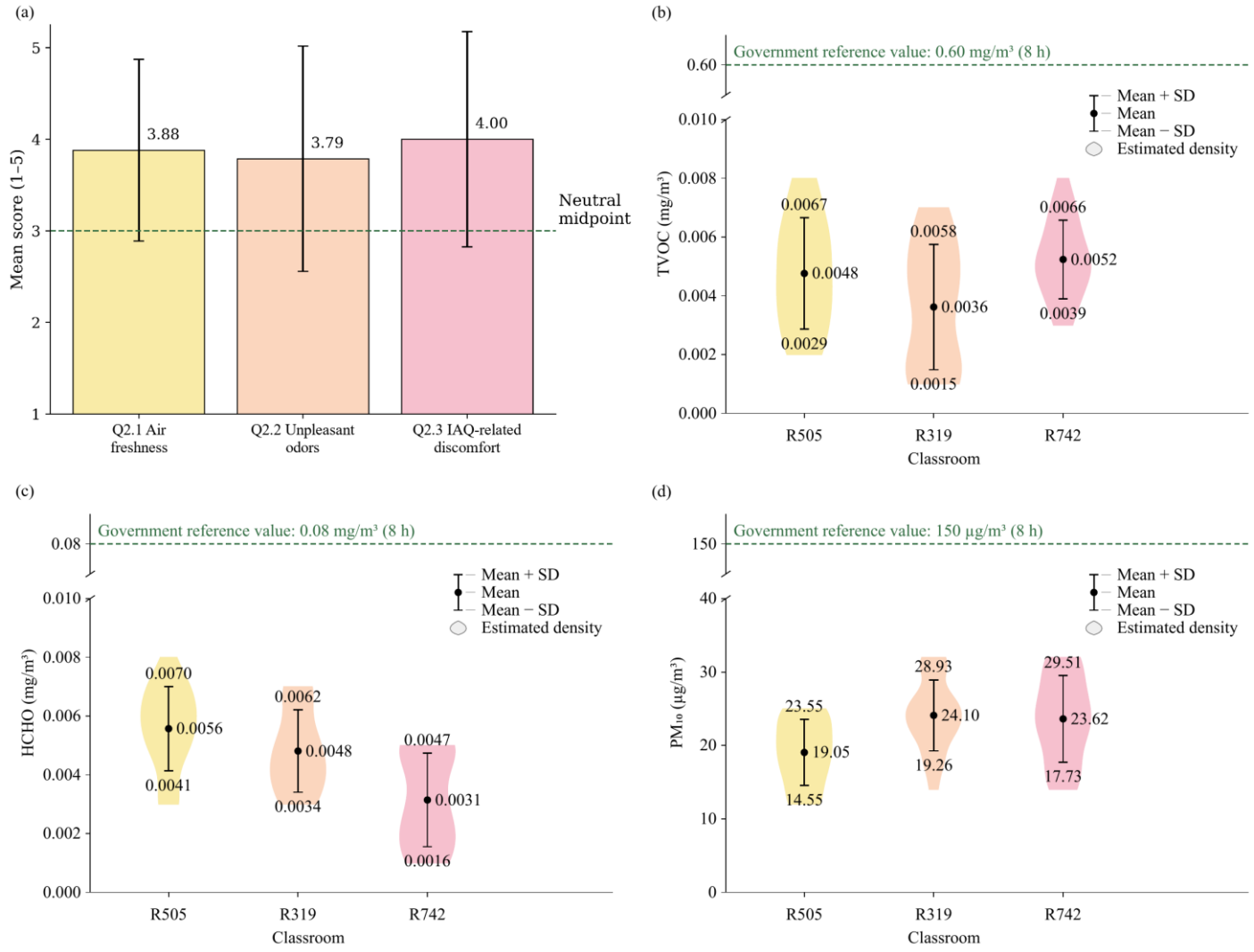


Figure 7: Indoor air quality evaluations and measured pollutant concentrations. (**a**) Mean questionnaire scores for Q2.1–Q2.3 (n = 108; error bars: SD). (**b**–**d**) Violin plots of room-averaged TVOC, HCHO, and PM_{10} concentrations, showing means ± SD and observed ranges. Dashed lines indicate government reference values for 8-h averages [43], provided for contextual comparison with the short-term measurements.

3.4. Ventilation Effectiveness

Ventilation effectiveness received a mean score of 3.65 ± 0.95, the lowest among the five IEQ dimensions. Although both questionnaire items scored above the neutral midpoint, respondents evaluated the ventilation system more favorably than natural ventilation adequacy (Fig. **8a**). During the monitored class breaks, with classroom windows closed and air-conditioning systems operating, all room-averaged CO_2 concentrations remained below the 1,000 ppm reference value specified in the Macau Guidelines for Indoor Air Quality in General Public Places [43] (Fig. **8b**).

Satisfaction with the ventilation system (Q3.1) received the higher mean score of 3.83 ± 0.86, with 68.5% of respondents selecting scores of 4 or 5. In contrast, natural ventilation adequacy (Q3.2) averaged 3.47 ± 1.23, with 55.6% favorable responses and 20.4% selecting scores of 1 or 2. The greater standard deviation of Q3.2 indicated more dispersed evaluations of natural ventilation adequacy. The measured mean CO_2 concentrations in R505, R319, and R742 were 689.81 ± 104.67 ppm, 863.67 ± 26.50 ppm, and 640.38 ± 21.81 ppm, respectively. The corresponding concentration ranges were 562–884 ppm, 803–897 ppm, and 602–680 ppm. Detailed monitoring statistics are provided in Supplementary Table **S2**.

The relatively low overall ventilation score was mainly associated with the less favorable evaluation of natural ventilation adequacy (Q3.2), rather than uniformly low ratings across both items. Compared with Q3.2, ventilation-system satisfaction (Q3.1) was 0.36 points higher in mean score and 12.9 percentage points higher in favorable-response rate. This difference is consistent with the operating conditions of the investigated classrooms, where air-conditioning systems were routinely used during teaching and windows remained closed during the monitored sessions, limiting opportunities for natural ventilation. Under these conditions, the CO_2 measurements showed distinct patterns across classrooms. R319 recorded the highest mean concentration but relatively limited within-session variation, whereas R505 exhibited the greatest variation despite a lower mean concentration. R742 had the lowest mean concentration and smallest observed range. Thus, although the monitored CO_2 concentrations remained below the local reference value, the relative concentration levels and short-term variability differed among the three classrooms.

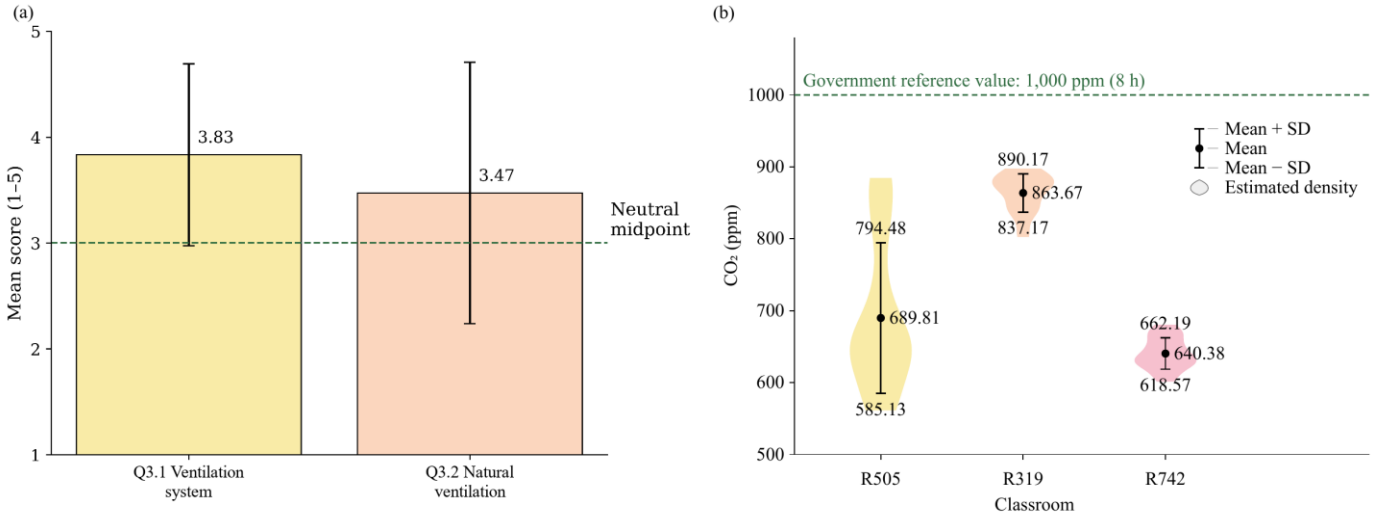


Figure 8: Ventilation evaluations and measured classroom CO_2 concentrations. (**a**) Mean questionnaire scores for Q3.1–Q3.2 (n = 108; error bars: SD), with the dashed line indicating the neutral midpoint. (**b**) Violin plots of room-averaged CO_2 concentrations, showing means ± SD and observed ranges. The dashed line indicates the government reference value for an 8-h average (1,000 ppm) [43], provided for contextual comparison with the short-term measurements.

3.5. Acoustic Comfort

Acoustic comfort received a mean score of 3.87 ± 0.88, with both questionnaire items showing generally favorable evaluations (Fig. **9a**). Respondents rated the effectiveness of sound-insulation measures slightly more

favorably than overall satisfaction with the acoustic environment. During the monitored class breaks, room-averaged operational sound levels across the three classrooms ranged from 46.3 to 57.2 dB(A), with differences in both mean levels and within-session variability (Fig. **9b**).

The effectiveness of sound-insulation measures (Q4.2) received the higher mean score of 3.91 ± 0.89, with 75.9% of respondents selecting scores of 4 or 5. Overall satisfaction with the acoustic environment (Q4.1) averaged 3.82 ± 1.03, with 68.5% favorable responses and greater response variability. The measured mean sound levels in R505, R319, and R742 were 47.82 ± 1.15 dB(A), 54.43 ± 1.88 dB(A), and 51.00 ± 0.84 dB(A), respectively. The corresponding ranges were 46.3–51.0 dB(A), 51.2–57.2 dB(A), and 49.3–52.5 dB(A). R319 recorded the highest mean level and greatest within-session variation, whereas R742 exhibited the smallest variation. Detailed monitoring statistics are provided in Supplementary Table **S2**.

The slightly higher Q4.2 rating, exceeding Q4.1 by 0.09 points and 7.4 percentage points in favorable responses, indicated more positive perceptions of sound-insulation effectiveness than of the overall acoustic environment. The greater response dispersion for Q4.1 also reflected more varied evaluations of general acoustic conditions. In the field measurements, R319 had a mean sound level 6.61 dB higher than R505 and 3.43 dB higher than R742, accompanied by the greatest within-session variability. Compared with the Taipa daytime indoor background-noise reference of 46 dB(A) [44], the mean operational sound levels were higher by 1.82 dB in R505, 8.43 dB in R319, and 5.00 dB in R742. However, the measurements were conducted during scheduled class breaks rather than under unoccupied background conditions. Student conversations and movement during these periods may have contributed to the recorded levels, together with HVAC operation and other environmental sound sources.

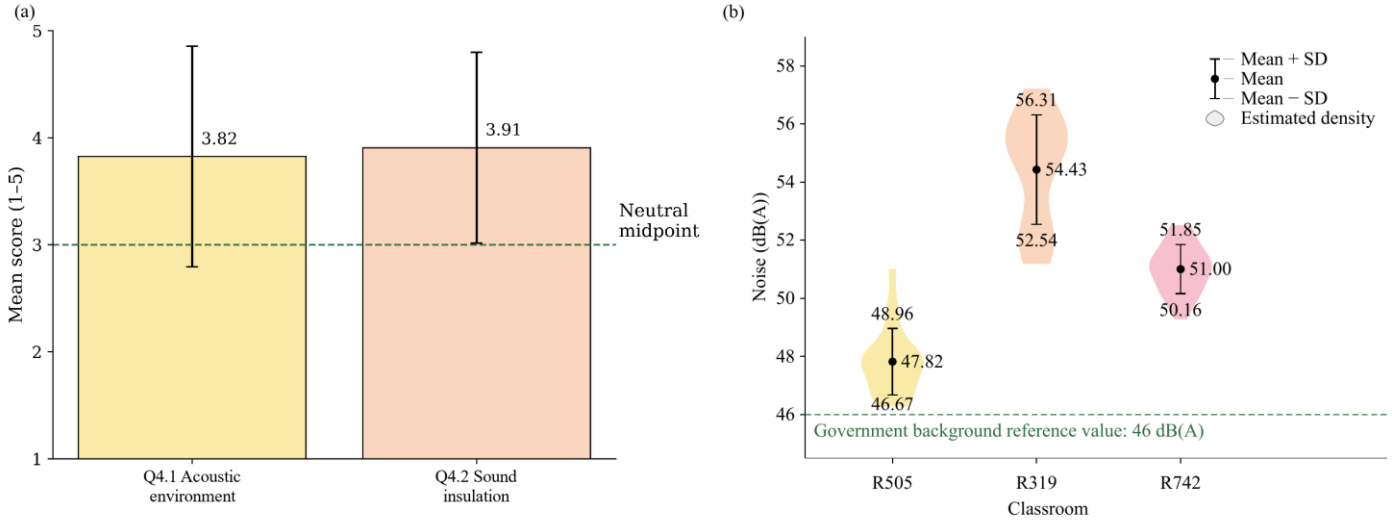


Figure 9: Acoustic comfort evaluations and measured operational sound levels. (**a**) Mean questionnaire scores for Q4.1–Q4.2 (n = 108; error bars: SD), with the dashed line indicating the neutral midpoint. (**b**) Violin plots of room-averaged operational sound levels, showing means ± SD and estimated distributions. The dashed line indicates the Taipa daytime indoor background-noise reference of 46 dB(A) [44], provided for contextual comparison with the measurements during class breaks.

3.6. Visual Environmental Quality

Visual environmental quality received the highest mean score among the five IEQ dimensions (3.94 ± 0.67). Occupants evaluated indoor lighting levels particularly favorably, whereas natural daylighting adequacy and the frequency of glare or insufficient lighting received lower and more dispersed ratings (Fig. **10**). The representative DIALux evo simulation showed that the average artificial illuminance exceeded the adopted classroom reference, while the maximum Unified Glare Rating (UGR) was above the corresponding criterion.

Among the three visual-environment items, satisfaction with indoor lighting level (Q5.1) received the highest mean score across all 13 IEQ items (4.33 ± 0.67), with 95.4% of respondents selecting scores of 4 or 5. Natural daylighting adequacy (Q5.2) averaged 3.82 ± 1.08, with 69.4% favorable responses, whereas infrequent glare or

insufficient lighting (Q5.3) received the lowest mean score (3.68 ± 1.09), with 63.9% favorable responses. Frequent or very frequent glare or insufficient lighting was reported by 13.9% of respondents. The artificial-lighting simulation yielded average, minimum, and maximum illuminance values of 668, 441, and 757 lx, respectively, with an overall uniformity (U_0) of 0.66. The average illuminance exceeded the adopted 500-lx classroom reference by 33.6% [45], while the simulated maximum UGR of 22 exceeded the reference criterion of 19 [46, 47]. Detailed simulation results are provided in Supplementary Section S4.

The contrast among the visual-environment indicators was particularly evident between general lighting satisfaction and glare-related conditions. Q5.1 exceeded Q5.3 by 0.65 points in mean score and 31.5 percentage points in favorable responses. Similarly, the simulated average illuminance was above the adopted classroom reference, whereas the maximum UGR exceeded the glare criterion by three units. The relatively high satisfaction with indoor lighting levels was therefore accompanied by a less favorable modeled glare result and more dispersed responses regarding glare or insufficient lighting. However, Q5.3 addressed both glare and insufficient lighting, rather than distinguishing between these conditions. Natural daylighting adequacy (Q5.2) was also evaluated less favorably than general lighting levels, with a mean score 0.51 points lower. Field observations indicated that classroom curtains remained closed for much of the teaching time to facilitate the use of projected teaching materials, reducing daylight availability during these periods. This operating arrangement provided context for the lower natural-daylighting evaluations, while the artificial-lighting simulation, which excluded daylight contributions, represented the lighting conditions associated with projector-assisted teaching.

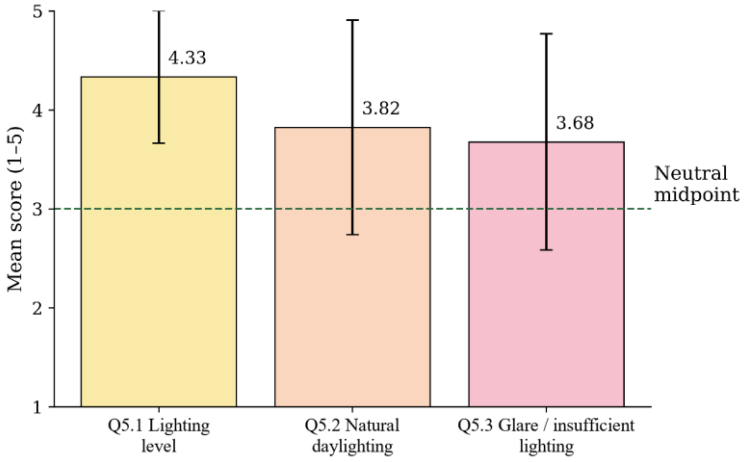


Figure 10: Occupant evaluations of visual environmental quality (Q5.1–Q5.3; n = 108). Error bars indicate standard deviations, and the dashed line marks the scale midpoint (score = 3). For Q5.3, higher scores indicate less frequent glare or insufficient lighting.

3.7. Integrated Summary of IEQ Performance

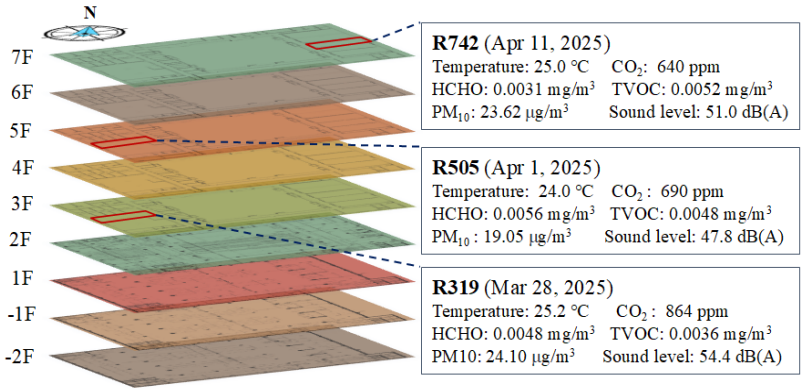
Fig. (**11**) reveals a distinction between favorable overall IEQ evaluations and the more differentiated environmental conditions experienced in Block R. Overall satisfaction (Q6: 4.30 ± 0.70) exceeded the five dimension-level mean scores (3.65–3.94), while localized overheating or overcooling, natural ventilation adequacy, and glare or insufficient lighting received comparatively less favorable evaluations (Fig. **11a**). The measured and simulated indicators further highlighted differences between average environmental conditions and specific IEQ attributes. Room-averaged temperatures and CO_2 concentrations remained within or below their respective reference values under air-conditioned, closed-window operation, whereas the simulated average illuminance exceeded the classroom reference despite a maximum UGR above the glare criterion. These differences must also be considered within the actual teaching context, including curtain closure for projected materials and occupied classroom activity during acoustic monitoring. Consequently, favorable overall evaluations and reference-level environmental conditions did not imply equally favorable performance across all aspects of the occupied environment.

The classroom-level evidence reinforced this distinction. The relative environmental profiles of R319, R505, and R742 varied across measured parameters, with no classroom consistently exhibiting the highest or lowest values (Fig. **11b**). These observations reflected different monitoring dates and conditions rather than a controlled ranking of classroom performance. Meanwhile, the shared artificial-lighting configuration produced a simulated working-plane illuminance range of 441–757 lx (U_0 = 0.66), demonstrating spatial variation that was not conveyed by the mean illuminance alone (Fig. **11c**). The combined findings indicate that aggregate satisfaction, specific IEQ attributes, and spatial environmental characteristics capture different aspects of building performance. Whether the five perceived IEQ dimensions also differed in their associations with overall satisfaction was subsequently examined through correlation and regression analyses in Section 3.8.

(a) Dimension-level summary and benchmark comparison

IEQ dimension	Occupant evaluation (mean ± SD)	Indicator(s)	Measured / simulated value(s)	Reference value
Thermal comfort	3.79 ± 0.72	Temperature	23.99–25.23 °C	22–28 °C [43]
Indoor air quality	3.89 ± 0.95	HCHO TVOC PM_{10}	0.0031–0.0056 mg/m³ 0.0036–0.0052 mg/m³ 19.05–24.10 μg/m³	≤0.080 mg/m³ [43] ≤0.600 mg/m³ [43] ≤150 μg/m³ [43]
Ventilation effectiveness	3.65 ± 0.95	CO_2	640.38–863.67 ppm	≤1000 ppm [43]
Acoustic comfort	3.87 ± 0.88	Operational sound level	47.82–54.43 dB(A)	46 dB(A)*[44]
Visual environmental quality	3.94 ± 0.67	Illuminance UGR_{max}	668 lx 22	≥500 lx [45] ≤19 [46,47]

(b) Locations and measured IEQ conditions of the three monitored classrooms



(c) Simulated illuminance distribution

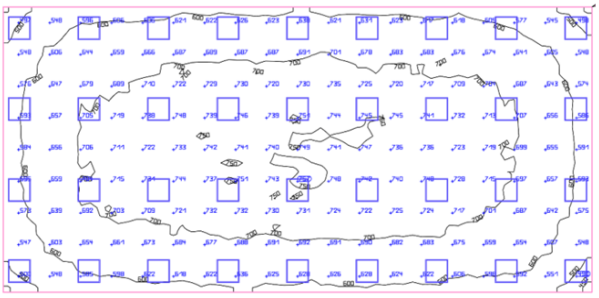


Figure 11: Summary of occupant evaluations, measured IEQ conditions, and simulated illuminance performance in Block R. (**a**) Dimension-level summary of occupant evaluations, measured or simulated indicators, and reference value. For measured parameters, reported ranges denote classroom-level mean values across R319, R505, and R742; illuminance and UGR are derived from the representative classroom model. (**b**) Locations and room-averaged IEQ profiles of the three monitored classrooms for R319 (March 28, 2025), R505 (April 1, 2025), and R742 (April 11, 2025). (**c**) Simulated working-plane illuminance distribution based on the common geometry and artificial-lighting configuration of R319, R505, and R742. *The acoustic value represents the daytime indoor background-noise reference derived for Taipa under the Macao Acoustic Regulation and is used for contextual comparison only, not as a regulatory compliance threshold for the occupied class-break measurements; the measured values represent occupied operational sound levels. The plotted field-measured IEQ parameters represent room-averaged values, whereas the lighting simulation illustrates the spatial distribution of illuminance.

3.8. IEQ Dimensions and Overall Satisfaction

Given the differentiated evaluations across the five IEQ dimensions, their relationships with overall satisfaction were examined at both the bivariate and multivariable levels. Spearman's ρ, with Kendall's τ-b as a sensitivity analysis, was used to compare the strength of the bivariate associations, followed by multiple linear regression and ordinal logistic sensitivity analysis to assess dimension-specific associations after simultaneous adjustment.

3.8.1. Spearman Correlation and Kendall's τ-b Sensitivity Analysis

Given the ordinal nature of the response variables and the pronounced concentration of overall satisfaction scores at the upper end of the scale, Spearman's rank correlation coefficient (ρ) was employed to assess the monotonic associations between the five IEQ dimensions and overall satisfaction. Kendall's τ-b was additionally estimated as a non-parametric sensitivity measure to account for the substantial number of tied observations in Q6. The complete Spearman correlation matrix is presented in Fig. (**12**), whereas Table **3** reports the associations between each IEQ dimension and overall satisfaction estimated using both Spearman's ρ and Kendall's τ-b.

All five IEQ dimensions were positively and significantly associated with overall satisfaction according to Spearman's ρ ($p < 0.001$). Acoustic comfort exhibited the strongest association ($\rho = 0.599$), followed by ventilation effectiveness ($\rho = 0.568$), indoor air quality ($\rho = 0.538$), visual environmental quality ($\rho = 0.468$), and thermal comfort ($\rho = 0.384$). The Kendall's τ-b sensitivity analysis yielded an identical ordering of the five dimensions, with coefficients ranging from 0.333 for thermal comfort to 0.527 for acoustic comfort; all associations remained statistically significant ($p < 0.001$). The concordance in direction and relative magnitude between Spearman's ρ and Kendall's τ-b indicates that the observed bivariate association pattern was preserved after explicitly accounting for tied ranks in the overall satisfaction variable.

The two rank-based analyses indicate that more favorable evaluations across each IEQ dimension were consistently associated with higher overall satisfaction. These coefficients quantify monotonic associations between perceived IEQ conditions and overall satisfaction and should not be interpreted as evidence of causal effects.

The Spearman correlation matrix further identified statistically significant positive associations among the five IEQ dimensions. The strongest inter-dimensional association occurred between ventilation effectiveness and acoustic comfort ($\rho = 0.691$). Indoor air quality was also moderately to strongly associated with ventilation effectiveness ($\rho = 0.578$) and acoustic comfort ($\rho = 0.554$). These inter-dimensional associations indicate substantial shared variation among the perceived IEQ dimensions.

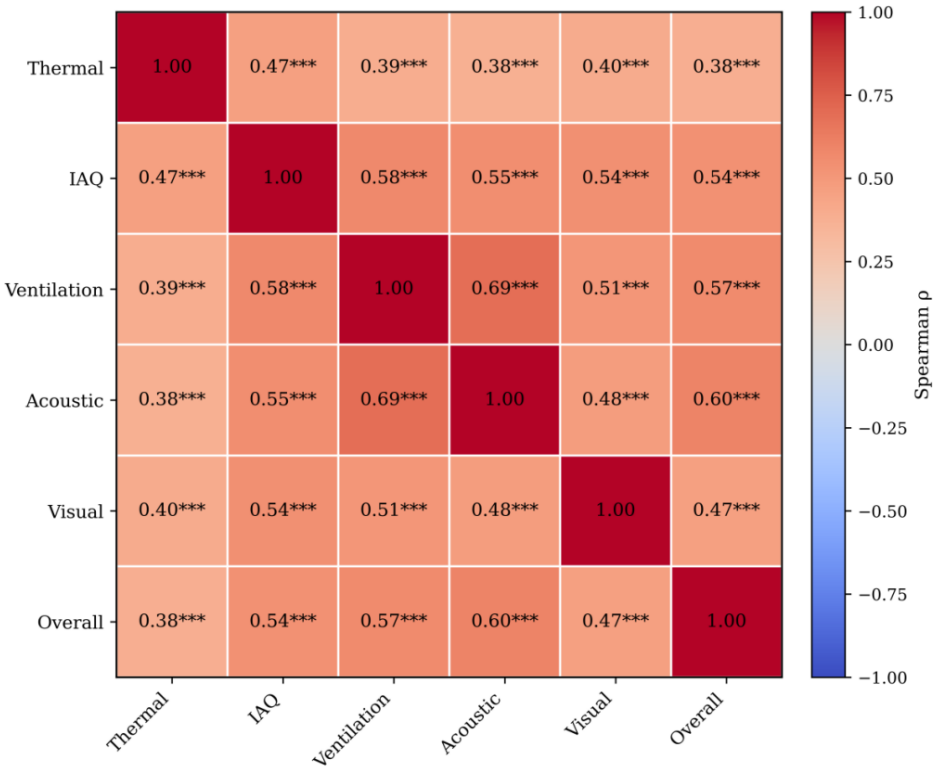


Figure 12: Spearman correlation coefficients among IEQ dimensions and overall IEQ satisfaction. Values represent Spearman's correlation coefficients (ρ). Statistical significance is denoted as follows: $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***).

Table 3: Rank-based correlations and multiple regression results for IEQ dimensions and overall satisfaction.

IEQ dimension	Mean ± SD	Spearman ρ	Correlation p-value	Standardized β	Kendall's τ-b	Kendall p-value	95% CI	Regression p-value	VIF
Thermal comfort	3.79 ± 0.72	0.384	<0.001	0.119	0.333	<0.001	[-0.044, 0.281]	0.154	1.43
Indoor air quality	3.89 ± 0.95	0.538	<0.001	0.244	0.472	<0.001	[-0.036, 0.524]	0.088	1.82
Ventilation effectiveness	3.65 ± 0.95	0.568	<0.001	0.080	0.496	<0.001	[-0.346, 0.506]	0.713	2.24
Acoustic comfort	3.87 ± 0.88	0.599	<0.001	0.190	0.527	<0.001	[-0.186, 0.567]	0.322	2.02
Visual environmental quality	3.94 ± 0.67	0.468	<0.001	0.211	0.406	<0.001	[-0.039, 0.461]	0.098	1.69

Notes: SD = standard deviation; ρ = Spearman's rank correlation coefficient; τ-b = Kendall's rank correlation coefficient adjusted for tied ranks; β = standardized regression coefficient; CI = confidence interval; VIF = variance inflation factor. Spearman's ρ and Kendall's τ-b evaluate monotonic associations between each IEQ dimension and overall satisfaction. Kendall's τ-b was included as a sensitivity analysis because of the substantial number of tied observations in Q6. The multiple regression model was estimated using standardized variables with HC3 heteroscedasticity-consistent standard errors (R^2 = 0.438, adjusted R^2 = 0.411, robust F = 8.01, $p < 0.001$).

3.8.2. Multiple Linear Regression and Ordinal Logistic Sensitivity Analysis

To examine the adjusted associations between the five IEQ dimensions and overall satisfaction, a multiple linear regression model was constructed utilizing the overall satisfaction score (Q6) as the dependent variable and the five composite IEQ dimension scores as predictors. All variables were standardized prior to model estimation, and HC3 heteroscedasticity-consistent standard errors were used to account for potential heteroscedasticity in statistical inference. The pronounced upper-end concentration of Q6 restricted variation in the dependent variable and consequently limited the information available for estimating dimension-specific adjusted associations. HC3 standard errors address heteroscedasticity but do not remove this restriction in outcome variability. The OLS coefficients were therefore interpreted in conjunction with the rank-based analyses and the ordinal logistic sensitivity analysis. The regression model was specified as follows:

$$Z_{overall}=\beta_0+\beta_1 Z_{Thermal}+\beta_2 Z_{IAQ}+\beta_3 Z_{Ventilation}+\beta_4 Z_{Acoustic}+\beta_5 Z_{Visual}+\varepsilon \quad \text{(Eq. 1)}$$

where $Z_{overall}$ represents the standardized overall satisfaction score, and $Z_{Thermal}$, Z_{IAQ}, $Z_{Ventilation}$, $Z_{Acoustic}$, and Z_{Visual} represent the standardized scores of thermal comfort, indoor air quality, ventilation effectiveness, acoustic comfort, and visual environmental quality, respectively. The intercept β_0 represents the expected standardized overall satisfaction score when all predictor variables are equal to zero; because all variables were standardized, its estimated value is expected to be approximately zero. The coefficients β_1-β_5 represent the adjusted associations of each IEQ dimension with overall satisfaction conditional on the other IEQ dimensions included in the model. Positive coefficients indicate that more favorable evaluations of a given IEQ dimension are associated with higher overall satisfaction after adjustment for the remaining dimensions. The residual term ε represents unexplained variability.

The regression results are presented in Table **3** and Fig. (**13**). The model was statistically significant overall (robust F = 8.01, $p < 0.001$), accounting for 43.8% of the observed variation in overall satisfaction scores (R^2 = 0.438; adjusted R^2 = 0.411).

When all five IEQ dimensions were entered simultaneously, the standardized coefficients were positive for thermal comfort (β = 0.119, 95% CI: −0.044 to 0.281, p = 0.154), indoor air quality (β = 0.244, 95% CI: −0.036 to 0.524, p = 0.088), ventilation effectiveness (β = 0.080, 95% CI: −0.346 to 0.506, p = 0.713), acoustic comfort (β = 0.190, 95% CI: −0.186 to 0.567, p = 0.322), and visual environmental quality (β = 0.211, 95% CI: −0.039 to 0.461, p = 0.098), but none reached statistical significance. VIF values ranged from 1.43 to 2.24, indicating no evidence of severe multicollinearity among the five predictors.

Although the five IEQ dimensions were collectively associated with overall satisfaction at the model level, no individual dimension demonstrated a statistically significant adjusted association in the OLS model. Given the restricted variability of Q6, the non-significant dimension-specific coefficients should be interpreted as insufficient evidence for adjusted associations within the present sample rather than as evidence that the individual IEQ

dimensions were unrelated to overall satisfaction. This distinction is consistent with the statistically significant positive bivariate associations identified by both Spearman's ρ and Kendall's τ-b in Section 3.8.1.

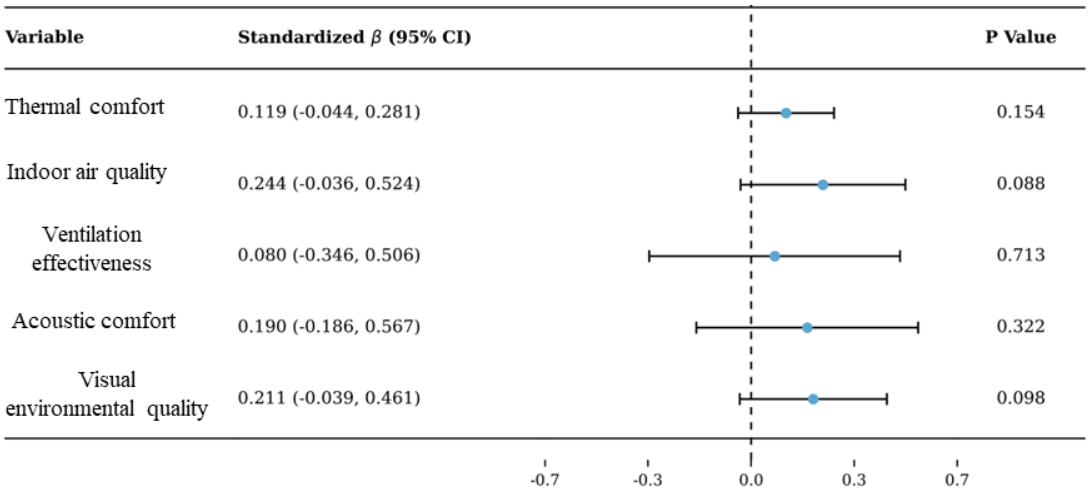


Figure 13: Standardized OLS regression coefficients for IEQ dimensions predicting overall satisfaction. Error bars represent the 95% confidence intervals of the standardized regression coefficients (β). The dashed vertical line indicates the null effect (β = 0). P-values indicate the statistical significance of individual predictors. The regression model was estimated using standardized variables with HC3 heteroscedasticity-consistent standard errors.

An ordinal logistic regression was fitted as a sensitivity analysis to assess whether the multivariable findings were sensitive to the treatment of Q6 as a continuous outcome in the OLS model, given that overall satisfaction was measured on a five-point ordinal scale. The full ordinal logistic regression results are reported in Table **4**. Acoustic comfort was significantly associated with a higher overall satisfaction category: for each one-standard-deviation increase, the odds of being in a higher satisfaction category were 2.18 times greater (95% CI: 1.07–4.41, p = 0.031). The associations for indoor air quality (OR = 1.73, 95% CI: 0.95–3.16, p = 0.075) and visual environmental quality (OR = 1.74, 95% CI: 0.94–3.24, p = 0.078) were positive but did not reach statistical significance. Thermal comfort (OR = 1.50, 95% CI: 0.87–2.58, p = 0.148) and ventilation effectiveness (OR = 1.57, 95% CI: 0.77–3.20, p = 0.216) were not statistically significant.

The ordinal logistic model yielded positive associations across all five IEQ dimensions, but differed from the OLS model in the statistical significance of acoustic comfort. This discrepancy should be interpreted in the context of the highly concentrated outcome distribution: 94.4% of respondents selected categories 4 or 5, while only six observations fell within categories 1–3. Such concentration limits discrimination among highly satisfied respondents and leaves relatively little information in the lower response categories. Accordingly, the statistical significance of acoustic comfort was sensitive to the specification of Q6.

Table 4: Sensitivity analysis using ordinal logistic regression.

IEQ dimension	OR (per 1-SD increase)	95% CI	p-value
Thermal comfort	1.50	[0.87, 2.58]	0.148
Indoor air quality	1.73	[0.95, 3.16]	0.075
Ventilation effectiveness	1.57	[0.77, 3.20]	0.216
Acoustic comfort	2.18	[1.07, 4.41]	0.031
Visual environmental quality	1.74	[0.94, 3.24]	0.078

Notes: OR = odds ratio; CI = confidence interval. ORs represent the change in odds of reporting a higher overall satisfaction category (Q6) associated with a 1-SD increase in each IEQ dimension. An OR > 1 indicates a positive association. Given the concentration of Q6 responses in the upper categories and the sparse observations in the lower categories, ordinal logistic regression was conducted as a sensitivity analysis to examine whether the dimension-specific association pattern was sensitive to treating Q6 as an ordinal rather than a continuous outcome.

4. Discussion

The discussion interprets the findings in relation to the operational IEQ performance of the Platinum-certified case building and the extent to which occupant evaluations correspond with measured environmental conditions. It further examines the implications of the observed performance patterns for post-occupancy building operation and management, followed by consideration of the study limitations and directions for future research.

4.1. IEQ Performance of Block R

Occupant evaluations of the investigated teaching spaces in Block R were generally favorable, with a high overall satisfaction score (4.30 ± 0.70) and 94.4% of respondents providing positive evaluations. However, the dimension-level results indicated that this favorable overall assessment was accompanied by notable variation across specific IEQ aspects.

According to the project's BEAM Plus final assessment report, Block R was classified as Platinum and awarded 13.5 credits in the Health and Wellbeing (HWB) category. Within HWB, the occupied-space IAQ assessment received the full four credits, while the thermal-comfort criterion was also achieved. Monitored pollutant concentrations remained below the applicable local recommended reference values during the investigated sessions, and IAQ was among the more positively evaluated IEQ dimensions. Nevertheless, ventilation effectiveness received the lowest dimension-level evaluation (mean = 3.65), while the reported frequency of localized overheating or overcooling received the lowest item-level score (mean = 3.14), despite acceptable CO_2 concentrations and generally stable room-average temperatures under the monitored operating conditions. This contrast highlights the difference between certification-based IEQ assessment and occupants' evaluations of specific environmental conditions during building use. Although Block R achieved the relevant BEAM Plus HWB credits, the POE identified less favorable evaluations of natural ventilation adequacy and localized overheating or overcooling. These differences reflect aspects of occupant experience not fully characterized by certification outcomes, rather than demonstrated non-compliance with BEAM Plus criteria or a quantified certification-to-operation performance gap. Similar distinctions between certified performance and occupant perceptions have been reported in previous POE studies [7, 48].

Although all five IEQ dimensions were positively associated with overall satisfaction in the bivariate analyses, none showed a statistically significant adjusted association in the OLS model. However, acoustic comfort was significantly associated with a higher overall satisfaction category in the ordinal logistic sensitivity analysis (OR = 2.18, 95% CI: 1.07–4.41, p = 0.031). This difference indicates that the inference regarding acoustic comfort was sensitive to model specification, and the results do not establish a consistently dominant IEQ dimension.

4.2. Interpretation of IEQ Performance Through Subjective-objective Assessments

Ventilation effectiveness exhibited the lowest dimension-level evaluation, primarily owing to the comparatively low rating of natural ventilation adequacy. During the monitored classroom sessions, however, the windows remained closed and the spaces were mechanically conditioned, while CO_2 concentrations in all three classrooms remained below the applicable local reference value. However, without real-time occupancy, outdoor CO_2, and outdoor-air supply data, these short-term CO_2 observations serve as qualitative background indicators of indoor air quality rather than as a basis for calculating absolute ventilation rates (L/s per person) or air changes per hour (ACH). They therefore do not establish ventilation adequacy or effectiveness. Natural ventilation was not the operating mode during monitoring, and the lower Q3.2 rating reflects occupants' perceptions of natural ventilation adequacy rather than demonstrated inadequacy of mechanical ventilation.

A similar pattern was observed for thermal comfort. Although overall satisfaction with indoor temperature was relatively high, local overheating or overcooling received the lowest evaluation among the IEQ items and showed considerable variability among occupants. Meanwhile, measured temperatures remained within a relatively stable range across classrooms, although differences between classroom means were observed. The room-averaged measurements did not resolve within-classroom thermal conditions and therefore could not establish the physical causes of the localized discomfort reported in Q1.3.

Facade orientation represents a potential source of spatial variation in classroom IEQ because it can influence solar heat gains, daylight availability, glare, and opportunities for natural ventilation. Windows remained closed during monitoring, and air-conditioning systems were in operation. Artificial lighting was also in use, while curtains remained closed for much of the observed teaching time to facilitate projection, reducing daylight availability. The simulation further showed that adequate average illuminance could coexist with a maximum UGR above the adopted glare criterion.

The three classrooms showed different parameter-specific profiles: R319 had the highest mean CO_2, PM_{10}, operational sound level, and temperature; R505 had the highest mean HCHO; and R742 had the highest mean TVOC. These observations do not establish an orientation effect. Each classroom was monitored on a different date, and occupancy and outdoor conditions were not available for adjustment, so room, session, and orientation effects cannot be separated. Orientation remains a plausible influence requiring repeated, comparable observations under different operating conditions.

These findings highlight the importance of integrating occupant feedback with objective environmental monitoring in POE studies. Previous research has suggested that evaluations based solely on physical thresholds may not fully capture the complexity of occupant experiences [16, 17]. The questionnaire survey and physical measurements were conducted during corresponding classroom sessions. However, the available respondent-level data did not permit classroom-specific linkage or direct statistical assessment of subjective–objective associations. The room-averaged measurements therefore provided operational context for interpreting the aggregated occupant evaluations.

The IEQ profile observed in Block R can be situated within the broader evidence from hot-humid Asian buildings. In Hong Kong university classrooms, thermal conditions have been identified as a major contributor to overall IEQ, while earlier investigations of air-conditioned teaching rooms also demonstrated substantial contributions from acoustic, air-quality, and visual conditions [27, 28]. The comparatively lower evaluations of ventilation effectiveness and reported localized overheating or overcooling in the present study are therefore consistent with the continuing importance of thermal and air-movement conditions in subtropical educational environments. A related pattern has been reported in Singaporean Green Mark-certified buildings, where temperature, air movement, personal control, and sound privacy remained among the principal sources of occupant dissatisfaction despite generally favorable overall environmental evaluations [29]. In hot-humid Guangzhou, classroom studies have similarly identified summer thermal stress and cooling requirements as persistent operational concerns [30]. In Block R, however, pollutant concentrations and CO_2 remained within the applicable local reference values during the monitored periods, while the principal variation occurred in dimension-specific occupant evaluations and inter-room environmental conditions. The Macau case therefore extends the regional evidence by showing that such variability can remain relevant in a Platinum-certified university building even when monitored environmental indicators satisfy applicable reference values.

4.3. Implications for Green Building Operation and Management

The findings of this study highlight that achieving a high-level green building certification should not be considered the endpoint of indoor environmental performance management. Although the investigated BEAM Plus Platinum building demonstrated favorable overall IEQ performance, variations among different environmental dimensions indicate that indoor environmental conditions require continuous evaluation after occupancy. Therefore, POE should be regarded as an ongoing feedback mechanism rather than a one-time assessment following certification. Integrating occupant feedback with operational monitoring can provide facility managers with evidence for identifying recurrent IEQ deficiencies and informing subsequent operational adjustments during building use.

For subtropical educational buildings, adaptive operation strategies may provide an effective approach for balancing indoor environmental quality and energy efficiency. Conventional HVAC operation based on fixed schedules may not fully respond to the pronounced temporal variation in classroom occupancy. Demand-controlled ventilation (DCV), which adjusts ventilation rates in response to occupancy and indoor environmental conditions, has been reported to improve ventilation efficiency while reducing unnecessary energy consumption

compared with conventional constant air volume strategies [23, 49, 50]. For teaching spaces such as those in Block R, scheduled class periods could be incorporated into HVAC and ventilation operating schedules to establish anticipated occupancy periods, while real-time occupancy and CO_2 measurements could be used to adjust outdoor-air provision according to actual classroom conditions. Distributed CO_2, temperature, and relative-humidity sensors could be integrated with the BMS and ventilation/HVAC control system, allowing ventilation provision to increase during occupied teaching periods and to decrease when classrooms are confirmed to be unoccupied. This combination of timetable-based scheduling and sensor-based feedback would enable ventilation operation to respond to both anticipated and actual classroom use rather than relying solely on fixed daily schedules. HVAC temperature set-points and operating periods should also be periodically reviewed using seasonal indoor measurements and occupant feedback, as climate- and occupancy-responsive control strategies can improve the balance between thermal comfort and energy use [51].

Continuous monitoring should also account for spatial differences among classrooms. In the present study, R319 recorded the highest mean CO_2 concentration (863.67 ppm) and sound level (54.43 dB(A)) among the three monitored classrooms. Although these values do not in themselves indicate non-compliance, their comparatively higher levels warrant targeted follow-up monitoring under comparable teaching and occupancy conditions. For classrooms in which such differences persist, facility managers could examine outdoor-air delivery, airflow distribution, HVAC operating schedules, localized thermal conditions, and sources of operational noise before implementing targeted adjustments. Continuous or repeated measurements could subsequently be used to evaluate whether these interventions improve the corresponding IEQ conditions. Integrating distributed environmental sensing with BMS records, teaching schedules, and periodic occupant feedback would therefore support classroom-specific diagnosis, operational adjustment, and subsequent performance verification [52, 53]. Evidence from a green building in Hong Kong similarly showed that occupant-facing IEQ information can facilitate occupant engagement and support operational improvement [53].

4.4. Limitations and Future Research

Several limitations should be acknowledged. First, the field measurements and questionnaire survey were conducted on three days between March 28 and April 11, 2025, during the spring transition period. These short-term observations may not fully represent seasonal variations in IEQ, particularly under Macau's hot and humid summer conditions or cooler winter conditions. The findings should therefore be interpreted within the investigated spring classroom conditions and do not establish thermal comfort, ventilation adequacy, or HVAC performance during the summer cooling season. Second, the participants were primarily university students aged 18-27 years; therefore, potential differences among faculty members, administrative staff, and other occupant groups were not examined. In addition, this study focused on a single BEAM Plus Platinum-certified educational building, which limits the generalizability of the findings to other buildings and climatic contexts. Room-level averages may obscure localized and short-term variations in environmental conditions, and the analysis therefore could not determine whether differences in individual perceptions were associated with conditions at specific locations or times. The thermal monitoring dataset did not include indoor relative humidity, air velocity, or mean radiant temperature; dry-bulb temperature measurements alone therefore do not constitute a comprehensive physical assessment of thermal comfort using indices such as PMV or PPD. The thermal-comfort evaluation relied primarily on subjective survey data obtained from occupants' questionnaire responses, with measured dry-bulb temperatures serving as contextual references to the monitored conditions.

The response matrix did not include respondent-level year of study, major, age, gender, weekly exposure hours, or classroom-session identifiers. These omissions prevent demographic subgroup analysis, an exposure-duration distribution, and room-specific linkage of questionnaire scores to measured conditions. The descriptive room comparisons are additionally confounded by monitoring date. The monitoring records do not demonstrate the 8-h averaging or intermittent sampling requirements of the local IAQ guideline. Although the instruments were factory-calibrated and the reported limits of detection (LODs) and resolutions for both HCHO and TVOC were 0.001 mg/m³ (Table **1**), small differences among the readings, particularly TVOC concentrations near the detection limit, should be interpreted cautiously.

The pronounced ceiling effect in Q6, characterized by heavy left-skewness and a high concentration of positive responses (94.4% in categories 4 and 5), limits the outcome variance available for OLS modeling, which may partly explain the discrepancy between the OLS and ordinal logistic regression results. The maximum score accounted for 38.9% of responses. Although Spearman's ρ and Kendall's τ-b yielded consistent positive bivariate associations, the statistical significance of acoustic comfort differed between the OLS and ordinal logistic models. The dimension-specific regression results should therefore be interpreted in light of the restricted distribution of overall satisfaction scores.

The correlation and regression analyses identified statistical associations between IEQ dimensions and occupant satisfaction but could not establish causal relationships or capture temporal interactions among environmental conditions, occupant behavior, and building operation. Future studies should therefore extend environmental monitoring and occupant surveys across seasons and certified buildings with different HVAC systems, occupancy patterns, and architectural configurations, while adopting response scales with greater discrimination at the upper end. Spatial and temporal correspondence between occupant responses and environmental measurements should also be improved through synchronized response records and continuous multi-point monitoring. Integration of these data with operational records may further support the development of POE from a one-time assessment toward a continuous feedback process for adaptive building operation [54, 55].

5. Conclusions

This study evaluated the operational indoor environmental quality (IEQ) in three classrooms of a BEAM Plus Platinum-certified university building in subtropical Macau, based on occupant surveys, short-term in-situ environmental measurements, and lighting simulation. By providing evidence from Macau, this study extends the regional POE evidence base for hot-humid Asian educational buildings and highlights the value of assessing dimension-specific post-occupancy IEQ alongside certification-level performance.

Overall satisfaction was favorable, with 94.4% of respondents selecting satisfied or very satisfied. Occupant evaluations nevertheless varied across the five IEQ dimensions: visual environmental quality received the highest evaluation, whereas ventilation effectiveness was comparatively lower, with less favorable responses concerning natural ventilation adequacy and localized overheating or overcooling. The findings therefore show that favorable certification and overall satisfaction can coexist with dimension-specific variation in post-occupancy IEQ evaluations. All five perceived IEQ dimensions showed significant positive correlations with overall satisfaction in the rank-based analyses, but no individual dimension reached statistical significance after adjustment in the OLS model. Acoustic comfort was significant in the ordinal logistic sensitivity analysis, indicating that its adjusted association was sensitive to model specification.

The physical measurements provided additional context for these occupant evaluations. Recorded HCHO, TVOC, PM_{10}, and CO_2 concentrations were below the adopted local reference concentrations in the three monitored classroom sessions, but the available sampling information does not establish 8-h guideline compliance. Room-average temperatures ranged from 23.99 to 25.23 °C across the three classrooms, while occupants reported variability in localized thermal experiences. The lower natural-ventilation rating concerns a condition not directly tested by monitoring with windows closed. The artificial-lighting model showed adequate average illuminance but a maximum UGR exceeding the adopted glare criterion. These results illustrate the complementary information provided by occupant evaluations, short-term measurements, and lighting simulation, while leaving respondent-specific measurement associations unresolved.

For building operation, the results support continued IEQ monitoring after certification, with particular attention to classroom occupancy, ventilation operation, localized thermal conditions, and spatial differences among teaching spaces. Teaching schedules, occupancy information, environmental sensing, and periodic occupant feedback may provide a practical basis for targeted operational adjustment and subsequent performance verification. Future studies should extend the monitoring period across seasons, include broader occupant groups and building types, and improve the spatial and temporal correspondence between occupant responses and environmental measurements.

Conflict of Interest

No potential conflicts of interest are reported by the authors.

Funding

The study was financially supported by the Science and Technology Development Fund of Macau (FDCT, No. 0007/2023/RIB1) and Macau University of Science and Technology (FRG-24-088-FIE).

Acknowledgements

The authors would like to express their sincere gratitude to all participants who contributed to this study. Special thanks are extended to Ms. Miranda Lam, Ms. Happy Lam, and Mr. Frankie Choi from the General Affairs Office, as well as Mr. Chuck Chung Yin Albert and Mr. Kar Kit Chu from the China Green Building and Energy Saving (Macau) Association, and Mr. Tim Lo from BEAM Society Limited, for their valuable support, insights, and contributions to this research. The authors also thank Haomin Gu, Liying Mo, Haopeng Huang, and Yu Qiu for their assistance with questionnaire distribution.

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