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Indoor Environmental Quality, Building-Related Symptoms and Perceived Productivity in Green-Certified and Conventional Tropical Offices

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Abstract

Although green building certification is widely promoted as a pathway to improved indoor environmental quality (IEQ) and occupant well-being, evidence of its effectiveness under tropical operating conditions remains limited and inconsistent. This study presents an integrated post-occupancy evaluation (POE) of indoor air quality (IAQ), occupant health, and workplace productivity across four office buildings in Colombo, Sri Lanka: two green-certified buildings (Buildings B and D) and two conventional buildings (Buildings A and C); the four buildings were broadly comparable in use but differed in age, size, occupancy, and HVAC configuration (Section 2.2). This exploratory, short-term (two-day per building) post-occupancy evaluation is intended as case-based screening evidence rather than a definitive assessment of green-building certification. Multi-parameter environmental monitoring (CO2, PM2.5/PM10, TVOC, formaldehyde, temperature, relative humidity, illuminance, and noise) was combined with a survey of 100 occupants covering thermal, air-quality, lighting, and acoustic comfort, self-reported building-related symptoms (SBS), and perceived productivity. Certified buildings recorded lower CO2 concentrations than conventional buildings (707 vs 841 ppm; p.adj < .001; d = -1.10), but higher relative humidity (66.0% vs 53.4%; d = 1.57) and noise (59.7 vs 56.6 dB(A); d = 0.47). The SBS symptom index was higher in certified buildings (2.51 vs 2.00; p.adj < .001), while comfort was lower (3.67 vs 4.18; p.adj = .003). Perceived productivity correlated most strongly with comfort (r = 0.62), IAQ satisfaction (r = 0.55), and acoustic comfort (r = 0.51). These findings reveal a case-specific divergence in which favorable ventilation performance coexisted with less favorable thermal, acoustic, and occupant-health outcomes. Certification alone therefore did not correspond to better occupant experience. The results support climate-responsive refinement of tropical green-building certification through consideration of humidity and acoustic performance, pending confirmation in seasonally sampled building cohorts.

Keywords: Indoor air quality; Indoor environmental quality; post-occupancy evaluation; Sick Building Syndrome; Tropical office buildings; Workplace productivity

1. Introduction

People in modern urban societies spend more than 90% of their time indoors, with office buildings representing one of the dominant microenvironments for daily exposure to indoor environmental conditions (Kim et al., 2022). This simple fact has pushed Indoor Environmental Quality (IEQ) to the

center of building science, because the air people breathe, the temperature they sit in, and the noise around them are no longer background conditions but active determinants of health and cognitive performance. Indoor air quality (IAQ) in particular, shaped by particulate matter (PM2.5/PM10), carbon dioxide (CO2), volatile organic compounds, temperature, and relative humidity, has been repeatedly linked to respiratory and cardiovascular strain as well as measurable declines in decision-making and concentration (Satish et al., 2012; Allen et al., 2015; Seppanen et al., 2006). The implications extend well beyond occupant comfort, affecting organizational productivity, public health, building operational performance, and economic sustainability. Even modest improvements in ventilation effectiveness and pollutant control can yield productivity gains that substantially exceed the associated operational costs, highlighting IEQ as both a public health priority and a strategic economic investment (Lee et al., 2019; Seppanen et al., 2006) Where conditions are poorly managed, occupants report a recognizable cluster of self-reported building-related symptoms, commonly termed Sick Building Syndrome (SBS) in the earlier literature: headaches, eye and throat irritation, fatigue, and dizziness that track closely with time spent in a particular building (Redlich et al., 1997; Europe, 2010)

Green building certification schemes such as LEED, BREEAM, and the WELL Building Standard were introduced partly to address this problem, embedding IEQ criteria into design and operational requirements on the assumption that certified buildings would consistently outperform conventional ones. However, empirical evidence supporting this assumption remains inconsistent across different climatic regions and building operational contexts. A growing line of post-occupancy evaluation (POE) research describes a “performance gap” between what certified buildings are designed to achieve and what they actually deliver once occupied, with several studies finding little or no meaningful difference in measured IAQ, occupant satisfaction, or health outcomes between certified and non-certified stock(Altomonte et al., 2020; Esfandiari et al., 2021; Khoshbakht et al., 2022) The reported performance gap has been linked in the literature to interactions among building operation, maintenance practices, occupant behavior, climatic conditions, and discrepancies between design intent and actual operational performance. That climatic mismatch matters a great deal in the tropics. High temperature, persistent humidity, and strong solar loads make mechanical air-conditioning close to unavoidable in tropical offices, and heavy reliance on air-conditioning can itself undermine ventilation adequacy if not carefully managed (Azhar et al., 2011; Hui et al., 2008) These challenges are expected to intensify under ongoing climate change, as increasing cooling demands may further complicate the balance between energy efficiency, adequate ventilation, and occupant health in tropical office buildings. Because the certification frameworks in wide use were not built around these conditions, it is genuinely unclear whether they protect IAQ and occupant wellbeing as effectively in Colombo as they might in London or Toronto. Sri Lanka provides an important representative case for rapidly urbanizing tropical regions, where green-certified commercial buildings are increasing despite limited empirical evidence demonstrating their operational performance under hot-humid climatic conditions. The literature also has some structural blind spots that make this question harder to answer than it should be. Much of the tropical evidence base still leans on temperate or hot-arid studies rather than humid, monsoon-influenced climates (Hui et al., 2008; Azhar et al., 2011). Furthermore, most existing investigations evaluate only selected dimensions of IEQ rather than considering the complex interactions among objective environmental conditions, occupant perception, health outcomes, and workplace productivity. Research also tends to split along methodological lines: studies either measure IAQ parameters directly or survey occupant perceptions, rarely both within the same analytical framework, which makes it difficult to say how measured conditions actually translate

into what people experience (Satish et al., 2012; Seppanen et al., 2006; Tham et al., 2015). Workplace productivity has also received comparatively limited attention within real-world building performance research because objective measurement is inherently difficult, leading most studies to rely on self-reported indicators that are rarely integrated with simultaneous environmental monitoring.

To address these scientific gaps, this study proposes an integrated building performance evaluation framework based on post-occupancy evaluation that simultaneously combines objective environmental monitoring, occupant perception, health outcomes, and workplace productivity within a unified analytical framework. To our knowledge, this is one of the few studies conducted in a tropical South Asian context that integrates calibrated multi-parameter environmental sensing, psychometrically validated occupant surveys, and statistical triangulation to evaluate the complete pathway linking IEQ, occupant health, and workplace productivity. Unlike previous studies that primarily rely on whole-building averages, this study benchmarks individual environmental parameters against WHO and ASHRAE criteria at the zone level,(Ashrae, 2022; WHO, 2021) enabling the identification of localized IEQ deficiencies that may otherwise remain undetected. Beyond comparative building assessment, the study introduces an integrated analytical framework that conceptualizes the pathway linking objectively measured IAQ, perceived IEQ, SBS symptoms, and workplace productivity, while considering the moderating influence of green building certification. This framework provides a more comprehensive understanding of building performance than conventional indicator-based assessments. Most importantly, the evidence that emerges directly complicates the standard narrative around certification: buildings in this sample that recorded more favorable ventilation performance also recorded higher humidity, more noise, more SBS symptoms, and lower overall comfort than their non-certified counterparts. This case-specific divergence in which more favorable ventilation performance coexisted with less favorable thermal, acoustic, and occupant-health outcomes indicates that, within this sample, alignment with existing certification systems did not correspond to consistently better operational building performance under tropical conditions. Accordingly, this study aims to (i) compare IAQ and workplace productivity between green-certified and conventional office buildings; (ii) quantify the relationships between objectively measured environmental conditions and occupant perceptions; (iii) examine the relationship between SBS and perceived productivity as part of the broader occupant-experience pathway; (iv) benchmark operational performance against WHO and ASHRAE guidelines; and (v) generate exploratory evidence to inform climate-responsive refinement of green building certification systems for hot-humid tropical environments. The findings contribute to the broader international discourse on evidence-based building performance evaluation by illustrating how climate-specific operational factors can influence the real-world effectiveness of green building certification systems beyond their original design assumptions.(Ashrae, 2022; WHO, 2021)

2. Materials and Methods

2.1 Study design and analytical framework

This study used a cross-sectional, comparative post-occupancy evaluation (POE) design combining objective environmental monitoring with a structured occupant survey across four commercial office buildings in Colombo, Sri Lanka. The analytical framework integrated four components: (i) multi-parameter environmental monitoring; (ii) a validated occupant questionnaire assessing perceived IEQ, Sick Building Syndrome (SBS) symptoms, and perceived workplace productivity; (iii) benchmarking of measured parameters against WHO and ASHRAE reference values; and (iv) joint-display triangulation of measured and perceived performance (Fig. 1). Because certification status was not experimentally assigned, the study was designed to compare operational performance between certification categories rather than to establish a causal effect of certification. This study is exploratory and short-term in design, evaluating four buildings that were each monitored for two weekdays; building-level findings are treated as the primary evidence, and pooled certification-category comparisons are reported as exploratory only.

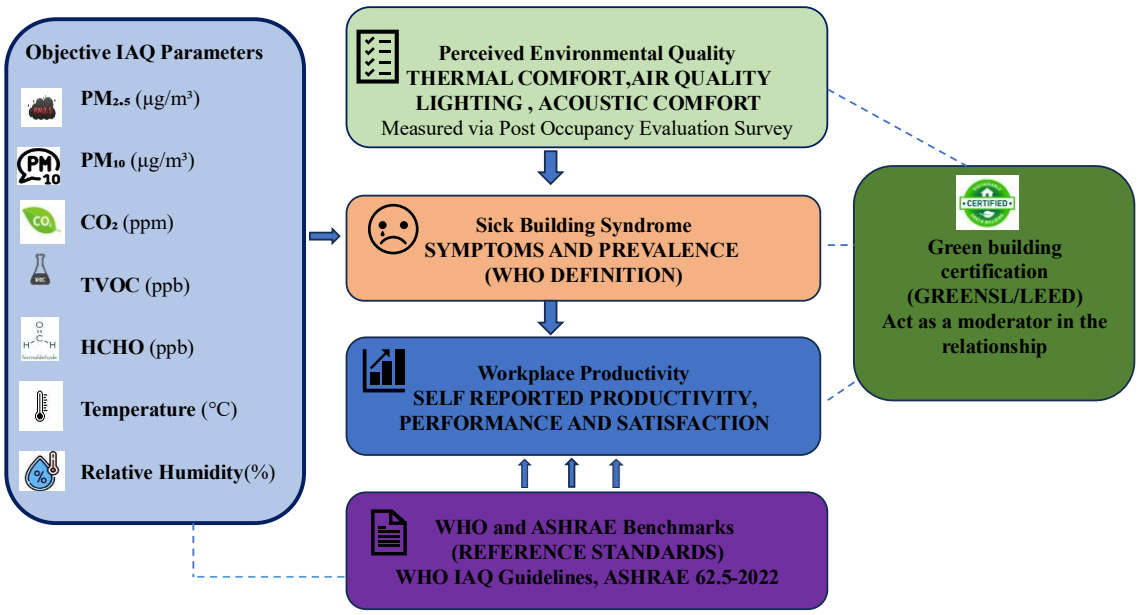


Fig. 1. Conceptual framework linking objectively measured indoor environmental quality, occupant-perceived IEQ, Sick Building Syndrome symptoms, and perceived workplace productivity, with certification category as a moderating factor.

2.2 Study setting and building selection

The study was conducted in the Colombo metropolitan region, Sri Lanka, which experiences a hot-humid tropical monsoon climate characterized by high ambient temperatures, elevated relative humidity, intense

solar radiation, and seasonally variable rainfall (Altomonte et al., 2019) These climatic conditions impose substantial demands on building ventilation, cooling systems, and indoor environmental control, making Colombo an appropriate setting for evaluating the operational performance of green-certified office buildings.

Four occupied multi-story commercial office buildings **(Figure 2)** were purposively selected, comprising two green-certified buildings (Building B and Building D) and two conventional non-certified buildings (Building A and Building C). To preserve organizational confidentiality, all buildings were anonymized throughout the study and are referred to consistently as Building A, Building B, Building C, and Building D.



Fig. 2. Exterior views of the four study buildings in the Colombo metropolitan region: Building A, non-certified; Building B, green-certified (GreenSL Silver); Building C, non-certified; Building D, green-certified (LEED Gold). Building identities were anonymized to preserve organizational confidentiality.

Buildings were selected using predefined eligibility criteria to maximize comparability between certification categories. Selection considered primary office function, gross floor area, occupancy density, HVAC operation, working schedules, and accessibility for environmental monitoring and occupant surveys. Although efforts were made to minimize major functional differences, natural variations remained in building age, certification system, ventilation configuration, occupancy characteristics, and operational management, reflecting the diversity of commercial office buildings in tropical urban

environments. These differences (Table 1) are treated explicitly as potential confounding factors rather than as evidence that the buildings were matched.

Because certification status was not experimentally assigned, the study was designed to compare operational building performance rather than establish causal effects of green-building certification. Accordingly, observed differences between certified and conventional buildings were interpreted as associations within the selected building sample. Detailed physical and operational characteristics of the study buildings are summarized in Table 1.

Table 1. Physical and operational characteristics of the four study buildings.

Characteristic	*Building A*	*Building B*	*Building C*	*Building D*
Certification category	Non-certified	Green-certified	Non-certified	Green-certified
Certification system/level	–	GreenSL Silver	–	LEED Gold
Building age (years)	35	16	37	18
Gross floor area (m2)	~46,450	~13,000	~30,000	~25,000
Occupied floors	22	8	7	14
Office function	Corporate HQ	Engineering/admin offices	Commercial offices	Corporate HQ
Typical occupancy	~1,000	~1000	~800	~1,200
Occupancy density (persons/100 m2)	2-3	7-8	2-3	4-5
HVAC system	Central chilled-water HVAC	High-efficiency central HVAC	Central HVAC	High-efficiency central chilled-water HVAC
Ventilation type	Mechanical, outdoor air supply	Mechanical, fresh air supply	Mechanical, outdoor air supply	Mechanical, fresh air supply
Operable windows	No	Limited	Partial	No
Working hours	08:30–17:00	08:00–17:00	09:00–18:00	08:30–17:30
Monitoring period	2 days	2 days	2 days	2 days

Building identities were anonymized (Buildings A–D) to maintain confidentiality. Information was compiled from building management records, on-site observations, and publicly available certification information. Monitoring followed a standardized protocol across all buildings during normal working hours. This building order (A, B, C, D) is used consistently in every table and figure in this manuscript.

2.3 Environmental monitoring design

Environmental monitoring was designed to characterize the spatial and temporal variability of IEQ under normal occupied operating conditions. Representative monitoring locations were selected within each building to encompass the principal functional spaces, including open-plan offices, enclosed private offices, meeting rooms, reception areas, and perimeter workspaces. Selection of monitoring locations was based on occupancy patterns, ventilation characteristics, and anticipated environmental variability to ensure that the monitored locations represented the diversity of indoor conditions experienced during routine building operation.

Within large open-plan office floors, monitoring locations were established using a systematic 4 × 3 spatial grid **(Figure 3)** to minimize spatial sampling bias and provide representative coverage of core, perimeter, and high-occupancy areas in accordance with recommended field practices for IEQ assessment

(Ashrae, 2022) In enclosed offices and smaller functional spaces, a centrally located monitoring position representative of the occupied zone was selected.

To capture potential vertical variation in indoor environmental conditions associated with ventilation effectiveness, solar heat gain, and outdoor pollutant infiltration, measurements were distributed across representative lower, intermediate, and upper occupied floors wherever building access permitted. During each monitoring campaign, a concurrent outdoor **(Figure 4)** reference station was established adjacent to each building in a shaded, well-ventilated location away from direct traffic emissions, HVAC exhaust outlets, and other localized pollution sources, intended to characterize background environmental conditions and support calculation of indoor-to-outdoor (I/O) concentration ratios where appropriate. Outdoor station values were not included in the summary dataset available for this revision, and I/O ratios are therefore not reported (Section 5, Limitations).

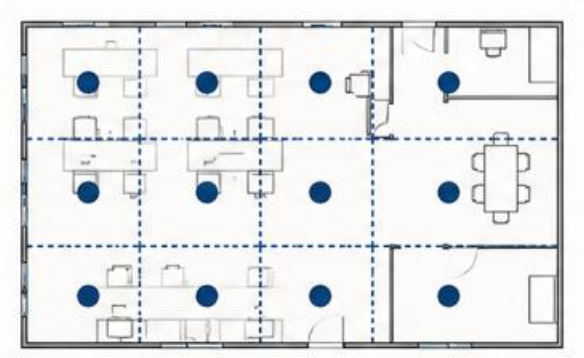


Fig. 3. Schematic representation of the systematic 4 × 3 spatial grid used to establish 12 monitoring locations, providing representative coverage of core, perimeter, and high-occupancy areas while minimizing spatial sampling bias.



Fig. 4. Schematic representation of indoor air-quality monitoring locations across upper, middle, and ground occupied floors, together with a concurrent outdoor reference station.

2.4 Environmental measurements and monitoring protocol

Eight environmental parameters were monitored to characterize indoor environmental quality, including carbon dioxide (CO2), particulate matter (PM2.5 and PM10), total volatile organic compounds (TVOC), formaldehyde (HCHO), air temperature, relative humidity, horizontal illuminance, and A-weighted sound pressure level. Instrument specifications, sensing principles, measurement accuracy, and reference standards used for benchmarking are summarized in Table 2. Prior to each monitoring campaign, all instruments were inspected, time-synchronized, allowed to stabilize according to manufacturer recommendations, and functionally checked to ensure measurement consistency (ISO 16000-1, 2004).

Table 2. Instrumentation, measured parameters, and reference standards used for environmental monitoring.

Parameter	*Instrument*	*Sensing principle*	*Range*	*Accuracy*	*Guideline/benchmark*
CO2	8-in-1 multi-parameter IAQ monitor	Non-dispersive infrared (NDIR)	400–5000 ppm	±15 ppm	ASHRAE 62.1-2022; WHO AQG (2021)
PM2.5	8-in-1 multi-parameter IAQ monitor	Laser particle counter	0–999 µg/m3	±10%	WHO AQG (2021)
PM10	8-in-1 multi-parameter IAQ monitor	Laser particle counter	0–999 µg/m3	±10%	WHO AQG (2021)
TVOC	8-in-1 multi-parameter IAQ monitor	Photoionization detector (PID)	0–9.99 mg/m3	±5%	EN 16516; WELL v2
Formaldehyde	8-in-1 multi-parameter IAQ monitor	Electrochemical sensor	0–1.999 mg/m3	±5%	WHO AQG (2021)
Air temperature	8-in-1 multi-parameter IAQ monitor	Digital thermistor	−10 to 50 °C	±1 °C	ASHRAE 55-2023
Relative humidity	8-in-1 multi-parameter IAQ monitor	Capacitive humidity sensor	0–100% RH	±2% RH	ASHRAE 55-2023
Illuminance	CEM DT-1308 lux meter	Silicon photodiode	0–400,000 lx	±3%	SLS 1264:2019; IES Handbook
Sound pressure level	PCE-MSL 1 sound level meter	Precision condenser microphone	30–130 dB(A)	±1.5 dB	ISO 9241-6; BS 8233:2014

Sensors were mounted at approximately 1.1 m above floor level to represent the seated breathing zone of a typical office occupant (ISO 7726, 1998), positioned at least 0.8 m from walls and away from HVAC diffusers, windows, and direct heat sources to avoid localized measurement bias. Monitoring was conducted over two consecutive weekdays per building during standard occupancy hours (08:00–17:30); weekends and public holidays were excluded to ensure that measurements reflected typical occupied operating conditions. Each monitoring day was divided into a morning session (09:00–12:00) and an afternoon session (13:30–16:00) to capture diurnal variation associated with changes in occupancy, solar gain, and HVAC loading, following a protocol adapted from (Dam-Krogh, Clausen, et al., 2024). Data were logged automatically at five-minute intervals throughout each session, and building-level observations (occupancy, HVAC operating mode, window status, and prevailing weather) were recorded concurrently to support interpretation of the environmental dataset.

2.4.1 Data quality assurance

To ensure the reliability and consistency of the environmental dataset, all monitoring instruments were inspected, time-synchronized, and allowed to stabilize according to the manufacturer's recommendations before deployment. Instrument functionality was verified prior to each monitoring campaign, and measurements were conducted following a standardized monitoring protocol to maintain consistency across all buildings and sampling locations.

Following data collection, the environmental dataset was subjected to a systematic quality assurance procedure. Raw measurements were screened for duplicate records, missing values, sensor malfunctions, timestamp inconsistencies, and implausible observations outside the operational measurement range of each instrument. Measurements recorded during instrument installation, relocation, or removal were excluded from subsequent analyses. Environmental observations were cross-checked against contemporaneous field records documenting occupancy level, HVAC operating status, window operation, weather conditions, and any unusual indoor activities that could influence measured parameters. Where instrument malfunction or abnormal operating conditions were identified, the affected observations were excluded from statistical analysis. Only validated measurements obtained under representative occupied building conditions were retained for subsequent data processing and statistical evaluation.

2.5 Occupant survey

Occupant perceptions were assessed using a structured questionnaire adapted from the internationally validated Building Use Studies (BUS) methodology and the Center for the Built Environment (CBE) Occupant Survey, supplemented with the World Health Organization (WHO) guidelines for reporting Sick Building Syndrome (SBS) symptoms. The questionnaire has been widely applied in office building post-occupancy evaluations and tropical indoor environmental quality studies (Esfandiari et al., 2021; Khoshbakht et al., 2022) supporting construct validity and cross-study comparability.

The questionnaire comprised six domains: respondent characteristics, satisfaction with building facilities, perceived thermal comfort, indoor air quality, lighting and acoustic comfort, SBS symptoms, and perceived workplace productivity. Responses were recorded using a five-point Likert scale (1 = very poor to 5 = excellent).

Only full-time employees who had occupied the building continuously for at least three months were eligible to participate; temporary staff, interns, contractors, and visitors were excluded. The questionnaire was administered electronically using a secure web-based survey platform (Google Forms) after participants received an information sheet describing the study objectives, voluntary participation, confidentiality, and informed consent procedures.

A target sample of approximately 30 occupants per building was established based on an a priori statistical power analysis (Cohen, 1988), resulting in 100 valid responses across the four buildings. Prior to implementation, the questionnaire was pilot-tested with 15 office workers outside the study sample to improve clarity and confirm completion time. Internal consistency was evaluated using Cronbach's alpha, with domain-specific reliability ranging from 0.66 to 0.87 and excellent overall reliability ($\alpha = 0.952$) (Table 3).

Table 3. Reliability analysis of the post-occupancy evaluation (POE) questionnaire.

Domain	*Representative items*	*Cronbach's α*
Thermal comfort	Temperature, relative humidity, air movement	0.664
Indoor air quality	Freshness, odor, perceived stuffiness	0.812
Lighting comfort	Illuminance, glare, daylight availability	0.660
Acoustic comfort	Noise level, speech privacy, distraction	0.750
Sick Building Syndrome symptoms	Headache, eye irritation, fatigue, dryness, respiratory discomfort	0.871
Workplace productivity	Concentration, work efficiency, overall productivity	0.859

2.6 Self-reported building-related symptoms (SBS) assessment

Self-reported building-related symptoms (SBS), historically labelled "Sick Building Syndrome," were assessed using the WHO framework for building-related symptoms (WHO, 1983) the more defensible term "self-reported building-related symptoms" is used throughout in preference to "Sick Building Syndrome," which is retained only as the abbreviation SBS for continuity with the tables and figures. Five symptom domains were evaluated: headache, eye irritation, fatigue, respiratory discomfort, and skin irritation. Participants rated the frequency of each symptom using a five-point Likert scale and indicated whether symptoms improved after leaving the building, consistent with the WHO definition of building-related symptoms. Responses were aggregated by averaging the individual symptom scores to generate a composite SBS index for each participant, with higher scores indicating greater symptom burden. The composite SBS index was subsequently used for comparative analysis between certified and conventional office buildings and for examining its relationship with measured indoor environmental quality and perceived workplace productivity.

2.7 Workplace productivity assessment

As objective organizational productivity records were unavailable because of confidentiality restrictions, workplace productivity was assessed using validated self-reported perceived productivity measures, a widely accepted approach in IEQ and post-occupancy evaluation (POE) research for evaluating occupants' functional performance under real workplace conditions (P et al., 2000; Allen et al., 2015). The productivity domain, adapted from the BUS methodology and the CBE Occupant Survey, evaluated perceived concentration, work efficiency, mental alertness, task completion, fatigue, and overall work

performance using a five-point Likert scale. Responses were averaged to generate a composite perceived productivity score for each participant, with higher scores indicating better self-reported workplace performance. The composite score was subsequently used to examine its associations with measured indoor environmental quality, occupant perceptions, and Sick Building Syndrome symptoms.

2.8 Integrated post-occupancy evaluation framework

Objective environmental measurements and subjective occupant responses were integrated within a unified POE framework to provide a comprehensive assessment of building performance. Environmental parameters were benchmarked against relevant international standards, while questionnaire responses were independently scored to derive domain-specific indices for occupant satisfaction, SBS, and perceived workplace productivity. The two datasets were subsequently integrated using a joint-display triangulation approach (Creswell & Inoue, 2025) linking building-level environmental measurements with corresponding occupant perception scores. This integrated framework enabled comparison of measured and perceived indoor environmental quality, facilitating the assessment of convergence or divergence between objective building performance and occupants' experiences across certified and conventional office buildings.

2.9 Statistical analysis

Statistical analyses were performed using R software (Version 4.6.0; R Foundation for Statistical Computing, Vienna, Austria). Data processing, descriptive statistics, and reliability analyses were conducted using the psych package, while inferential statistical analyses were performed using the rstatix package and base R statistical functions. Descriptive statistics, including mean, standard deviation, median, minimum, and maximum values, were calculated for all environmental and questionnaire variables. Internal consistency of questionnaire domains was evaluated using Cronbach's alpha.

Prior to inferential analysis, datasets were screened for completeness, implausible values, and outliers. Variable distributions were assessed using the Shapiro–Wilk test. Comparisons between certified and conventional office buildings were performed using independent-samples t-tests for normally distributed variables and the Mann–Whitney U (Wilcoxon rank-sum) test when normality assumptions were not satisfied ((Jr. et al., 2019) Effect sizes were reported as Cohen's d for parametric comparisons, together with 95% confidence intervals, to facilitate interpretation of the practical significance of observed differences Because multiple comparisons were performed across the environmental parameters and survey domains, Holm-Bonferroni correction was applied within each comparison family, and adjusted p-values (denoted p.adj) are reported as the principal inferential values throughout the Results; unadjusted p-values are reported only where they materially aid interpretation.

Associations among objectively measured IEQ parameters, occupant satisfaction, SBS symptoms, and perceived workplace productivity were examined using Pearson correlation analysis. Measured environmental parameters were additionally compared with relevant international guideline values to evaluate building performance relative to established indoor environmental quality standards, subject to the averaging-period caveats set out in Table 2. Statistical significance was accepted at $p < 0.05$ for all analysis.

3. Results

3.1 Dataset composition and participant characteristics

Following data-quality screening, the environmental dataset comprised 320 validated five-minute-interval observations, 80 per building, collected over two consecutive weekdays per building across morning and afternoon monitoring sessions. The occupant survey yielded 100 valid questionnaires: Building A (n = 30), Building B (n = 21), Building C (n = 21), and Building D (n = 28). For exploratory certification-category comparisons (Section 3.3), Buildings B and D (green-certified) were pooled (environmental n = 160; survey n = 49) and Buildings A and C (non-certified) were pooled (environmental n = 160; survey n = 51). Building-level results (Section 3.2) are reported as the primary, case-based comparison given the small number of buildings sampled, with pooled certification-category results reported as exploratory secondary comparisons throughout this section.

3.2 Building-level environmental performance

Table 4 reports building-level descriptive statistics for the eight monitored environmental parameters, presented in a consistent building order (A, B, C, D) throughout. Mean CO2 concentration was lowest in Building D and Building B and highest in Building C and Building A; relative humidity followed the reverse ranking, with the highest building means recorded in Building D and Building B (Fig. 5). Air temperature, noise, and the particulate and VOC parameters showed a more mixed pattern across buildings (Table 4). All four buildings remained below the ASHRAE 62.1 CO2 reference value and the WHO 24-hour PM2.5/PM10 reference values on a whole-building average basis; screening-level exceedance at the observation level is reported separately in Section 3.4, together with the averaging-period caveats summarized in Table 2.

Table 4. Building-level distributions of measured indoor environmental quality parameters (building mean; n = 80 observations per building).

Parameter	*Building A*	*Building B*	*Building C*	*Building D*
Temperature (°C)	25.4	27.0	25.7	26.3
Relative humidity (%)	56.4	63.5	50.3	68.4
CO2 (ppm)	829	735	853	680
PM2.5 (µg/m3)	5.9	3.9	1.6	6.8
PM10 (µg/m3)	6.0	4.5	2.1	6.4
TVOC (µg/m3)	76	110	42	73
Formaldehyde (mg/m3)	0.0080	0.0101	0.0041	0.0159
Illuminance (lux, work plane)	332	257	292	379

Noise (dB(A))	57.0	57.8	56.2	61.6

Note. Certification category: Building A, non-certified; Building B, green-certified; Building C, non-certified; Building D, green-certified. Illuminance was measured at the work plane at each monitoring point.

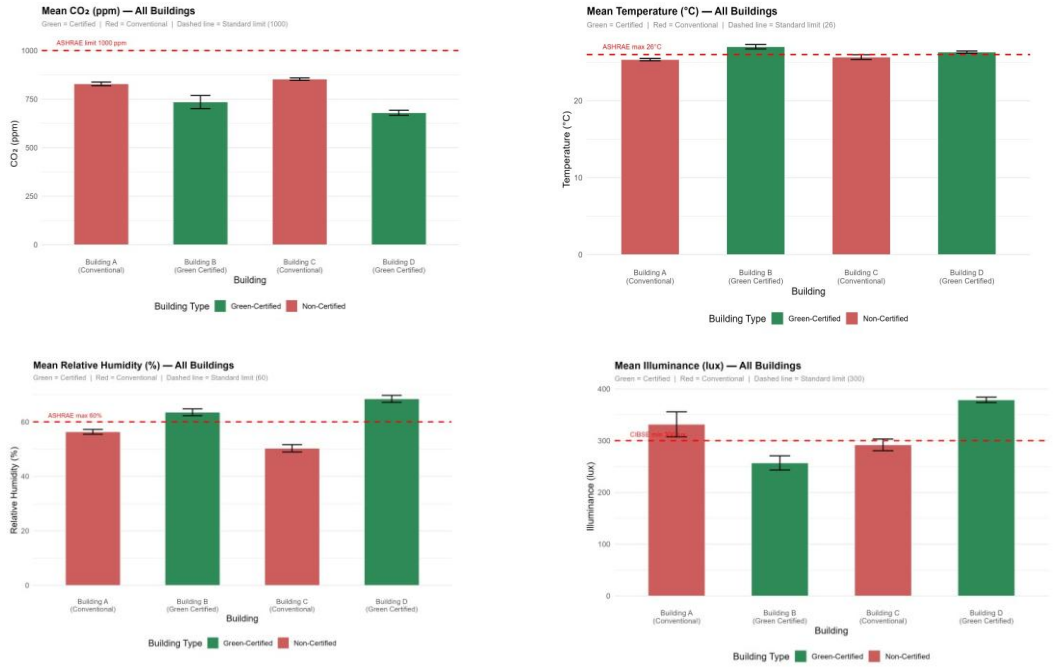


Fig. 5. Building-level environmental parameters (building means, n = 80 observations per building), building order A–D held constant across panels.

3.3 Exploratory comparison by certification category

Table 5 compares environmental parameters pooled by certification category (Fig. 6). CO2 concentration was lower in certified buildings than in non-certified buildings (707 vs 841 ppm; adjusted mean difference −134 ppm, 95% CI −172 to −96; p.adj < .001; d = −1.10, 95% CI −1.43 to −0.77). Relative humidity, temperature, and noise were each higher in certified buildings: relative humidity (66.0% vs 53.4%; difference 12.6 percentage points, 95% CI 10.1 to 15.1; p.adj < .001; d = 1.57, 95% CI 1.21 to 1.92), temperature (26.7 °C vs 25.6 °C; difference 1.1 °C, 95% CI 0.7 to 1.5; p.adj < .001; d = 0.78, 95% CI 0.46 to 1.10), and noise (59.7 vs 56.6 dB(A); difference 3.1 dB(A), 95% CI 1.1 to 5.2; p.adj = .028; d = 0.47, 95% CI 0.16 to 0.79). PM2.5, PM10, TVOC, formaldehyde, and illuminance did not differ between categories after adjustment (Table 5). This category-level comparison pools observations within each category and is reported as an exploratory, observation-level screening comparison; because repeated five-minute readings within the same building and session are not independent replicates, it should be read alongside the building-level pattern in Section 3.2 rather than as a substitute for it (see Limitations, Section 5).

Table 5. Exploratory comparison of environmental parameters between certification categories (independent-samples t-test, n = 160 observations per category).

Parameter	*Certified*	*Conventional*	*Adjusted difference (95% CI)*	*Effect size d (95% CI)*	*Adjusted p*
CO2 (ppm)	707	841	−134 (−172, −96)	−1.10 (−1.43, −0.77)	<.001
Temperature (°C)	26.7	25.6	1.1 (0.7, 1.5)	0.78 (0.46, 1.10)	<.001
Relative humidity (%)	66.0	53.4	12.6 (10.1, 15.1)	1.57 (1.21, 1.92)	<.001
Noise (dB(A))	59.7	56.6	3.1 (1.1, 5.2)	0.47 (0.16, 0.79)	.028
PM2.5 (µg/m3)	5.4	3.8	1.6 (0.3, 2.9)	0.40 (0.08, 0.71)	.122
PM10 (µg/m3)	5.5	4.1	1.4 (0.2, 2.6)	0.36 (0.05, 0.67)	.226
TVOC (µg/m3)	92	59	33 (3, 63)	0.35 (0.04, 0.66)	.266
Formaldehyde (mg/m3)	0.013	0.006	0.007 (0.000, 0.014)	0.23 (−0.08, 0.54)	> .05
Illuminance (lux)	318	312	6 (−26, 38)	0.06 (−0.25, 0.37)	> .05

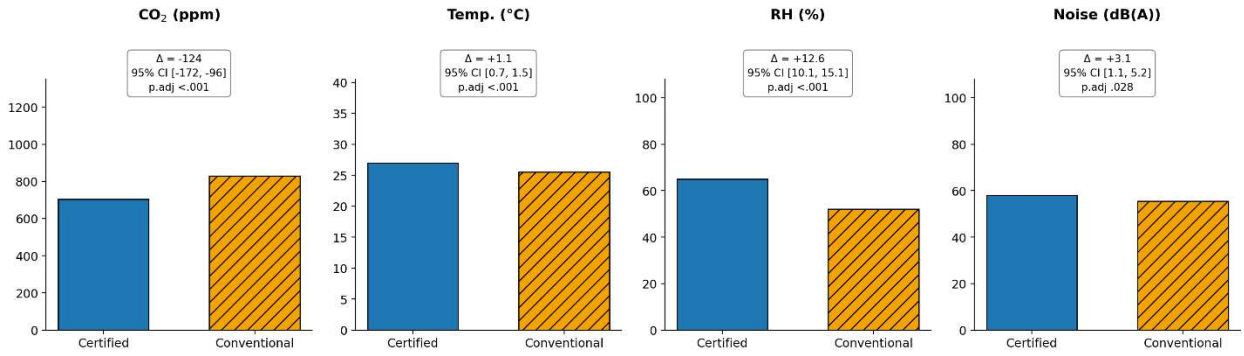


Fig. 6. Exploratory comparison of environmental parameters between certification categories. Bars show category means (n = 160 observations per category); annotations show the adjusted mean difference, its 95% CI, and the adjusted p-value

3.4 Screening-level comparison with IEQ reference values

Table 6 reports the percentage of five-minute observations exceeding the reference values defined in Table 2, by building (A, B, C, D). Noise showed the highest exceedance rates of any parameter, from 55.0% (Building C) to 92.5% (Building D); the two certified buildings recorded the two highest noise-

exceedance rates in the sample. Relative-humidity exceedance followed a similar pattern, occurring more often in Building B (62.5%) and Building D (77.5%) than in Building A (17.5%) and Building C (10.0%). CO2 exceedance of the 1000-ppm reference value was rare overall (0% in three of the four buildings) but occurred in 17.5% of readings at Building B; this case-specific pattern is examined further in Section 3.5. Because the five-minute logging interval does not match the 24-hour averaging period specified for the WHO PM2.5/PM10 reference values, and comparable duration mismatches apply to several other parameters (Table 2), these results are reported as screening-level comparisons with numerical reference values rather than as compliance determinations.

Table 6. Percentage of five-minute observations exceeding the reference values in Table 2, by building.

Building	*CO2*	*PM2.5*	*Temp.*	*RH*	*HCHO*	*Noise*	*Illuminance (low)*
Building A	0.0	0.0	10.0	17.5	0.0	77.5	55.0
Building B	17.5	0.0	57.5	62.5	0.0	67.5	65.0
Building C	0.0	0.0	42.5	10.0	0.0	55.0	45.0
Building D	0.0	17.5	52.5	77.5	2.5	92.5	0.0

Values are percentages of 80 observations per building. Temperature, relative humidity, and noise exceedance are reported against the screening-level indicative thresholds in Table 2, not against a formal compliance limit.

3.5 Spatial and temporal variability of IEQ

Comparison of morning (09:00–12:00) and afternoon (13:30–16:00) monitoring sessions showed a decline in relative humidity from morning to afternoon in the two certified buildings (Fig. 7): Building B (66.3% morning vs 60.8% afternoon) and Building D (72.0% morning vs 64.9% afternoon). CO2 and noise did not show a consistent morning-to-afternoon pattern across buildings, varying instead by building.

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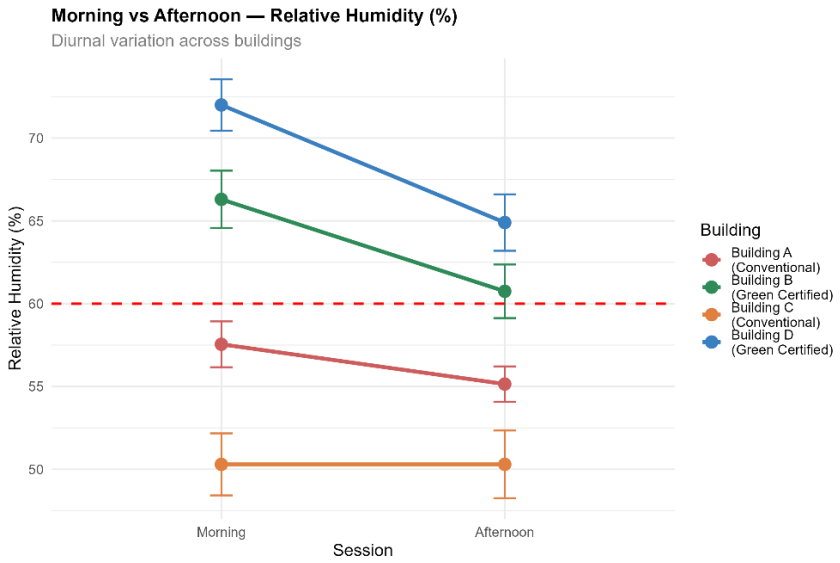


Fig. 7. Morning versus afternoon relative humidity, certified buildings.

At the zone level, two case-specific patterns departed from their respective building-wide means. A printer/reprographics zone at Building B recorded a mean CO2 concentration of 1120 ppm against a building-wide mean of 735 ppm. A zone beneath a ceiling-mounted air-conditioning unit at Building D recorded a mean TVOC concentration of 372 µg/m3 against a building-wide mean of 73 µg/m3, and a closed-office zone at Building D recorded a mean PM2.5 concentration of 16.2 µg/m3, above the WHO 24-hour reference value despite an unremarkable building-wide average. These zone-level values indicate that whole-building averages can conceal case-specific divergence in particular occupied micro-environments; a complete zone-by-parameter summary, including coefficient of variation and the proportion of zones above each reference value, requires the full zone-level export and is not available for the present analysis.

3.6 Occupant-perceived IEQ and overall comfort

Domain-specific internal consistency for the occupant questionnaire ranged from acceptable to excellent (Cronbach's α = 0.66–0.87; overall α = 0.95; Table 3). At the domain level (Fig. 8), mean satisfaction scores were higher among occupants of non-certified buildings than certified buildings across all five comfort domains: indoor air quality (3.97 vs 3.76; p.adj = .75), ventilation (3.71 vs 3.30; p.adj = .05), thermal comfort (3.71 vs 3.34; p.adj = .08), lighting (3.75 vs 3.47; p.adj = .26), and acoustic comfort (3.89 vs 3.71; p.adj = 1.00). None of these five domain-level differences remained below the adjusted significance threshold. Overall comfort, the composite index, was lower in certified buildings (3.67 vs 4.18; mean difference −0.51, 95% CI −0.83 to −0.19; Mann-Whitney U = 776, p.adj = .003; d = −0.64, 95% CI −1.04 to −0.24).

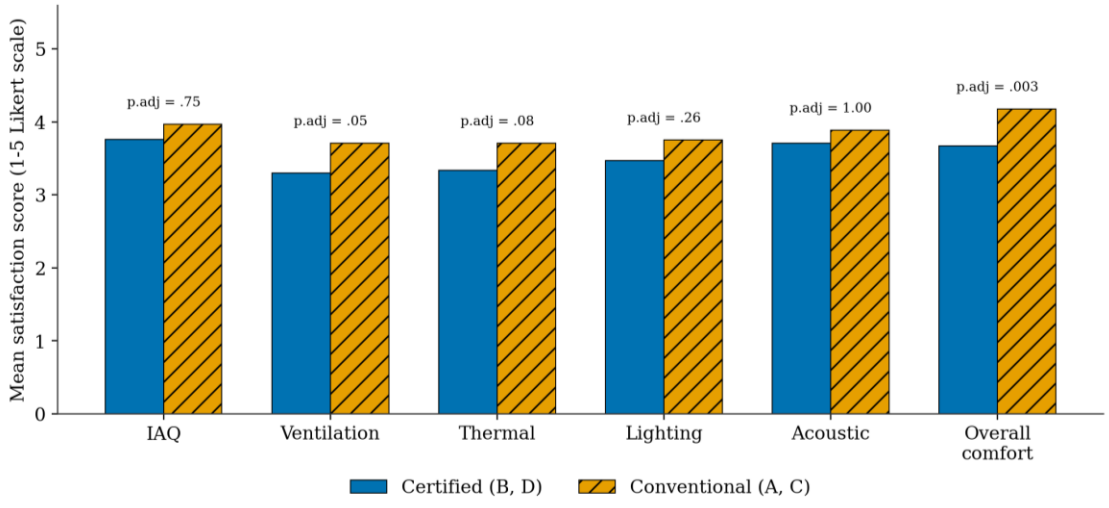


Fig. 8. Occupant survey domain scores by certification category. Error bars are omitted because per-respondent standard deviations were not available; adjusted p-values (reported in Section 3.6 above) are annotated above each domain.

3.7 Building-related symptom burden

The composite SBS index was higher in certified buildings than in non-certified buildings (2.51 vs 2.00; mean difference 0.51, 95% CI 0.24 to 0.78; Wilcoxon p.adj < .001; d = 0.75, 95% CI 0.35 to 1.16). Building-level symptom-prevalence rates (percentage of occupants reporting a symptom score ≥ 3) are reported in Table 7 and Fig. 9, ordered A, B, C, D. Headache was the most frequently reported symptom overall, ranging from 20.0% (Building A) to 75.0% (Building B). Building A recorded the lowest prevalence in every symptom category, including breathing discomfort (3.3%, compared with 20.0–52.6% in the other three buildings).

Table 7. Sick Building Syndrome symptom prevalence (% of occupants reporting a symptom score ≥ 3), by building.

Building	*Headaches*	*Eye irritation*	*Fatigue / drowsiness*	*Breathing discomfort*	*Dry throat / coughing*
Building A	20.0	16.7	26.7	3.3	6.7
Building B	75.0	55.0	52.6	52.6	47.6
Building C	65.0	38.1	26.3	20.0	33.3
Building D	61.5	39.3	71.4	28.6	39.3

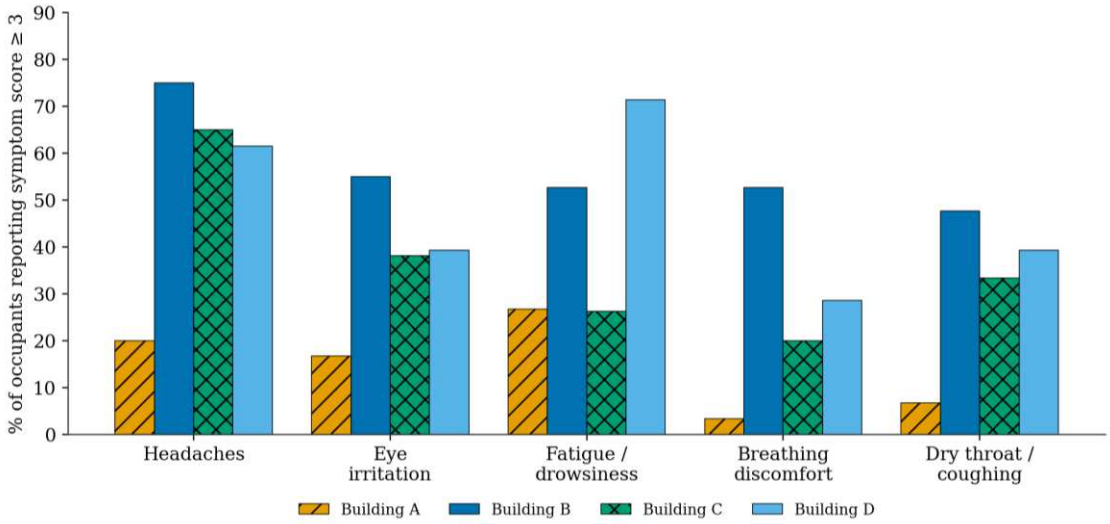


Fig. 9. Sick Building Syndrome symptom prevalence by building.

3.8 Perceived productivity and its determinants

Self-reported perceived productivity was lower, at the unadjusted level, in certified buildings than in non-certified buildings (3.76 vs 4.05; mean difference −0.29, 95% CI −0.53 to −0.05; p = .017; p.adj = .13). Table 8 and Fig. 10 report the correlation of perceived productivity with each occupant-reported IEQ domain and with the SBS index. Productivity was associated most strongly with overall comfort (r = 0.62), IAQ satisfaction (r = 0.55), and acoustic comfort (r = 0.51), followed by lighting (r = 0.41), ventilation (r = 0.37), and thermal comfort (r = 0.28), and was negatively associated with the SBS index (r = −0.27).

Table 8. Pearson correlations (r) between perceived productivity and occupant-reported IEQ domains (n = 100).

Predictor	*r with perceived productivity*
Overall comfort	0.62
IAQ satisfaction	0.55
Acoustic comfort	0.51
Lighting	0.41
Ventilation	0.37
Thermal comfort	0.28
SBS index	−0.27

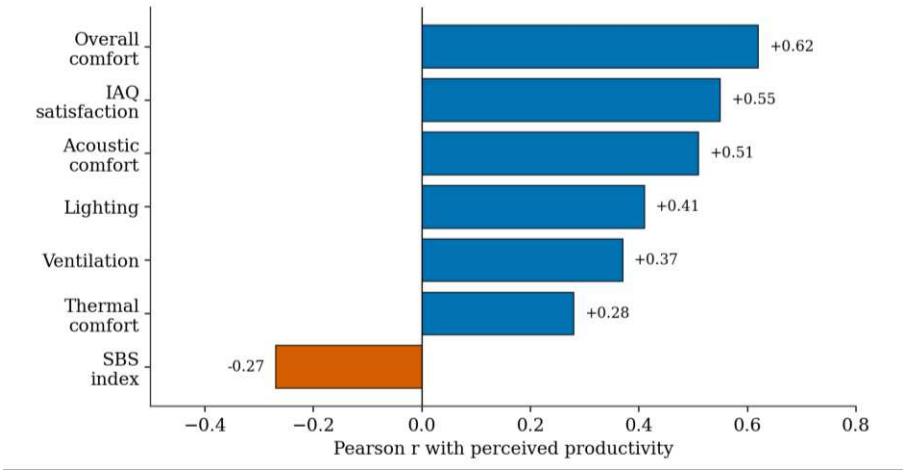


Fig. 10. Correlation of perceived productivity with occupant-reported IEQ domains and the SBS index (n = 100).

3.9 Associations among environmental and occupant outcomes

Among the objectively measured parameters, CO2 was negatively associated with relative humidity (r = −0.57) and temperature (r = −0.39); PM2.5 and PM10 were strongly associated (r = 0.96), and TVOC and formaldehyde were moderately associated (r = 0.49) **(Figure 11).** On the occupant-perceived side, overall comfort was most strongly associated with IAQ satisfaction (r = 0.59) and ventilation satisfaction (r = 0.58), and negatively associated with the SBS index (r = −0.39), indicating that the domains most closely associated with perceived comfort were not identical to those most closely associated with symptom burden.

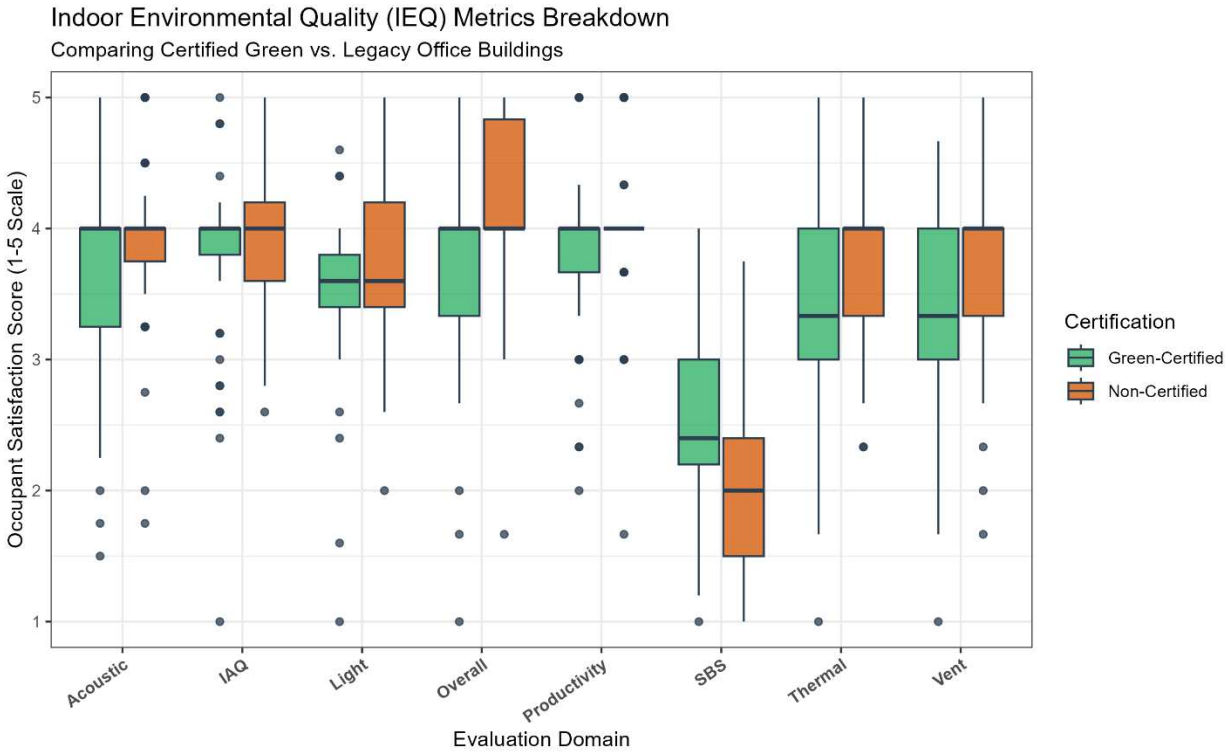


Fig. 11. Comparison of occupant satisfaction across IEQ domains between green-certified and non-certified office buildings. Boxes represent the interquartile range, with median values shown by the central lines

3.10 Joint-display triangulation of measured and perceived performance

Table 9 integrates building-level environmental measurements with corresponding occupant-perception scores (Section 2.8) for all four buildings, in a consistent order (A, B, C, D), to allow direct comparison of measured and perceived performance. Both certified buildings (Building B, Building D) recorded comparatively favorable CO2 means alongside comparatively favorable IAQ-satisfaction scores. For relative humidity, acoustic performance, SBS burden, and overall comfort, the two certified buildings instead diverged from their CO2 performance: both recorded less favorable relative humidity and acoustic conditions, higher SBS indices (2.55 and 2.47), and, for Building B, the lowest overall-comfort score of the four buildings (3.30). Building A, despite the second-highest building CO2 mean in the sample (829 ppm), recorded the lowest SBS index (1.81) and the highest overall-comfort score (4.22) of the four buildings. Within this four-building sample, favorable CO2 performance did not consistently correspond to favorable outcomes on the other measured and perceived IEQ domains; this pattern is interpreted further in the Discussion.

Table 9. Joint-display matrix triangulating building-level environmental measurements with occupant-perceived outcomes.

Building	*Ventilation (CO2)*	*Hygrothermal (RH/Temp.)*	*Acoustic performance*	*SBS burden*	*Overall comfort*	*Perceived productivity*	*Convergence classification*
A	↓ less favorable (829 ppm)	↑ favorable (56.4%, 25.4 °C)	Moderate	Low (1.81)	High (4.22)	Category-level only*	Objective(ventilation)–subjective divergence
B	↑ favorable (735 ppm)	↓ unfavorable (63.5%, 27.0 °C)	Unfavorable	High (2.55)	Low (3.30)	Category-level only*	Strong divergence
C	↓ less favorable (853 ppm)	↑ favorable (50.3%, 25.7 °C)	Moderate	Moderate (2.23)	High (4.13)	Category-level only*	Partial divergence
D	↑ favorable (680 ppm)	↓ unfavorable (68.4%, 26.3 °C)	Unfavorable	High (2.47)	Moderate (4.04)	Category-level only*	Partial divergence

4. Discussion

4.1 Principal findings and the certification-performance divergence

This study integrated objective environmental monitoring with occupant-reported comfort, building-related symptoms, and perceived workplace productivity to evaluate the operational performance of four tropical office buildings. The findings revealed a complex and multidimensional pattern rather than a uniform advantage associated with green-building certification. The two certified buildings recorded lower mean CO2 concentrations than the two conventional buildings, indicating more favorable ventilation-related conditions within the selected cases. However, this advantage did not extend consistently to the broader IEQ profile: the certified buildings were warmer, substantially more humid, and noisier, while their occupants reported a greater Sick Building Syndrome (SBS) symptom burden and lower overall comfort. Perceived productivity was associated most strongly with overall comfort, perceived indoor air quality, and acoustic comfort rather than with any single objectively measured environmental parameter. Building-level triangulation further showed that the conventional Building A recorded the lowest SBS burden and highest overall comfort despite having a comparatively high mean CO2 concentration. Taken together, these findings demonstrate a case-specific certification-performance divergence, in which favorable performance in one certification-relevant domain did not translate into consistently better environmental or occupant outcomes across the complete performance profile.

This divergence is consistent with the wider building-performance-gap literature, which distinguishes intended or modelled performance from the conditions ultimately delivered during routine occupation (Altomonte et al., 2019b; Dam-Krogh, Clausen, et al., 2024; Esfandiari et al., 2021; Hong et al., 2023) Certification indicates that a building has satisfied a defined set of design, construction, management, or performance requirements, but it cannot independently guarantee that all IEQ dimensions will remain optimized after changes in occupancy, tenant fit-out, equipment density, operating schedules, control settings, and maintenance practices. Studies of certified offices have consequently reported mixed outcomes. Some have found improved environmental conditions, health, and satisfaction in certified or green-refurbished buildings (Lee et al., 2020); Ildiri et al., 2022)), whereas others have reported limited, inconsistent, or domain-specific differences between certified and conventional offices(Esfandiari et al.,

2021; Khoshbakht et al., 2022) These apparently contradictory findings indicate that certification outcomes are strongly conditioned by climate, building typology, certification system, office layout, facility management, and the environmental domains included in each assessment. Lee et al. (2020), for example, reported more favorable IEQ in green-certified and green-refurbished Singaporean offices using measurements and surveys across 14 buildings and a generalized mixed-modelling approach, illustrating both the potential benefits of certification and the importance of adequately accounting for building-level clustering.

The present findings should therefore not be interpreted as evidence that certification is ineffective or that conventional buildings are generally more effective. Certification status was not experimentally assigned, and only two buildings represented each category. Rather, the results demonstrate that certification is an incomplete proxy for operational building quality and should be evaluated alongside measured post-occupancy outcomes. This interpretation is supported by evidence showing that energy or certification performance does not necessarily correspond linearly with every IEQ outcome and that the relationships among environmental performance, energy consumption, occupant satisfaction, and certification level are context dependent (Ildiri et al., 2022; Lee et al., 2020; Zhang & Srinivasan, 2020) Large certification databases may show overall performance advantages, but individual buildings can still exhibit substantial domain-specific weaknesses and diminishing improvements at higher certification levels.

4.2 Ventilation-related gains versus latent-moisture control in hot-humid offices

The lower CO2 concentrations recorded in the certified buildings represent the clearest favorable objective finding associated with certification category in this sample. Mean CO2 concentrations were approximately 707 ppm in certified buildings compared with 841 ppm in conventional buildings, and the difference was large in standardized magnitude. Because indoor CO2 in occupied offices is primarily generated by human metabolism, lower concentrations under otherwise comparable conditions are generally consistent with greater dilution, lower effective occupancy, or more effective outdoor-air distribution (Persily, 2015:Ashrae, 2022) However, CO2 is not a direct measurement of ventilation rate, and the observed difference cannot be attributed exclusively to certification or outdoor-air provision. Occupant density, room volume, infiltration, HVAC scheduling, workstation use, and temporal variation in occupancy may also have influenced the measured concentrations.

The most important accompanying finding was that the lower CO2 levels in the certified buildings coexisted with substantially higher relative humidity. Mean RH was approximately 66.0% in certified buildings compared with 53.4% in conventional buildings, representing the largest standardized difference among the measured environmental parameters. In a hot-humid climate, this pattern is physically plausible because increasing the outdoor-air fraction introduces not only sensible heat but also a substantial latent-moisture load. Unless cooling coils, reheat systems, dedicated outdoor-air systems, or control sequences are capable of removing this moisture under both full- and part-load conditions, increased ventilation may reduce CO2 while allowing indoor humidity to rise. Comparable concerns have been reported in tropical and subtropical office research, where ventilation, cooling demand, humidity management, and energy efficiency must be optimized concurrently rather than independently (Azhar et al., 2011; Shukla et al., 2025; Tsay et al., 2022; Zhang & Srinivasan, 2020)).

Nevertheless, the present study did not directly measure outdoor-air flow rates, air-change rates, supply-air humidity ratio, coil leaving-air temperature, condensate removal, envelope infiltration, or latent

cooling capacity. The observed inverse association between CO2 and RH should therefore be interpreted as consistent with a possible ventilation-latent-load imbalance, not as proof of such a mechanism. It is also possible that differences in HVAC schedules, outdoor weather, occupancy patterns, facade exposure, and internal moisture generation contributed to the category-level pattern. Follow-up investigations should measure indoor and outdoor humidity ratio, supply- and return-air conditions, fresh-air fractions, dew-point temperature, equipment run time, and condensate production to distinguish among these mechanisms.

The high RH recorded in the certified buildings has potential implications for comfort, material durability, perceived stuffiness, and occupant health. Persistent dampness and moisture accumulation can create conditions conducive to microbial growth and have been associated with respiratory, ocular, nasal, throat, dermal, and fatigue-related symptoms (WHO.,2021; Mendell et al., 2024). In a recent large Sri Lankan study, (Sun et al., 2024) found that indicators of indoor dampness were associated with multiple symptom categories among university residents, emphasizing the relevance of moisture management in the national climatic context. However, the present study did not assess surface dampness, condensation, mould, fungal spores, bacteria, or microbial volatile organic compounds. Elevated RH should therefore be treated as an operational risk indicator rather than evidence that microbial contamination occurred.

The morning-to-afternoon decline in RH observed in the certified buildings (Section 3.5) provides an additional operational insight. The reduction may indicate that dehumidification improved as the air-conditioning systems approached steady-state operation. Early working-hour conditions may therefore represent a period of incomplete latent-load control, especially where cooling systems start shortly before or after occupant arrival. Such a pattern could also reflect changes in outdoor humidity, internal sensible loads, occupancy, or system control sequences. Future studies should use continuous time-series monitoring before, during, and after occupied hours to evaluate HVAC start-up, morning moisture accumulation, part-load operation, and afternoon stabilization.

These findings support the use of tropical HVAC strategies that decouple ventilation from sensible cooling. Dedicated outdoor-air systems, independent temperature-and-humidity control, controlled low-dew-point supply air, energy recovery, improved envelope airtightness, and demand-controlled ventilation may help maintain ventilation while avoiding excessive moisture loads (Zhang & Srinivasan, 2020). Temperature-and-humidity-independent air-conditioning systems have shown potential advantages in humid climate zones, although their suitability must be assessed in relation to climate, control complexity, energy use, and life-cycle cost.

4.3 Multidomain performance divergence across thermal, acoustic, and occupant-health outcomes

The ventilation-related advantage observed in the certified buildings did not extend to thermal or acoustic conditions. Certified buildings were approximately 1.1 °C warmer on average and recorded higher A-weighted sound pressure levels than the conventional buildings. These differences coincided with greater SBS burden and lower overall comfort, producing a multidomain divergence between lower CO2 and less favorable outcomes elsewhere.

The thermal findings require careful interpretation because air temperature and RH alone do not constitute a complete thermal-comfort assessment. Thermal comfort also depends on mean radiant temperature, air

velocity, metabolic rate, clothing insulation, personal adaptation, control opportunities, workstation position, solar exposure, and individual characteristics (Ashrae, 2022b; Schweiker et al., 2025). Recent field research has shown that traditional thermal-comfort models can be affected by uncertainties in clothing, activity, context, and perceived humidity and that thermal conditions associated with maximum productivity may vary among occupant groups(Indraganti & Humphreys, 2021; Takasu et al., 2017). The measured temperatures should therefore be discussed as indicators of hygrothermal conditions, not as evidence that a building formally complied or failed to comply with ASHRAE Standard 55.

The combination of warmer air and higher RH may nevertheless have increased perceived thermal load. Under humid conditions, reduced evaporative heat loss can make a given temperature feel warmer, particularly where air movement is limited. The slightly lower thermal-satisfaction scores in the certified buildings were directionally consistent with this interpretation, although the individual thermal-comfort difference did not remain statistically significant after correction for multiple comparisons. The finding should therefore be described as a coherent objective-subjective pattern rather than a demonstrated causal effect. Recent evidence indicates that moderately elevated office temperatures can impair work performance over time, particularly for skilled tasks, but the magnitude and threshold vary according to exposure duration, task, acclimatization, and personal characteristics (Lan et al., 2011; Seppanen et al., 2006; Takasu et al., 2017)

The acoustic findings were also important. Sound levels were above the selected office reference value during a substantial proportion of monitoring intervals in all four buildings, with the highest levels recorded in certified Building D. This indicates that acoustic conditions may represent a broader weakness of the sampled office stock rather than an issue exclusive to certification. Open-plan layouts, collaborative spaces, high occupant densities, exposed services, reflective materials, office equipment, external traffic, and HVAC operation can all contribute to elevated sound levels and reduced speech privacy. However, the present study did not measure reverberation time, distraction distance, speech transmission, frequency spectra, or individual noise sources, and it cannot determine which architectural or operational factor caused the observed levels.

Acoustic quality is increasingly recognized as a central determinant of workplace experience(Kang et al., 2023) found that the acoustic environment exerted a strong influence on productivity in university open-plan research offices, while large international survey evidence indicates that noise and perceived air quality are particularly important for occupants spending longer periods in office environments (Khoshbakht et al., 2022) Experimental soundscape research similarly shows that audiovisual office context influences perceived productivity, environmental preference, and work-related quality .These findings support the present correlation between acoustic comfort and perceived productivity and indicate that acoustic quality should not be treated as a secondary design issue.

The co-occurrence of warmer, more humid, and noisier conditions in the certified cases illustrates why operational IEQ should be assessed as a multidimensional system. Improving ventilation without simultaneously addressing latent cooling and acoustic performance may produce a building that performs favorably against a single indicator but less favorably from the occupant's integrated perspective. Similar inconsistencies have been observed in certified buildings where improvements in cleanliness, image, or selected air-quality indicators did not necessarily yield better noise, visual, thermal, SBS, or productivity outcomes (Esfandiari et al., 2021; Ildiri et al., 2022; Khoshbakht et al., 2022) The present results therefore

strengthen the argument that certification and POE systems should assess the balance among environmental domains rather than reward isolated performance achievements.

4.4 Spatial heterogeneity and the limitations of whole-building averages

A major contribution of this study was the identification of localized conditions that were obscured by whole-building averages. Building B had a favorable mean CO2 concentration of 735 ppm, yet the printer/reprographics zone recorded a mean of approximately 1120 ppm. Building D had a relatively low building-wide TVOC mean, but the monitoring point beneath an air-conditioning unit recorded a value approximately five times greater. A closed office in Building D also recorded a short-term PM2.5 value above the numerical WHO 24-hour reference value despite an unremarkable building mean. These observations demonstrate that acceptable building-wide averages can coexist with potentially important spatial hotspots.

Office environments are inherently heterogeneous. Occupant density, space volume, door position, supply-air distribution, return-air pathways, enclosure, equipment, furnishings, cleaning activity, printing, and proximity to outdoor sources can vary markedly among zones. Single-point measurements or overall means may consequently underestimate conditions in densely occupied meeting rooms, enclosed offices, photocopying areas, reception zones, storage areas, and perimeter workstations. Multizone POE studies have similarly reported substantial variation by room type, ventilation strategy, floor, and workstation position (Geng et al., 2022; Parkinson et al., 2019; Tang et al., 2022; Dam-Krogh et al., 2024; Shukla et al., 2025). A recent intervention-oriented study of 15 Portuguese open-plan offices found that opportunities for improvement differed by parameter and workplace, reinforcing the importance of targeted rather than exclusively building-level diagnosis (Almeida et al., 2023a)

The localized results should nevertheless be interpreted as screening observations requiring confirmation. The study design cannot attribute the high CO2 concentration to the printer equipment itself, nor can it determine whether the TVOC value originated from the nearby air-conditioning unit, recirculated pollutants, interior materials, cleaning products, or another source. Similarly, a short-term PM2.5 concentration above the numerical value of a 24-hour guideline does not, by itself, establish an exceedance of that guideline, because the sampling and averaging periods differ. The most scientifically appropriate interpretation is that these locations represented potential hotspots warranting source-specific and longer-duration investigation.

The operational implications are direct. Reprographics areas should be assessed for enclosure, local exhaust, outdoor-air distribution, equipment maintenance, and separation from continuously occupied workstations. Enclosed offices and meeting rooms require verification of air-change effectiveness under actual occupancy. Suspected VOC zones should be investigated through repeated monitoring, activity logs, source inventories, and, where feasible, compound-specific sampling. PM hotspots should be evaluated alongside outdoor concentrations and indoor-to-outdoor ratios to distinguish infiltration from indoor generation.

These findings support risk-based spatial monitoring as part of POE and certification renewal. Monitoring should prioritize high-density, enclosed, source-dominated, and complaint-prone areas rather than relying

solely on conveniently located central sensors. Continuous or repeated low-cost monitoring may support this approach, but sensors should be quality-assured and periodically compared with reference instruments because multiparameter devices may have cross-sensitivity, drift, and compound-dependent response characteristics (Geng et al., 2022; Mujan et al., 2021)

4.5 Multidomain occupant experience and building-related symptom burden

Occupants in the conventional buildings reported directionally higher satisfaction across all individual comfort domains, including perceived air quality, ventilation, thermal conditions, lighting, and acoustics. None of these individual differences remained significant after Holm-Bonferroni adjustment, but the consistency of direction across domains is noteworthy. At the composite level, overall comfort was significantly lower in the certified buildings, while SBS burden was significantly higher. This pattern suggests that the difference in occupant experience was distributed across several modest environmental disadvantages rather than concentrated in one dominant domain.

Occupants experience buildings holistically rather than as a set of independent physical parameters. Thermal, acoustic, visual, spatial, and air-quality conditions interact with cleanliness, furniture, personal control, workload, expectations, health, and organizational culture to shape overall satisfaction (Al horr et al., 2016; Dam-Krogh, Clausen, et al., 2024; Frontczak et al., 2012; Liu et al., 2026; Schweiker et al., 2025) Structural-equation evidence indicates that workplace comfort and productivity emerge from combined satisfaction with multiple environmental and spatial domains and that different user groups may weight these domains differently (Liu et al., 2026) Longitudinal living-laboratory research similarly identifies cross-domain relationships among thermal, visual, spatial, comfort, and productivity variables (Fissore et al., 2023)

The stronger statistical distinction observed for overall comfort may partly reflect the greater reliability obtained when multiple related items are aggregated. However, this should not be interpreted as evidence that all five separate comfort domains were independently affected by certification. Composite outcomes can reduce random measurement error, but they may also combine overlapping constructs. The manuscript therefore emphasizes the integrated pattern while acknowledging that individual domain estimates remained uncertain after multiplicity adjustment.

The SBS result requires similarly cautious interpretation. The composite symptom index was higher in the certified buildings, and Building A reported the lowest prevalence across the symptom categories. However, SBS symptoms such as headache, eye irritation, fatigue, respiratory discomfort, and throat dryness are non-specific. They may be affected by environmental conditions, workload, stress, screen exposure, sleep, allergies, infections, commuting, hydration, and pre-existing health status (*WHO Global Air Quality Guidelines: Particulate Matter (PM2.5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*, 2021); (Azuma et al., 2018; Redlich et al., 1997). They should therefore be described as self-reported building-related symptoms rather than clinically diagnosed disease.

A rigorous operational definition should incorporate both symptom frequency and improvement after leaving the workplace. Merely recording a Likert score at or above a selected threshold does not establish building-relatedness unless temporal improvement away from the building is also present. Recent SBS studies have used standardized symptom instruments together with measured CO2, PM, formaldehyde,

temperature, humidity, and ventilation characteristics and have emphasized multivariable associations rather than single-cause explanations (Malakan et al., 2025; Rahman et al., 2025)

Several pathways may plausibly contribute to the greater symptom burden in the certified cases. Higher RH and warmer conditions could increase stuffiness, thermal discomfort, fatigue, and perceived air-quality dissatisfaction. Noise may contribute to distraction, stress, headache, and fatigue. Localized pollutant sources may affect specific occupant groups even when whole-building averages appear acceptable. Nevertheless, the present study did not measure microbial contamination, psychosocial stress, allergy status, workload, or individual exposure, and no single mechanism can be identified from these data.

The finding that lower CO2 did not correspond to lower SBS burden is scientifically important because it shows that CO2 cannot represent the complete health quality of an indoor environment. CO2 may provide useful information on occupancy-related dilution, but it does not capture humidity, sound, thermal stress, VOC mixtures, PM sources, biological agents, lighting, or psychosocial conditions. Healthy-building assessment therefore requires multidomain environmental and occupant-outcome indicators rather than reliance on one ventilation proxy.

4.6 Perceived productivity was associated with comfort, IAQ perception, and acoustics

Perceived workplace productivity correlated most strongly with overall comfort, perceived IAQ, and acoustic comfort, followed by lighting satisfaction, ventilation satisfaction, and thermal comfort. It was negatively associated with SBS burden. These relationships support a holistic model of workplace performance in which occupants' perceived ability to concentrate, remain alert, complete tasks, and work efficiently reflects their combined experience of the indoor environment rather than a response to any single physical parameter.

This interpretation agrees with a growing body of evidence(Kang et al., 2023) found significant relationships between layout, air quality, thermal comfort, lighting, acoustics, and productivity in open-plan research offices, with acoustic quality exerting a particularly strong influence. (Khoshbakht et al., 2022) analyzing responses from more than 5000 office workers, reported that noise and perceived air quality were prominent predictors of productivity, comfort, and health, especially among people spending longer periods at work. (Liu et al., 2026) found that IEQ factors influenced contextual performance directly and task performance indirectly through interrelated workplace outcomes. (Fissore et al., 2023) similarly demonstrated cross-domain effects in a year-long living-laboratory study.

The relationship between thermal conditions and performance is also complex. Experimental and field studies have associated thermal discomfort with fatigue, impaired cognitive performance, and lower self-assessed productivity, but optimum conditions differ by task, exposure duration, sex, adaptation, and personal preference(Lan et al., 2011; Seppanen et al., 2006; Takasu et al., 2017; Zhang & Srinivasan, 2020) A recent meta-analysis concluded that moderately elevated office temperatures can reduce work performance after prolonged exposure, with larger effects for skilled tasks, while moderately cool conditions may have less consistent adverse effects (Wyon, 2004) At the same time, studies in humid subtropical offices show that air-conditioning does not automatically ensure greater self-assessed productivity and that localized discomfort and personal differences remain important (Lovric et al., 2025)

The present productivity findings must nevertheless remain qualified. Productivity was self-reported rather than objectively measured, and the group-level difference did not remain significant after correction for multiple comparisons. Self-reported productivity may reflect general workplace satisfaction, organizational culture, workload, mood, or common-method variance because the comfort and productivity outcomes were collected in the same questionnaire. The term perceived productivity is therefore used consistently throughout this manuscript.

Furthermore, the stronger correlations between productivity and other survey domains than between productivity and objective measurements may partly reflect the absence of respondent-specific exposure assignment. Unless each respondent is linked to a monitored floor, zone, workstation, and relevant time period, building-average sensor values may not accurately represent individual exposure. Weak objective-subjective associations should not therefore be interpreted as evidence that measured conditions are unimportant.

The observed relationships are consistent with a conceptual pathway in which perceived IEQ influences overall comfort and symptom burden, which in turn may influence perceived productivity. However, the current cross-sectional correlations do not demonstrate mediation or temporal causality. A formal mediation analysis would require estimation of direct, indirect, and total effects, preferably with bootstrapped confidence intervals and adjustment for building clustering and relevant occupant covariates. Unless such analysis is added, this pathway should be read as a conceptual interpretation rather than a tested causal model.

From a practical perspective, the results imply that interventions aimed at only one environmental parameter may produce limited productivity benefits. Ventilation improvement should be accompanied by humidity management; acoustic treatment should address both noise level and speech privacy; thermal interventions should consider air movement and personal control; and lighting interventions should balance task illuminance, daylight, and glare. The economic relevance of such integrated improvements is increasingly recognized. Recent benchmarking research has developed methods for valuing work-performance gains associated with better IEQ across large office datasets, strengthening the business case for post-occupancy optimization (Dam-Krogh, Clausen, et al., 2024; Dam-Krogh, Rupp, et al., 2024)

4.7 Building-level heterogeneity and the role of operational management

The four buildings exhibited substantial within-category heterogeneity, indicating that certification category alone could not explain the observed outcomes. Building A, a conventional building, recorded the lowest self-reported SBS burden and highest overall comfort despite having the second-highest mean CO_2 concentration. Building C, also conventional, displayed less favorable symptom patterns for some outcomes than Building A. Among the certified buildings, Building D had lower mean CO_2 than Building B but higher RH and noise, while Building B showed localized CO_2 elevation despite a favorable whole-building mean. These differences demonstrate that neither certification category nor a single environmental indicator adequately characterized the performance of an individual building.

Operational performance is shaped by a network of building-specific factors, including commissioning quality, HVAC balancing, maintenance, filter replacement, control settings, space management, equipment loads, cleaning, occupancy schedules, tenant behavior, workstation location, facade exposure, and responsiveness to complaints(Choi et al., 2020; de Wilde, 2019; Shukla et al., 2025; Tang et al.,

2022) Field evidence from Indian offices has identified improper system operation and maintenance as major contributors to substandard indoor conditions, even in mechanically conditioned buildings (Shukla et al., 2025)

Building age is also not a sufficient explanation. Older buildings may have less efficient systems, leakage, and obsolete controls, but they may also have lower internal equipment loads, heavier construction, different layouts, or more experienced maintenance teams. Newer certified buildings may have advanced systems but still perform poorly if controls are not commissioned, sensors are misplaced, ventilation is unbalanced, or tenant modifications alter design assumptions. Similarly, certification schemes differed between Buildings B and D, preventing certification from being treated as a uniform intervention.

The building-level joint display therefore provides a more informative interpretation than the pooled category means alone. It identifies where measured and perceived performance converged and where they diverged. Building A showed a divergence between comparatively high CO2 and favorable occupant outcomes; Buildings B and D showed a divergence between favorable CO2 and less favorable humidity, noise, comfort, and SBS outcomes. These patterns should not be interpreted as evidence that higher CO2 is beneficial or that certification is harmful. Rather, they show that building performance is multidimensional and that favorable performance in one domain cannot compensate automatically for weaknesses in others.

This heterogeneity also has statistical implications. Repeated five-minute measurements are nested within zones and buildings and cannot be treated as independent building-level replications of certification. A final analysis should prioritize building- and zone-level distributions, hierarchical modelling where feasible, and sensitivity analyses based on session or zone aggregation. (Lee et al., 2019) used generalized mixed models to account for clustering in a substantially larger 14-building study; with only four buildings, the present certification-category comparisons remain exploratory and case based.

4.8 Implications for climate-responsive certification and operational building management

The findings have implications for tropical green-building certification, HVAC design, commissioning, and facility management. Most importantly, ventilation-related achievement should be assessed together with latent-moisture performance. In hot-humid climates, outdoor-air provision cannot be optimized solely around CO2 or calculated ventilation rates; it should also be evaluated against supply-air dew point, indoor humidity ratio, condensation risk, infiltration, and part-load dehumidification performance. Certification systems could strengthen requirements for climate-specific latent-load calculations, dedicated humidity control, seasonal commissioning, and measured verification under occupied conditions.

Acoustic performance also requires greater attention. The widespread occurrence of elevated sound levels across both certification categories suggests that noise may be an under-addressed issue in tropical commercial offices generally. Certification and POE protocols should consider open-plan speech distraction, reverberation, privacy, equipment noise, HVAC background noise, and facade transmission rather than relying only on generic sound-level targets. ISO 22955 and ISO 3382-3 provide more functionally relevant approaches for assessing acoustic quality in open-plan offices than a single undifferentiated sound-level threshold.

The results further support a transition from one-time design certification toward performance-informed certification and recertification. Building systems, tenant layouts, occupancy, and operating practices evolve after construction. Periodic post-occupancy verification could combine:

- spatially resolved IEQ measurements;
- occupant surveys;
- HVAC and maintenance records;
- complaint data;
- energy and carbon performance;
- corrective-action plans; and
- confirmation that interventions improved conditions.

Evidence from WELL-certified workplaces indicates that certification and relocation can improve selected satisfaction, health, wellbeing, and productivity outcomes, but improvements are not universal across all buildings or domains (Ildiri et al., 2022; Khoshbakht et al., 2022b)). This reinforces the need to verify outcomes rather than assume that the certification label guarantees them.

Post-occupancy evaluation should also be embedded in routine facility management. A practical performance cycle would be: measure → survey → identify convergence and divergence → diagnose causes → intervene → verify performance. Such a cycle would convert POE from a one-time research exercise into a continuous quality-management mechanism. Recent reviews show that office POE remains methodologically heterogeneous, with no single protocol dominating and productivity assessed in only about one-third of studies (Dam-Krogh, Clausen, et al., 2024) Standardized reporting of monitoring duration, spatial coverage, instrument quality, respondent characteristics, averaging periods, and statistical hierarchy would improve comparability across buildings and climates.

The study also has wider international relevance. Rapidly urbanizing tropical regions are expanding mechanically cooled commercial-building stock while adopting certification systems often developed from international standards and experience extending well beyond hot-humid monsoon climates. Increasing cooling demand under climate change will intensify the need to reconcile energy efficiency, ventilation, humidity control, thermal resilience, and occupant health. Climate-responsive certification should therefore evaluate performance balance rather than assume that design strategies transfer unchanged across climatic contexts. A balanced tropical-office performance framework should simultaneously consider:

- outdoor-air provision and pollutant dilution;
- particulate and gaseous contaminant control;
- latent and sensible cooling;
- acoustic quality;
- visual comfort;
- occupant symptoms and wellbeing;
- perceived and objective productivity;

- operational energy;
- carbon emissions; and
- climate resilience.

This multidomain approach is consistent with recent benchmarking and structural-equation research showing that workplace value emerges through interacting environmental and human outcomes rather than from individual indicators considered in isolation(Dam-Krogh, Rupp, et al., 2024; Liu et al., 2026)

4.9 Strengths, limitations, and research priorities

A principal strength of this study is its integrated POE design. Objective measurements of CO2, PM2.5, PM10, TVOC, formaldehyde, temperature, RH, illuminance, and noise were combined with occupant evaluations of perceived IEQ, SBS symptoms, and perceived productivity. This allowed the study to identify both convergence and divergence between physical conditions and occupant experience. The inclusion of multiple buildings, floors, zones, functional spaces, and occupied monitoring sessions provided greater spatial and contextual detail than a single-point or survey-only assessment. The joint-display analysis was particularly valuable because it demonstrated that favorable ventilation-related performance did not automatically correspond with favorable health, comfort, or productivity outcomes.

The study also used effect sizes and multiplicity-adjusted probabilities, reducing exclusive reliance on unadjusted statistical significance. The zone-level analysis identified localized conditions concealed by building averages, while the combination of building-level and certification-category reporting exposed within-category heterogeneity. These features respond to calls for multidomain and mixed-evidence POE methods capable of supporting actionable building interventions (Almeida et al., 2023b; Dam-Krogh, Clausen, et al., 2024; Li & Tao, 2025)

Several limitations constrain the conclusions. First, the purposive sample contained only four buildings, with two buildings in each certification category. The results should therefore be interpreted as case-based evidence rather than population-level estimates for tropical certified and conventional offices. Certification status was not randomly assigned, and the buildings differed in age, size, occupancy, function, HVAC configuration, certification scheme, and management. These differences prevent the observed contrasts from being attributed solely to certification.

Second, the repeated environmental measurements were nested within monitoring sessions, zones, floors, and buildings. Treating individual five-minute observations as independent replications risks pseudo replication and underestimation of uncertainty. The final analysis should use zone- or session-level aggregation, cluster-aware methods, building-stratified sensitivity analysis, or multilevel models where statistically feasible. Given the very small number of buildings, even mixed-model category effects should be interpreted cautiously.

Third, environmental monitoring was conducted over two weekdays per building. This duration captures short-term occupied conditions but cannot represent long-term variability, wet- and dry-season differences, monsoon conditions, maintenance cycles, extreme weather, or changes in occupancy. Longer campaigns covering multiple seasons and repeated weeks are required before drawing conclusions about annual operational performance.

Fourth, some comparisons with reference values were screening level because the data-logging period did not match the averaging period specified by the corresponding standard or guideline. Five-minute PM readings cannot establish an exceedance of a 24-hour WHO guideline. Similarly, formal thermal-comfort assessment requires variables beyond air temperature and RH, and office acoustic assessment requires metrics beyond short-term A-weighted sound level. These results should therefore be described as comparisons with numerical reference values rather than formal compliance determinations.

Fifth, CO2 was not a direct measurement of outdoor-air ventilation rate. Occupancy, room volume, infiltration, and system scheduling may influence CO2 independently of mechanical fresh-air delivery. Direct ventilation measurements, tracer-gas testing, supply-air flow data, and occupancy-normalized analyses would strengthen future studies.

Sixth, the portable multiparameter instruments may have sensor-specific uncertainty, cross-sensitivity, drift, and response limitations, particularly for TVOC and particle measurements. Future research should report exact models, calibration procedures, co-location results, uncertainty, and comparison with reference-grade instruments. Compound-specific VOC analysis would be necessary to identify sources and evaluate health relevance.

Seventh, SBS and productivity were self-reported. SBS symptoms are non-specific and may be influenced by personal health, allergies, stress, workload, screen exposure, and infections. Perceived productivity may reflect general satisfaction or mood and is not equivalent to measured task performance. Future studies should include clinical or validated health information where appropriate and objective or semi-objective productivity indicators such as cognitive testing, error rate, processing time, absenteeism, presenteeism, and task completion.

Eighth, the objective and subjective datasets were integrated primarily at building level. Unless respondents can be linked to specific monitored zones, floors, workstations, and exposure periods, building-average environmental values may not represent individual exposure. Future research should use respondent-to-zone linkage, wearable or workstation sensors, repeated ecological surveys, and temporal alignment of exposure and response.

Ninth, the study did not measure outdoor-air flow, humidity ratio, supply-air dew point, HVAC energy, microbial contamination, reverberation, speech privacy, glare, or personal environmental control. These omissions limit mechanistic interpretation of the humidity, acoustic, health, and productivity results.

Future research should extend the framework to a larger and more diverse sample of buildings monitored across dry and monsoon seasons. A robust future design should combine continuous indoor and outdoor monitoring, measured ventilation, HVAC control and energy data, detailed acoustics and lighting measurements, occupant-level exposure linkage, health and psychosocial covariates, and objective productivity outcomes. Intervention studies are particularly important. Humidity-control optimization, ventilation balancing, acoustic treatment, localized exhaust, source removal, and control-system recommissioning could be evaluated using before-after, crossover, or stepped-wedge designs.

Larger datasets would also permit multilevel mediation or structural-equation modelling to test whether the relationship between environmental conditions and productivity operates through perceived comfort and SBS burden and whether these pathways vary by certification system, climate, building type, or

occupant characteristics. Such research would move the field beyond binary certified-versus-conventional comparisons toward evidence-based optimization of operational building performance.

5. Conclusion

Overall, the findings indicate that, within these four cases, certification status and CO2 alone were incomplete indicators of operational IEQ, and that green certification and satisfactory operational IEQ cannot be assumed to be synonymous. Within the four tropical office buildings examined, the certified cases exhibited a ventilation-related advantage through lower CO2 concentrations, but this coexisted with higher humidity, warmer conditions, greater noise exposure, higher SBS burden, and lower overall comfort. Perceived productivity was associated primarily with the integrated occupant experience, particularly overall comfort, perceived air quality, and acoustics, rather than with any single measured parameter. The central contribution is therefore not that conventional buildings universally outperform certified buildings, but that operational building quality is multidimensional, climate dependent, spatially heterogeneous, and strongly influenced by post-certification management. Tropical green-building systems should consequently move beyond design-stage and single-domain achievement toward verified post-occupancy performance that balances ventilation, moisture control, acoustics, occupant health, comfort, productivity, energy efficiency, and carbon outcomes. These findings should be regarded as short-term screening evidence from four cases rather than a generalizable assessment of certification performance; larger building samples and longer, seasonally distributed monitoring are required before broader conclusions can be drawn.

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The study protocol involving human participants was reviewed and approved by the Ethic Committee of the faculty of Agriculture, University of Ruhuna.. The study was conducted in accordance with the ethical guidelines and regulations of the approving committee and applicable institutional requirements.

Consent to Participate
Informed consent was obtained from all participants prior to participation. Participation was voluntary, and participants were informed about the purpose of the study, confidentiality of their responses, and their right to withdraw at any time without consequence.

Data Availability Statement
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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The authors declare that they have no competing interests.

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