RESEARCH ARTICLE

How Compliant HVAC Systems Affect Indoor Environment Quality and Occupant Sick Building Syndrome in Malaysian Academic Buildings

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Abstract

Indoor environmental quality (IEQ) has a significant impact on human well-being, with thermal comfort and air quality being two critical factors. This study presents both objective and subjective evaluations of centralized and VRF air-conditioning systems in a university library, examining their effects on thermal comfort, IEQ, and sick building syndrome (SBS). Objective measurements (air and radiant temperatures, humidity, air velocity, and CO_2 levels) were collected using data loggers over five days in April 2025 in two areas of a university library in Malaysia, alongside questionnaire surveys (n=100 respondents) on thermal sensation, thermal comfort, and SBS symptoms. Results showed that the VRF system exhibited a warmer, more stable environment (24.02°C, PMV=0.58), higher CO_2 levels (950 ppm), and lower humidity (45% RH), leading to increased headaches and eye irritation symptoms. Central AC's stricter IAQ control (CO_2 <800 ppm, humidity 55% RH) and better airflow uniformity (PMV=0.34, PPD=7.68), but its overcooling (22.68°C) triggered nasal congestion and skin irritation. However, the subjective assessments indicate that the VRF system achieved better thermal satisfaction compared to central AC. The findings reveal a divergence between standardized comfort metrics and occupant preferences in tropical climates, underscoring the need to integrate user feedback into thermal management.

Keywords: *CO2 PPM, HVAC system, Indoor Environmental Quality (IEQ), Split unit, Sick Building Syndrome (SBS), Thermal Comfort, University library.*

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Introduction

Indoor Environmental Quality (IEQ) covers a range of elements that influence comfort and health in indoor spaces, such as air quality, temperature regulation, and carbon dioxide (CO2) levels. Enhancing IEQ can positively affect people's daily experiences, boost the value of buildings, and increase productivity in workspaces (Mujeebu, 2019; Kim & de Dear, 2012); this can be achieved with a compliant Heating, Ventilation, and Air Conditioning (HVAC) system that meets the standards and codes set for safety and energy efficiency. Another key factor in IEQ and HVAC is thermal comfort, which refers to the level of satisfaction individuals feel with the temperature around them (Du et al., 2020; Zhang et al., 2019). According to Du et al. (2020), thermal comfort is essentially a mental state where one feels content with the surrounding temperature. There are two main ways to assess thermal comfort: the heat-balance method, which includes Fanger and Toftum's Predicted Mean Vote (PMV), and the adaptive model, which is based on real-life surveys (Nicol & Roaf, 2017; Fanger & Toftum, 2002). These techniques help provide a more accurate picture of people's comfort and can be used to create more personalized temperature control systems, especially in places like open offices and libraries (Crosby and Rysanek 2021, Gialelis et al., 2022; Karatzas et al., 2024).

CO_2 levels inside buildings are also a growing concern because they often go beyond safe limits. While CO_2 was once just seen as a marker for inadequate ventilation, new research suggests it can directly affect people's health and mental performance (Fisk et al., 2019). Higher levels of indoor CO_2 have been linked to worse air quality, more health complaints, and decreased ability to think clearly (Tillett, 2012). Schools and libraries are particularly affected, with high CO_2 levels causing tiredness, headaches, breathing problems, poor academic results, and even more sick days (Honan et al., 2024). Other studies show that excess CO_2 in places like lecture halls can cause symptoms of Sick Building Syndrome (SBS), such as concentration issues, fatigue, and headaches (Jayasooriya et al., 2020). When CO_2 levels go beyond 1000 ppm, the air feels stuffy and people become more sensitive to heat (Shin et al., 2021; Ameen et al., 2023); this suggests a need to combine air conditioning and ventilation in more innovative ways. While better airflow usually improves mood and air perception, it can sometimes lead to dry skin and mouth (Strøm-Tejsen et al., 2016). All of these highlight why keeping CO_2 levels in check is crucial for well-being and mental performance.

Creating the right indoor environment can be tricky, especially in places like libraries that store delicate collections. It's important to control temperature, humidity, and airflow carefully (Aflaki et al., 2023). People also value IEQ differently depending on factors such as gender and the duration of their stay in a space (Lai & Yik, 2009). These insights can help design or upgrade libraries to be more comfortable and better preserve their materials. Poor IEQ and uncomfortable temperatures can contribute to SBS, affecting both the health and focus of library users (Abdul-Wahab et al., 2015). Research shows SBS is quite common in libraries and brings symptoms like tiredness, sensitivity to smells, and breathing issues (Morris & Dennison, 1995; Nduka et al., 2021). In places like Malaysia and other countries with a tropical climate, SBS has been linked to high CO_2 levels, volatile chemicals, and humidity (Sulaiman et al., 2013; Abdul-Wahab et al., 2015; Nduka et al., 2021). Libraries with air conditioning tend to have more SBS problems than naturally ventilated ones (Morris & Dennison, 1995). Poor airflow, along with extreme temperatures and humidity, adds to the problem (Abdul-Wahab et al., 2015; Nduka et al., 2021). Solving these issues is key to creating healthier, more productive spaces.

People using central air conditioning (CAC) and split air conditioning (SAC) systems generally report similar levels of thermal comfort. Still, those in CAC buildings have a lower tolerance for high temperatures by about 2.7°C (Zhang et al., 2019). Central systems also tend to cool better and have environmental benefits over split systems (Puspitasari et al., 2024). In tropical areas, raising the thermostat can actually make people more comfortable (Schiavon et al., 2017). For example, university students in SAC buildings felt comfortable even when temperatures were 2–3°C above standard model predictions (Balbis-Morejon & Noya-Sambrano, 2020). However, it's not always easy to find the right balance in warm climates. In one Malaysian university, temperatures were too cold compared to American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards (Yau & Chew, 2014). in poorly ventilated SAC spaces, CO_2 often builds up, leading to drowsiness and discomfort (Pingale & Bhavsar, 2020; Rasli et al., 2021; Shin et al., 2021). That is why ongoing monitoring of IEQ is so essential. A study of a university library found slight issues with temperature and humidity, and CO_2 levels in reading areas were too high (Aflaki et al., 2023). Clearly, proper ventilation and temperature control are essential in air-conditioned buildings.

At Malaysian universities, studies show IEQ is acceptable and meets national standards (Asadi et al., 2014). The standard method to evaluate IEQ in academic buildings looks at temperature, humidity, air movement, and CO2 (Sulaiman et al., 2013). Recommended levels for a comfortable, eco-friendly environment in Malaysia include 27°C temperature, 40% humidity, and 0.30 m/s airflow (Jethi et al., 2024; Machado et al., 2022). These guidelines help facility managers improve building performance and support sustainable campuses (Yusoff & Sulaiman, 2014). Consistent IEQ is especially important for student comfort and success (Norazman et al., 2024). In offices with air conditioning, people preferred temperatures around 23–24.4°C (Yau & Chew, 2014). Humidity levels often surpassed ASHRAE recommendations but still met local standards (Abass et al. 2021). Air movement was usually lower than suggested, ranging from 0.02 to 0.5 m/s (Abass et al., 2021; Mustafa et al., 2023). Still, most people felt comfortable, even when conditions didn't meet ASHRAE standards (Mustafa et al., 2023). These studies highlight the importance of considering local climates and human adaptation in designing indoor spaces for Malaysia's hot, humid environment.

Recent evidence from Malaysia suggests persistent issues with thermal comfort, CO_2 accumulation, and SBS symptoms, particularly in air-conditioned libraries and university offices (Mohamad et al., 2025). Additionally, occupant low satisfaction was frequently reported in Malaysian buildings, especially the low satisfaction associated with inadequate control of ventilation and temperature (Mohamad et al., 2025; Kamaruddin & Abdull, 2023). Centralized and split-unit air-conditioning systems perform differently, yet their comparative effectiveness in maintaining IEQ remains understudied (Kamaruddin & Abdull, 2023). Therefore, the current study aims to compare the IEQ (thermal comfort and CO2 concentration) between the centralized air-conditioning system and the split-unit system and identify the key IEQ characteristics (e.g., thermal comfort, CO2 levels, SBS) in the two different air-conditioning systems (central AC vs. split unit), by analyzing university library users' perceptions of the IEQ in the Sultan Abdul Samad library Block A and Graduate Wing, at University Putra Malaysia.

Material and Method

This study follows a quantitative data collection using objective (physical) measurement and subjective measurement (questionnaire survey). The study was conducted in the first floor of Sultan Abdul Samad library at Universiti Putra Malaysia (UPM), in the Block A (central AC) and Graduate Wing (VRF split-unit) for 5 days, using both objective measurement (physical measurement) and subjective measurement (survey questionnaire) for assessment of the thermal comfort conditions, CO2 concentration and identifying SBS symptoms among library users in both buildings. The classified of each hall's HVAC operation as standards-compliant only when all concurrently logged values during a survey window satisfied the thresholds above, namely PMV within ±0.5 and PPD ≤ 10% based on ASHRAE 55 (ASHRAE, 2020), 23–26 °C, 55–70% RH, and ~0.05–0.20 m/s air speed based on MS 1525 (Department of Standards Malaysia, 2019), plus CO_2 < 1000 ppm as a practical indicator of adequate ventilation in occupied spaces based on ASHRAE 62.1 (ASHRAE, 2019). Any breach was flagged as non-compliant for that specific parameter and discussed accordingly.

Site location

The data collection procedure was designed based on the approaches of Geng et al. (2022), Piasecki et al. (2020), and Larsen et al. (2020) for short-term physical measurements. In these approaches, a specific location is targeted to measure both objective physical and subjective measurements simultaneously, usually over a short period of 5 to 12 days. Therefore, this study was conducted on the first floor of Sultan Abdul Samad Library at Universiti Putra Malaysia (UPM), in Block A (central AC) and the Graduate Wing (VRF split unit) for 5 days, using both objective measurement (physical measurement) and subjective measurement (survey questionnaire). The target population consisted of adult library users aged 18 years and over who had been in the hall for at least 15 minutes at the time of approach.

The selection of the Sultan Abdul Samad Library is because it gives a rare "like-for-like" comparison in one place: two adjacent first-floor halls with different HVAC types, Block A with centralized air-conditioning, and the Graduate Wing with VRF split units, sharing the same building shell, floor level, climate, and daily use. That setup reduces many of the usual confounders (different buildings, orientations, or user profiles) and lets us isolate how the system type shows up in IEQ and user experience. The library's consistently busy daytime occupancy also makes it practical to pair on-site surveys with co-temporal measurements. This study limited the data collection to five consecutive days (22–26 April 2025, 9 AM–5 PM) to capture both weekday and weekend patterns while keeping instrument stability, access permissions, and staffing manageable. This approach supports clean time-matching between logged data and survey responses without stretching the campaign beyond the study's resources.

Sultan Abdul Samad Library (PSAS) at Universiti Putra Malaysia (UPM) is located on the UPM Serdang campus. It comprises two blocks (Block A and Block B, also known as the Graduate Wing), with a total floor area of approximately 19,007 square meters. The library can accommodate around 2,000 users at any given time. The PSAS was inaugurated in 2002, named after Sultan Abdul Samad, the fourth Sultan of Selangor. The library began with the establishment of the Malaya Agricultural College on 21 May 1931, which aimed to support learning and research activities (see Figure 1). PSAS has gone through several phases of development and service improvements. The library was inaugurated and named after Sultan Abdul Samad on 23 May 2002. Block A is one of the original and main buildings of the PSAS. Designed during the early phases of UPM's development, it serves as the central hub for administrative services and core library functions. The main hall on the first floor of Block A is selected for this study. It is equipped with a centralized air conditioning system (central AC), ensuring consistent temperature control across its facilities (see Figure 2.a). The Graduate Wing at the PSAS was established in April 2012 as part of a library expansion, aiming to provide a dedicated and conducive study space for postgraduate students. The first-floor hall is selected for this study, where objective and subjective data will be observed and measured. Graduate Wing utilizes split-unit air conditioning systems, allowing for individualized climate control in specific areas (see Figure 2. b).

Figure 1: Sultan Abdul Samad Library (PSAS), Universiti Putra Malaysia (UPM).

a) b)

Figure 2: Two blocks of PSAS, UPM. (a) Block A. (b) Graduate wing.

Data Collection

As mentioned, the data collection consisted of two parts, objective (physical) measurement and subjective measurement (survey questionnaire) in both the library Block A and the Graduate Wing at the same time, to compare between two different type of air-condition system (Central AC and VRF Split unit) for indoor spaces in the PSAS, for 5 days starting from 9 AM 22 April 2025, until 5 PM 26 April 2025, including two weekend days and three week days at the mentioned library in UPM.

For physical measurement, the interval was 5 minutes at each point, for a total of five positions using the HOBOs and one position in the center using the data logger OHM, in both the first level of Block A and the Graduate Wing, continuously. The equipment used to measure the thermal comfort environment includes air temperature (°C), radiant temperature (°C), air velocity (m/s), and relative humidity (%).

The instruments used in this study were a data logger, the Delta OHM HD 32.3, a portable device designed for measuring and analyzing thermal comfort and indoor air quality (see Figure 3.a). It specifically measures and calculates the WBGT (Wet Bulb Globe Temperature), PMV (Predicted Mean Vote), and PPD (Predicted Percentage of Dissatisfied) indices. The instrument is used in various settings, including hot environments to assess heat stress and moderate environments to evaluate thermal comfort. In this study, Delta OHM is used to measure the air temperature, relative humidity, air velocity, and radiant temperature. Once these environmental parameters are measured, they are used in Fanger and Toftum's PMV equation to calculate the PMV. Then, the PPD is calculated based on the PMV value (Fanger & Toftum, 2002).

The second instrument is Onset Computer Corp HOBO H08-004-02, a data logger manufactured by Onset Computer Corp. It was designed to record temperature, light, humidity, and external sensor data. In this study, HOBO was used to validate and confirm the temperature recorded by Delta OHM. The Lutron PM-1064SD air quality monitor is also used for measuring CO2 PPM levels (see Figure 3.b). It is an air quality monitor and data logger that measures and records various parameters. It is equipped with a built-in SD card for convenient data logging, allowing users to transfer and analyze the data in spreadsheet applications easily. The device also features an LCD and generates alarms when specific health index levels are exceeded.

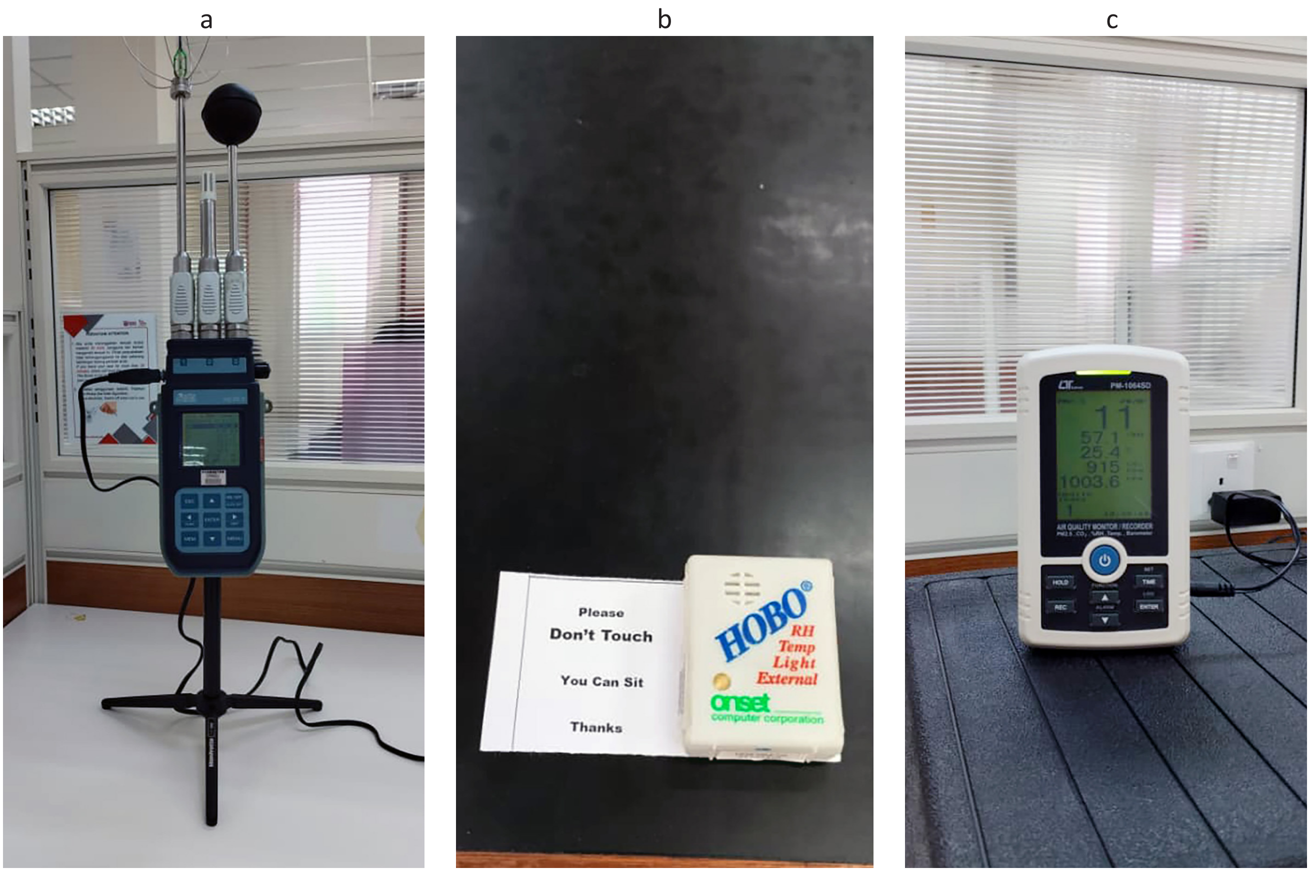


Figure 3: Objective (physical) Measurements Instruments. a) Delta OHM HD 32.3. b) Onset Computer Corp HOBO. c) LUTRON PM-1064SD.

A subjective assessment was a face-to-face questionnaire survey consisting of 25 items arranged in four sections to understand a different perception of PMV of thermal sensation, with clothing factors (clothing insulation) thermal environmental satisfaction, thermal environmental comfortable, thermal ecological acceptability, and SBS symptoms adapted from the American Society of Heating, Refrigerating and Air-conditioning Engineer (ASHRAE 55; ASHRAE, 2020). It is estimated to take around 5 to 10 minutes to answer all the questions. The total number of questionnaire survey respondents was n100, with n50 for Block A and n50 for the Graduate Wing.

Section A of the questionnaire included the demographics and context (participant variables; PV), such as gender (male and female), age range (below 20, 20–30, 30–40, and above 40 years old), education level (bachelor, master, PhD, and other), and field of study (open ended question). Context questions included duration of current stay (<30 min, 30–60 min, and >60 min), block (Block A and Graduate Wing), floor level (ground floor and first floor), and approximate orientation (south, west, north, east, core, and don't know).

Section B included four items about the perceived thermal comfort (dependent variables; DV), including questions about: (i) thermal sensation using a 7-point categorical scale from "-3= cold" to "3 =hot"; (ii) thermal satisfaction using a 7-point scale from "-3= very dissatisfies" to "3 =extremely uncomfortable"; (iii) thermal comfort using 5-point scale from "-4= extremely uncomfortable" to "1= comfortable"; and (iv) thermal acceptability using also 5-point scale from "-2= clearly unacceptable" to +2 =clearly acceptable". The items of perceived thermal comfort reflect momentary comfort judgements consistent with ASHRAE 55 occupant-survey practice.

Section D included 18 items about the SBS (health outcome variable). Respondents indicated whether they often experience any of 18 SBS symptoms during library stays (including cough/wheezing, throat irritation, eye irritation/watering, nasal congestion/runny nose, sneezing, skin irritation, headache, dizziness, difficulty concentrating, sensitivity to odors, chest tightness, nausea, vomiting, low-grade fever, fatigue, etc.). Each item was assessed using 0= yes and 1= no coding. Time, temperature, RH, and AV were also recorded on the form and used to pair each response with the nearest objective measurement record for co-temporal analysis.

Data Analysis

The data analysis compares objective measurements and subjective responses. The thermal comfort model, which includes the PMV and Predicted Percentage Dissatisfied (PPD), adapted from the ASHRAE 55 standard, is used to measure the predicted comfort level (ASHRAE, 2020). The comfort zone for PMV is ±0.5, with less than 10% for PPD, and almost 80% of occupants would have to be satisfied. A two-tailed and unpaired T-test with a P-value was calculated to show the difference between each result. Also, the standard deviation SD was calculated using Excel to understand how much the value differs from the mean. Regression analysis is necessary to demonstrate the differences between variables and to understand their correlation. Microsoft Excel is used to conduct linear regression analysis to determine the mean of each day's air and radiation temperature compared to PMV for Block A and the Graduate Wing, illustrating the relationship between them. Microsoft Excel is also used to conduct study charts (figures) and tables.

Results

Air and Radiant Temperatures

Using Delta OHM, the 5-day average indoor air temperature recorded in Block A was 22.68°C, which is slightly below the recommended thermal comfort range of 23°C to 26°C, as stated in ASHRAE standard 55-2020 and Malaysia's MS 1525 guideline for non-residential buildings (Department of Standards Malaysia, 2019). In contrast, the Graduate Wing achieved a mean temperature of 24.02°C, which sits comfortably within both standards' optimal indoor range for sedentary activities such as reading and studying (see Figure 4.a). Statistical analysis supports this difference; the p-value of 0.0017 confirms a statistically significant temperature variation between the two spaces ($p < 0.05$), meaning the difference is not random. Furthermore, the standard deviation for Block A was 0.11, indicating very stable but consistently cooler temperatures. In contrast, the Graduate Wing showed slightly higher variation (0.44) yet maintained comfort levels more effectively (see Figure 4.a). Therefore, Block A's temperature falls outside the minimum comfort boundary, potentially contributing to thermal dissatisfaction and SBS symptoms, while the Graduate Wing complies with both ASHRAE and MS 1525 standards, offering a more user-aligned environment (ASHRAE, 2020; Department of Standards Malaysia, 2019).

Delta OHM measurement also shows that over 5 days, Block A recorded a mean radiant temperature of 22.54°C, while the Graduate Wing averaged 23.84°C. The mean radiant temperature (Tr) represents the average temperature of all surrounding surfaces that affect how warm or cool a person feels indoors. According to ASHRAE standard 55-2020, the radiant temperatures in the library buildings ideally fall within a comfort zone of 23°C to 26°C for sedentary indoor activities, making the Graduate Wing compliant; however, Block A is slightly below the lower threshold (ASHRAE, 2020). The statistical comparison further reinforces the difference: a p-value of 0.002 shows the variation in radiant temperature between the two zones is highly significant ($p < 0.05$), meaning this is not a random fluctuation. In terms of temperature consistency, Block A displayed a lower standard deviation (0.19°C), indicating very stable conditions, though consistently on the cooler side. In contrast, the Graduate Wing had a standard deviation of 0.48°C, showing slightly more variation, but all within a comfortable and thermally acceptable range (see Figure 4.b). Therefore, Block A registers cooler and very consistent radiant temperatures, but those temperatures fall just below comfort standards, which may contribute to thermal discomfort and colder thermal sensation reports.

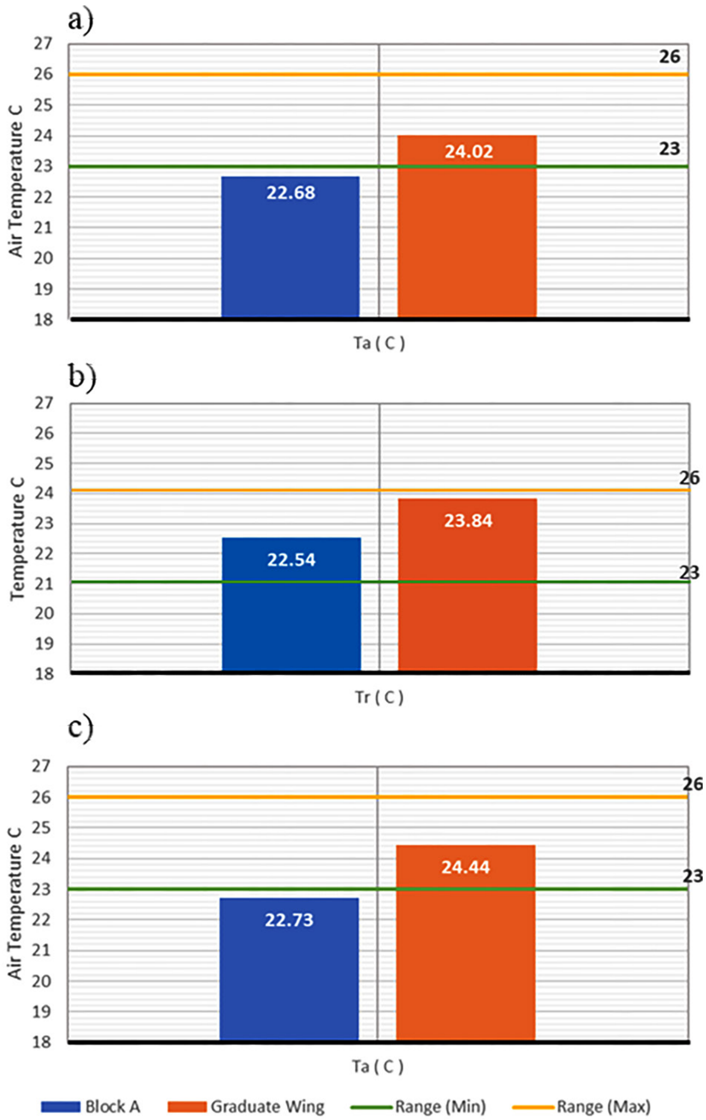


Figure 4: Registered Temperature for Block A and Graduate Wing Compared to Standard Range (23-26)°C. a) Air Temperature using Delta OHM Data Logger, b) Radiant Temperature using Delta OHM Logger, c) Air Temperature using HOBO Data Logger.

Similarly, based on Hobo Data Logger, Block A reports a mean temperature of 22.73°C, which is slightly below the ASHRAE standard 55-2020 and Malaysian MS 1525 (see Figure 4.c). The Graduate Wing also maintains a temperature of 24.44°C, placing it squarely within the accepted comfort zone based on the mentioned standards. From a thermal comfort perspective, this slight difference is meaningful. However, Block A shows cooler temperatures, which fall just outside the lower boundary of the comfort range, aligning with respondents' reports of feeling "cool" or "slightly cold" in the Thermal Sensation Vote (TSV) data mentioned in the coming sections (see Section 3.2). Meanwhile, the Graduate Wing's warmer profile supports its higher PMV value, explaining why more users rated it as thermally "neutral" or "slightly warm" (see Section 3.2.). The results confirm that accurate and continuous temperature logging, like that provided by HOBOs, helps validate and support subjective survey results done earlier by the Delta OHM, and also supports the data of the occupant survey (subjective data).

Relative Humidity

Over the 5 days, the average relative humidity (RH) using the Delta OHM Data Logger in Block A is 62.91%, and in the Graduate Wing, it is slightly lower at 59.27%. Both values fall comfortably within the recommended relative humidity (RH) range of 55% to 70%, as stated by both ASHRAE standard 55-2020 and MS 1525:2019 (Department of Standards Malaysia, 2019). This result suggests that, from a technical perspective, both spaces meet acceptable indoor air moisture standards, which are essential for occupant comfort and the prevention of issues such as dry eyes, respiratory irritation, or mold growth. Statistically, the p-value of 0.11 indicates that the difference in RH between the two zones is not statistically significant ($p > 0.05$), meaning any slight difference could be due to normal variation. However, the Graduate Wing showed higher variability in humidity (STDEV = 4.006) compared to Block A's more stable conditions (STDEV = 1.43). This stability may contribute to Block A's more consistent thermal and humidity perception, though not necessarily a more comfortable one, especially when combined with cooler temperatures (see Figure 5.a). Both Block A and the Graduate Wing successfully maintained relative humidity levels within recommended standards, ensuring a safe and comfortable indoor environment in terms of moisture. While Block A offered more stability, the Graduate Wing's humidity was still well controlled, despite slightly greater fluctuations.

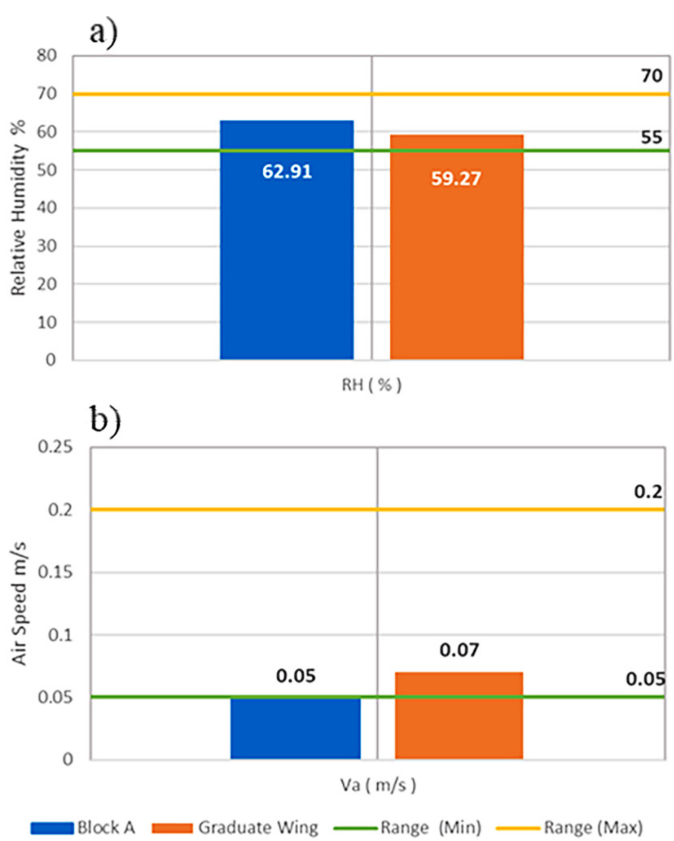


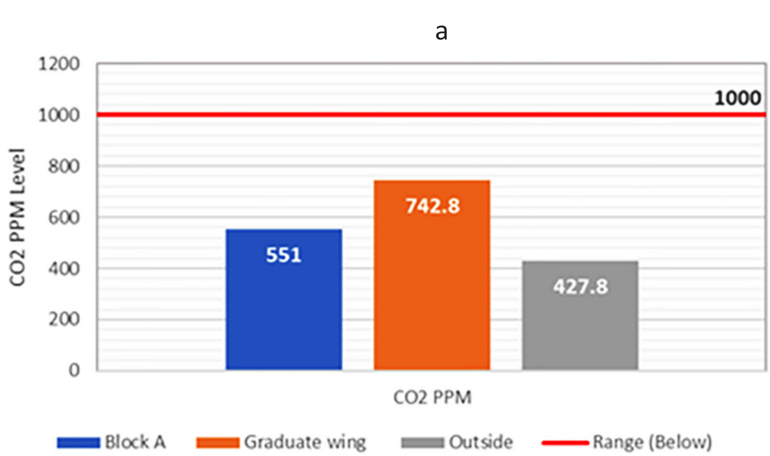
Figure 5: Relative Humidity and Air Velocity Using Delta OHM Logger in Block A and Graduate Wing Compared to Standard Ranges. a) Relative Humidity with Standard Range (55-70) %, b) Air Velocity with Standard Range (0.05-0.2) m/s.

Air Velocity

The average air velocity measured over 5 days using Delta OHM is 0.05 m/s in Block A and 0.07 m/s in the Graduate Wing (see Figure 5.b). According to ASHRAE standard 55-2020, for typical sedentary activities in naturally conditioned spaces, acceptable indoor air speed ranges from 0.05 m/s up to 0.2 m/s, depending on ambient temperature and user clothing insulation (Clo) (ASHRAE, 2020). Similarly, MS 1525 (Malaysian standard) supports the recommendation that indoor air movement should fall within this comfort-enhancing range, especially in warm, humid climates, where even slight airflow can improve perceived comfort (Department of Standards Malaysia, 2019). The statistical analysis yields a p-value of 0.35, indicating that the difference in air velocity between the two spaces is not statistically significant. In other words, although the Graduate Wing had slightly more air movement, this variation may not have meaningfully impacted occupant experience. However, it is worth noting that the Graduate Wing's higher air velocity (0.07 m/s) may still contribute to its more favorable comfort ratings, as seen in the following Thermal Sensation Vote (TSV) and satisfaction charts, discussed in section 3.6.3. Additionally, Block A displayed a tighter range of values (STDEV = 0.025) compared to the Graduate Wing (STDEV = 0.034), showing more consistent airflow in Block A, but possibly less dynamic ventilation.

CO2 PPM

The CO_2 levels measured in Block A, the Graduate Wing, and outdoors reveal essential insights into ventilation performance and IEQ. Over 5 days using the manometer Lutron PM-9107, Block A recorded an average of 551 ppm, Graduate Wing averaged 742.8 ppm, while outdoor CO_2 levels stood at 427.8 ppm. According to ASHRAE standard 62.1, indoor CO_2 concentrations should ideally remain below 1000 ppm to ensure adequate ventilation and minimize the buildup of contaminants in occupied spaces (ASHRAE, 2019). The results indicate that the Graduate Wing had noticeably higher CO_2 levels, suggesting lower ventilation efficiency, likely due to its use of split-unit air conditioning, which often recirculates air without introducing sufficient fresh outdoor air. In contrast, Block A's centralized HVAC system likely integrates more effective ventilation, maintaining lower CO_2 levels and better air quality for its occupants. Figure 6 shows that the Graduate Wing contributes to 42% of the overall CO_2 distribution, while Block A accounts for 31%, and outdoor levels make up only 27%. Although all spaces complied with the <1000 ppm CO_2 threshold, the Graduate Wing exhibited a 35% higher CO_2 level than Block A, indicating less effective fresh air circulation.



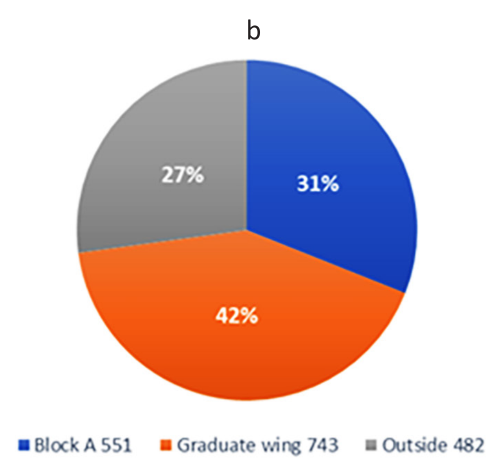


Figure 6: CO2 Levels. a) CO2 PPM in Block A, Graduate Wing, and Outdoor Compared to the Standard Range (1000) PPM b) CO2 PPM percentages in Block A, Graduate Wing, and Outdoor.

PMV and PPD

The PMV index reflects how occupants feel about the thermal environment, ranging from -3 (cold) to +3 (hot). According to ASHRAE standard 55-2020, the acceptable PMV comfort range is ±0.5, which indicates that 80% of people would find the environment thermally acceptable. The results show that Block A scored a mean PMV of 0.34, which falls comfortably within the standard, suggesting good thermal acceptability. However, the Graduate Wing had a mean PMV of 0.586, exceeding the upper limit, which may indicate a slight shift toward thermal discomfort perceived as "slightly warm." The p-value of 0.003 reveals a statistically significant difference between the thermal environments in Block A and the Graduate Wing ($p < 0.05$). Additionally, Block A showed very stable thermal conditions (STDEV = 0.021). At the same time, the Graduate Wing exhibited more variability (STDEV = 0.095), possibly due to less consistent environmental controls with split-unit air conditioning (see Figure 7.a). While the Graduate Wing's higher PMV aligns with its warmer air temperature and radiant heat, it exceeds ASHRAE's preferred comfort boundary, which could explain some reported dissatisfaction, as seen in TSV and SBS responses (in sections 3.6.3 and 3.6.7).

Block A remained within the PMV thermal comfort standard, while the Graduate Wing slightly exceeded the limit, indicating a higher tendency for occupants to feel too warm. These findings emphasize the importance of precise thermal management, especially in climates where maintaining temperatures within a narrow comfort band is key to occupant satisfaction (ASHRAE, 2020).

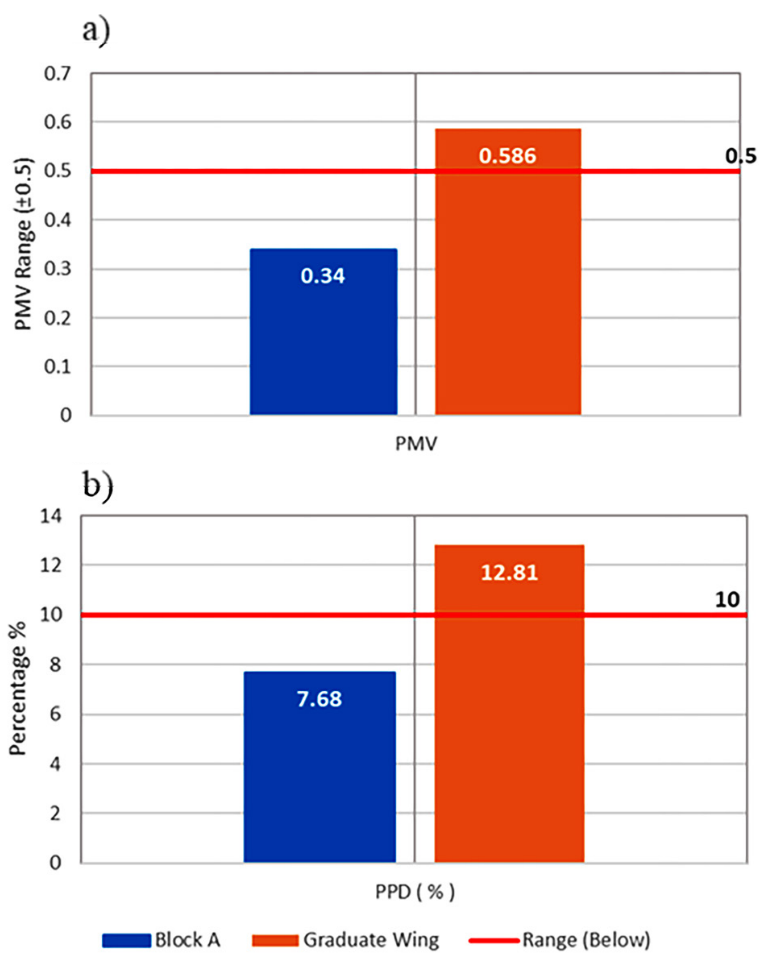


Figure 7: PMV and PPD in Block A and Graduate Wing Compared to the Standard Ranges. a) PMV with the Standard Range (0.5). b) PPD with the Standard Range (10%).

The PPD index estimates the percentage of people likely to be thermally dissatisfied in a given indoor environment. According to ASHRAE standard 55-2020, the recommended upper limit for PPD is 10%, meaning at least 90% of occupants should feel thermally comfortable. The results show that Block A recorded a PPD of 7.68%, well within the acceptable range. In contrast, the Graduate Wing exceeded the standard, with a PPD of 12.81%, suggesting a higher proportion of occupants may have experienced thermal discomfort, likely feeling a bit warm, as supported by the higher PMV (0.586) in that space (see Figure 7.b). The difference between the two areas is statistically significant, with a p-value of 0.011 ($p < 0.05$), confirming that the higher discomfort level in the Graduate Wing isn't due to random variation. Moreover, Block A displayed very consistent comfort ratings with a standard deviation of just 0.34, while the Graduate Wing showed more fluctuation (STDEV = 2.62), reflecting less predictable indoor thermal experiences. These numbers further reinforce the following subjective feedback from TSV, satisfaction, and SBS surveys, which will be discussed in the following sections (3.3.5 and 3.3.15). While Block A meets ASHRAE's thermal comfort requirements with fewer than 10% predicted to be dissatisfied, the Graduate Wing falls short, with nearly 13% likely to experience discomfort, a critical insight when designing or modifying HVAC systems. These results are in contrast with those from the mean temperature discussed earlier; this disagreement emphasizes that maintaining thermal neutrality isn't just about average values, but also about limiting variability and staying within established thresholds for occupant well-being.

Subjective Survey Results

Responses demography

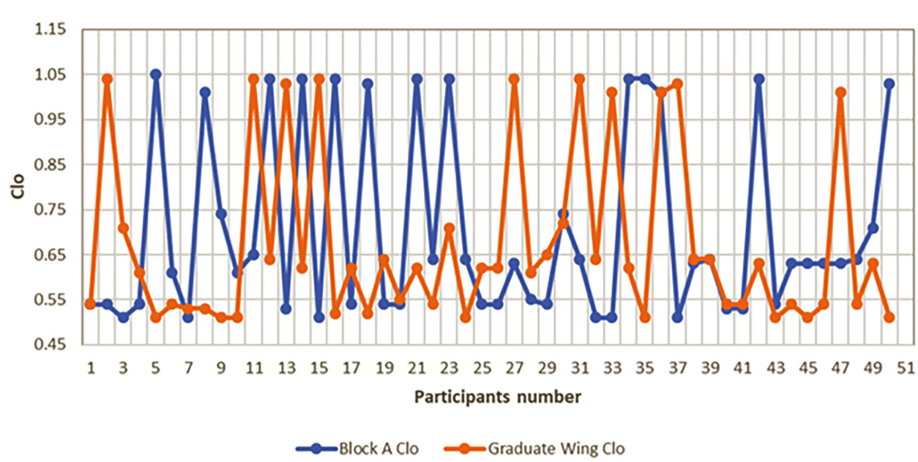
A total of (n=100) respondents were involved in the study, with an equal split between Block A and the Graduate Wing (see Table 1). The gender distribution shows a relatively balanced mix, with Block A having (n=22) males and (n=28) females, and the Graduate Wing consisting of (n=24) males and (n=26) females. This balance ensures a gender-diverse perspective in the evaluation of IEQ. In terms of age groups, the majority of respondents were between 20 and 40 years old, with (n=40) respondents out of (n=50) in Block A and (n=43) out of (n=50) in the Graduate Wing falling within this range. A small portion (12%) was above 40 years, likely representing faculty or PhD students. Regarding education level, the respondents were predominantly postgraduate students, with 27% PhD respondents in each location, followed by Master's students (8% in Block A and 21% in the Graduate Wing), and 16% of bachelor students (21% in Block A and only 2% in the Graduate Wing). This supports the Graduate Wing's role as a postgraduate space, highlighting the high cognitive demands of its users and making thermal comfort even more critical for performance and satisfaction. For the responses about the duration of stay, the majority of users in both areas spent more than one hour in the library (80% of the respondents, including 37% of the respondents in Block A and 43% of the respondents in the Graduate Wing, spent over 1 hour in the space. This extended exposure makes the occupants more sensitive to environmental factors such as temperature, humidity, and air quality, thereby reinforcing the relevance of the study's findings on thermal comfort and SBS symptoms shown in the following sections.

Table 1: Demographic Characteristics of the Respondents Based on Two Areas in PSAS.

Variable		Block A: No (%)	Graduate Wing: No (%)	Ranges	**Subtotal**	**Total**
Gender	Male	22 (22%)	24 (24%)	1-2	46 (46%)	100 (100%)
	Female	28 (28%)	26 (26%)		54 (54%)	
Age	Below 20	5 (5%)	1 (1%)	1-4	6 (6%)	100 (100%)
	20 – 30 years old	19 (19%)	24 (24%)		43 (43%)	
	30 – 40 years old	21 (21%)	18 (18%)		39 (39%)	
	Above 40 years old	5 (5%)	7 (7%)		12 (12%)	
Education status	Bachelor	14 (14%)	2 (2%)	1-4	16 (16%)	100 (100%)
	Masters	8 (8%)	21 (21%)		29 (29%)	
	PhD	27 (27%)	27 (27%)		54 (54%)	
	Others (staff)	1 (1%)	1 (1%)			
Duration of staying in the library	< 30 min daily	3 (3%)	3 (3%)	1-3	6 (6%)	100 (100%)
	30 min – 1 h daily	10 (10%)	4 (4%)		14 (14%)	
	≥ 1 hour daily	37 (37%)	43 (43%)		80 (80%)	

Comparing Clothing Insulation

The mean CLO value recorded in Block A was 0.70. In contrast, the Graduate Wing recorded a slightly lower mean of 0.67, suggesting that occupants in Block A wore marginally warmer clothing (see Figure 6). This difference aligns with the cooler temperature conditions observed in Block A. However, a t-test analysis (t-stat = 0.78, p = 0.43) indicates that the difference in clothing insulation between the two groups is not statistically significant. The high p-value (> 0.05) suggests that this variation could be due to chance and does not reflect a meaningful behavioral difference in clothing adjustment. Therefore, while Block A may have felt slightly cooler, it did not lead to a significantly higher clothing insulation response among occupants, even though the standard range for clothing insulation is between 0.5 and 0.7 clo (ASHRAE, 2020) (see Figures 8).



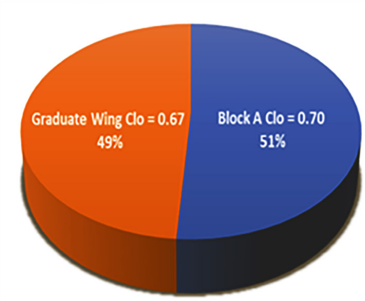


Figure 8: Clothing (Clo) Value for Respondents in Block A and Graduate Wing.

Thermal Sensation Vote (TSV)

The Thermal Sensation Vote (TSV) results show apparent differences in perceived comfort between the two zones. In Block A, 64% of respondents (n=32 out of n=50) reported thermal conditions as cool, slightly cool, or cold, while only 28% (n=14 out of n=50) rated it as neutral. In contrast, in the Graduate Wing, 54% (n=27 out of n=50) rated the environment as neutral, with another 24% feeling it was slightly cool or cool, indicating that most found it more thermally comfortable. According to ASHRAE (2020), thermal comfort is typically achieved when most occupants report sensations within the TSV range of -1 (slightly cool) to +1 (slightly warm). Both zones fall within this range, but the Graduate Wing's concentration around the neutral zone suggests it more consistently meets ASHRAE-defined comfort expectations (see Figure 9).

The accompanying independent t-test for TSV between Block A and the Graduate Wing yielded a t-statistic of 3.01 and a p-value of 0.0038. This confirms a statistically significant difference in thermal comfort perception between the two spaces ($p < 0.05$). The lower TSV scores in Block A reflect its cooler indoor temperature (22.73°C), while the Graduate Wing's average of 24.44°C aligned more closely with ASHRAE's recommended thermal comfort temperature range of 23°C to 26°C for sedentary indoor activities (ASHRAE, 2020). The data indicate that Graduate Wing occupants experienced a thermally neutral environment more consistently, while Block A leaned toward overcooling, potentially increasing discomfort or SBS symptoms among some users.

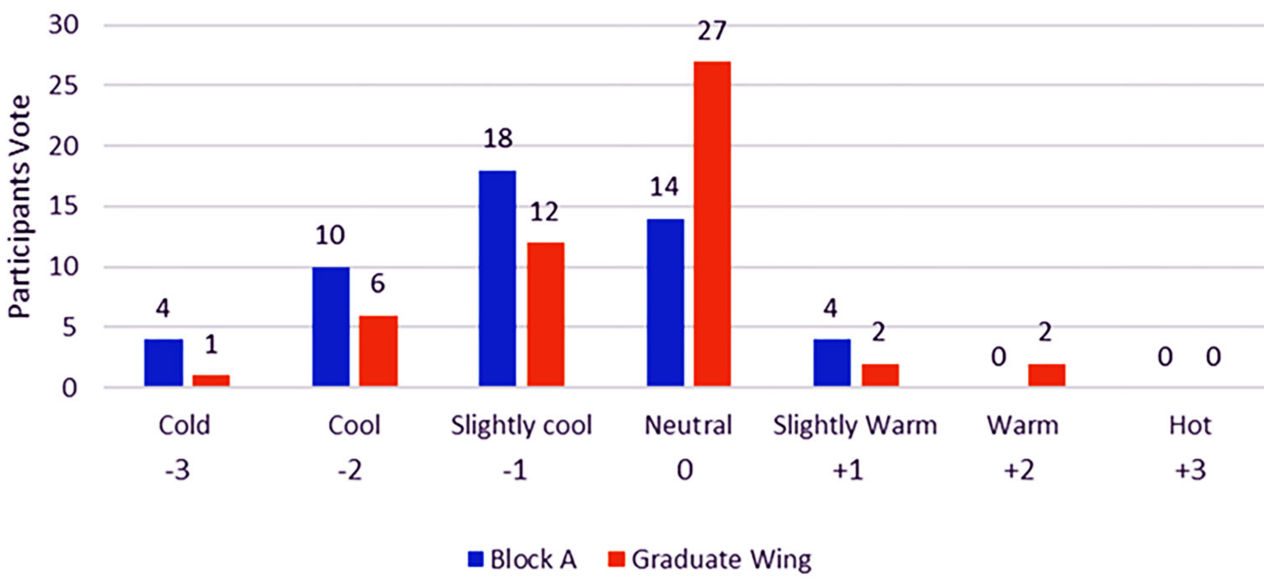


Figure 9: Thermal Sensation Vote for Block A and Graduate Wing.

Thermal Environmental Satisfaction

The results indicate a clear difference in thermal satisfaction between Block A and the Graduate Wing. In Block A, 64% of respondents (n=32 out of n=50) rated their satisfaction from neutral to very satisfied (votes 0 to +3), while in the Graduate Wing, this figure rose to 86% (n=43 out of n=50). Notably, 21 respondents in the Graduate Wing (42%) marked the environment as "satisfied" (vote +2), compared to only 32% in Block A. Furthermore, only 2 respondents in the Graduate Wing marked "Slightly Dissatisfied." In contrast, (n=11) respondents (22%) in Block A selected this option, suggesting that cooler conditions in Block A led to less favorable perceptions of comfort (see Figure 10).

According to ASHRAE (2020), thermal satisfaction is achieved when at least 80% of occupants find the environment acceptable. The Graduate Wing meets this standard comfortably, whereas Block A falls slightly below the ideal threshold, likely due to its colder indoor conditions. These findings align with previous TSV results, highlighting that the Graduate Wing provides a more consistently satisfying thermal environment for occupants. At the same time, Block A may require adjustments to avoid overcooling and improve user satisfaction.

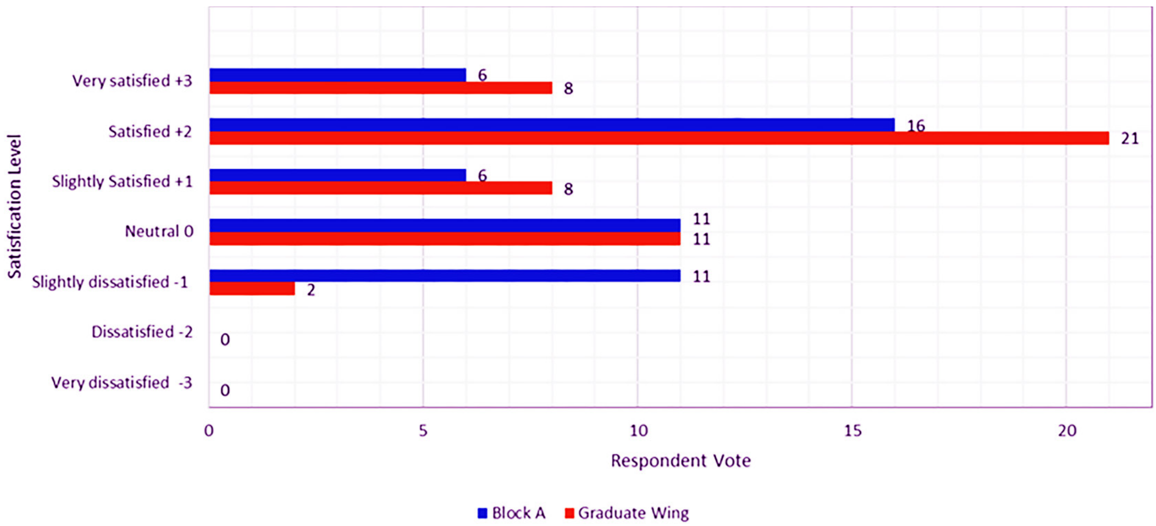


Figure 10: Thermal Environmental Satisfaction for Block A and Graduate Wing.

Thermal Environmental Comfortable

Figure 11 shows the comfort respondents felt in the overall thermal environment of Block A and the Graduate Wing. In the Graduate Wing, 72% of respondents (n=36 out of n=50) rated the space as “comfortable,” while 64% (n=32 out of n=50) in Block A selected the same. While both values suggest generally acceptable thermal conditions, the Graduate Wing had slightly fewer discomfort ratings, with only 1 respondent selecting “uncomfortable” compared to 3 in Block A, and none rating it as extremely uncomfortable in either space.

Interestingly, (n=14) respondents (28%) in Block A reported feeling “slightly uncomfortable,” which is double the number in the Graduate Wing. This aligns with earlier findings that Block A, with its cooler environment, may lead to mild overcooling for some occupants, while the Graduate Wing maintains more consistent warmth. As mentioned before, according to ASHRAE standard 55-2020, thermal environments are considered acceptable when at least 80% of occupants feel thermally comfortable. Both buildings are close to that benchmark, but only the Graduate Wing exceeds it, achieving a more comfortable thermal balance overall (ASHRAE, 2020).

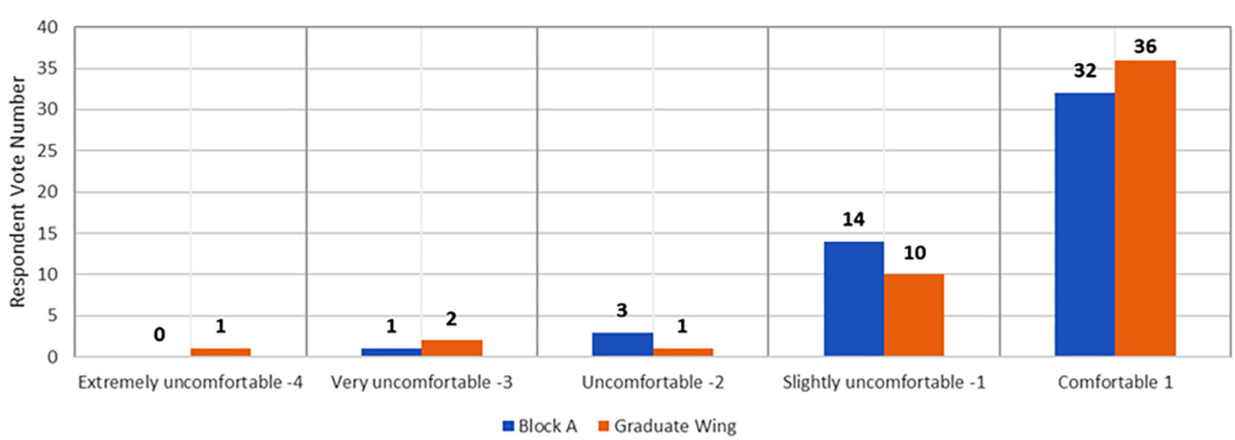


Figure 11: Overall Thermal Environmental Comfort Vote for Block A and Graduate Wing.

Thermal Environmental Acceptability

Figure 12 illustrates the respondents' responses regarding the thermal environment that is acceptable in both Block A and the Graduate Wing. In Block A, 58% of respondents (n=29 out of n=50) voted the conditions as "just acceptable" or "clearly acceptable." At the same time, the Graduate Wing showed stronger acceptability, with 76% (n=38 out of n=50) selecting these two options. Notably, no respondents in either group rated the conditions as "clearly unacceptable," suggesting both spaces fell within an acceptable baseline but to varying degrees.

Interestingly, Block A had (n=4) respondents (8%) who rated the environment as "just unacceptable," compared to none in the Graduate Wing. This may be related to Block A's lower temperatures and slightly more varied thermal conditions, which could have led to discomfort among more sensitive users. In contrast, the Graduate Wing's consistently moderate and warm conditions appeared to foster higher thermal satisfaction and overall perceived acceptability. Therefore, the Graduate Wing closely aligns with ASHRAE standards compared to Block A, demonstrating that even minor adjustments in indoor conditions can significantly impact occupants' perception of acceptability and comfort (ASHRAE, 2020).

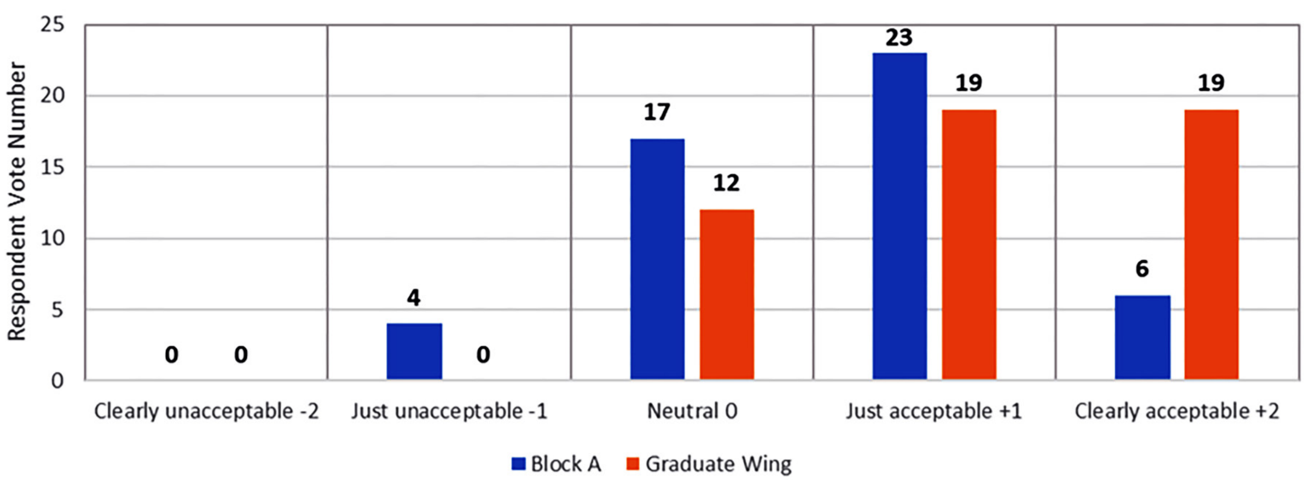


Figure 12: Thermal Environmental Acceptability Votes for Block A and Graduate Wing.

SBS Symptoms Experienced by Respondents

Figure 13 displays the types and frequency of symptoms of SBS experienced by respondents in Block A (centralized AC) and the Graduate Wing (split-unit AC). More than 60% of respondents in both locations reported experiencing 1 to 5 SBS-related symptoms, with some reporting up to 7. Notably, eye irritation, sneezing, and fatigue were the most common complaints in both places. The Graduate Wing exhibited higher incidences of headaches (n=5 votes), sneezing (n=7 votes), and eye irritation (n=7 votes), which are commonly associated with elevated CO_2 levels, dryness, and limited ventilation. Meanwhile, Block A respondents reported more nasal congestion (n=10) and dry or itchy skin (n=7), which are often associated with overcooling and higher humidity levels.

In the Graduate Wing, higher CO_2 levels (up to 874 ppm) and lower humidity may contribute to dryness-related symptoms like eye irritation and throat discomfort. At the same time, Block A's cooler and more humid environment might lead to sinus congestion and dry skin (ASHRAE, 2020).

Regression Analysis: The Relationship Between Air Temperature and PMV

Regression analysis is used to test the relationship between air temperature (°C) and PMV in Block A and the Graduate Wing. The equation of the regression analysis for Block A, y = 4.1111x + 21.282, shows a positive correlation, meaning that as the air temperature increases, the PMV also increases, indicating that occupants perceive the space as warmer. The coefficient of determination (R^2 = 0.6391) suggests that approximately 64% of the variation in PMV can be explained by changes in air temperature alone, which indicates a moderately strong relationship between the two variables. According to ASHRAE standard 55, PMV values should remain within the comfort band of ±0.5 to ensure the majority of occupants (at least 80%) are thermally satisfied (ASHRAE, 2020). Thus, Block A's PMV consistently stays within this range and correlates linearly with temperature shifts, confirming that temperature is a significant predictor of comfort in this zone. This result supports the effectiveness of the centralized air conditioning system in Block A, maintaining both consistent temperature and comfort levels for users (see Figure 14.a).

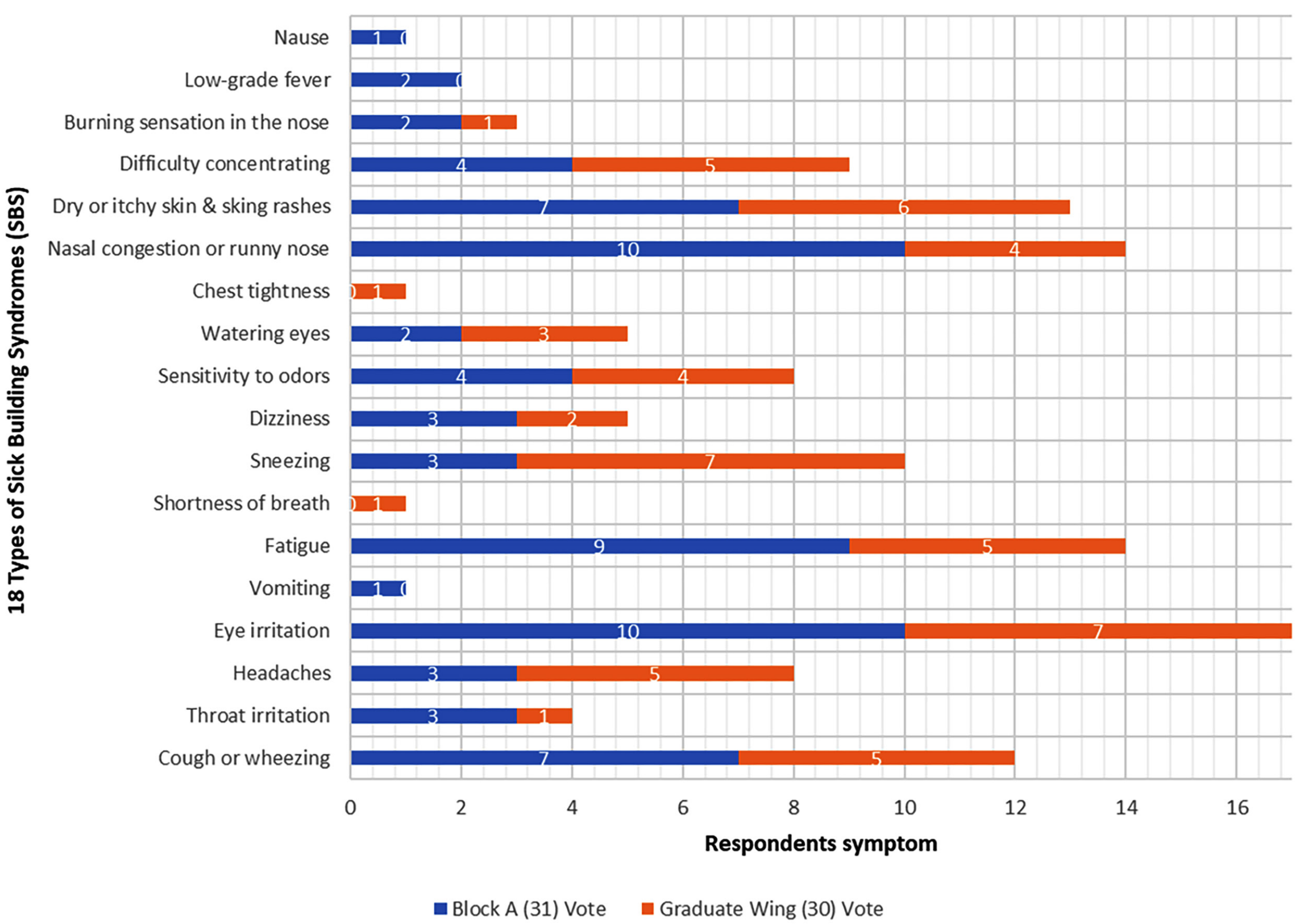


Figure 13: List Of 18 SBS Symptoms Experienced by Respondents During Staying in the Library, Block A and Graduate Wing.

On the other hand, the regression analysis demonstrates a strong positive linear relationship between air temperature and thermal comfort sensation (PMV) in the Graduate Wing. The regression equation y = 4.343x + 21.449 indicates that PMV increases steadily with temperature, suggesting that occupants feel progressively warmer as the indoor temperature rises. The coefficient of determination (R^2 = 0.913) highlights a strong correlation, meaning 91.3% of the variation in air temperature can be explained by PMV responses. This level of correlation suggests that the thermal environment in the Graduate Wing is highly sensitive to even small changes in temperature (see Figure 14.b.). Several PMV values above +0.5 indicate thermal conditions are drifting into a slightly warm to warm zone, which may reduce overall occupant satisfaction. This result aligns with other measured data where PMV and temperature values in the Graduate Wing exceed ideal thresholds more frequently than in Block A, likely due to its split-unit air conditioning system, which lacks the more stable regulation and fresh air intake typical of centralized systems. The regression analysis confirms that temperature strongly influences perceived comfort in the Graduate Wing, but current conditions are edging beyond ASHRAE's recommended PMV range. This could lead to decreased comfort and productivity, reinforcing the need for HVAC improvements or adaptive thermal strategies to maintain occupant satisfaction and air quality (ASHRAE, 2020).

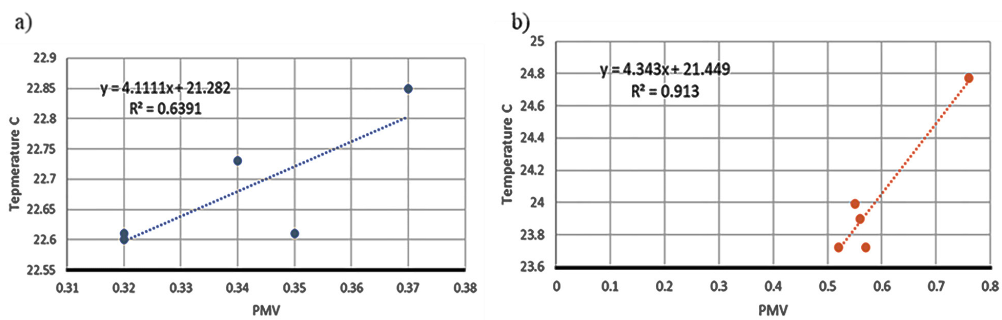


Figure 14: The Relationship Between Air Temperature And PMV. a) Air Temperature Compared to PMV In Block A. b) Air Temperature Compared to PMV in Graduate Wing.

Similarly, the regression analysis between radiant temperature and PPD in Block A demonstrates a moderately strong positive correlation, with an R^2 value of 0.6773 and a regression equation of $y = 0.4536x + 19.062$. This result indicates that approximately 67.7% of the variance in radiant temperature can be explained by the change in predicted dissatisfaction (PPD), suggesting a meaningful relationship between the indoor radiant heat environment and occupant discomfort levels. According to ASHRAE standard, PPD values should ideally remain below 10% to ensure acceptable thermal comfort for at least 90% of occupants (ASHRAE, 2020). In this analysis, Block A's PPD levels remained within the recommended range, aligning with its controlled central HVAC system and relatively stable thermal conditions (see Figure 15.a.). The trend suggests that as radiant temperature increases slightly, the predicted dissatisfaction also increases, highlighting the importance of radiant heat control in maintaining optimal comfort.

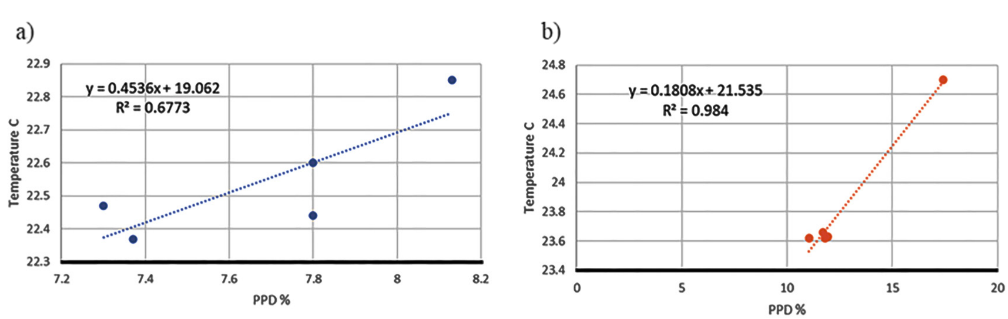


Figure 15: The Relationship Between Radiation Temperature and PMV. a) Radiation Temperature Compared to PMV in Block A. b) Radiation Temperature Compared to PMV in Graduate Wing.

The regression analysis of radiant temperature against PPD in the Graduate Wing reveals a strong positive correlation, with an R^2 value of 0.984 and the regression equation $y = 0.1808x + 21.535$. This result indicates that 98.4% of the variability in radiant temperature can be predicted by changes in PPD, demonstrating an extremely tight relationship between thermal radiation conditions and occupants' thermal dissatisfaction levels. Despite the slight slope, the Graduate Wing's PPD values exceeded the ASHRAE (2020) standard threshold of 10% maximum PPD for acceptable thermal comfort. These elevated dissatisfaction rates correlate with a mean radiant temperature of 23.84°C, which, although seemingly moderate, may combine with other indoor factors, such as air velocity and humidity, to increase discomfort perceptions. This correlation suggests that in naturally ventilated or less tightly controlled zones, such as the Graduate Wing, even subtle shifts in radiant temperature significantly affect perceived comfort.

Discussion

This study has explored the impact of two distinct air-conditioning systems, the central AC of Block A and the split unit of the Graduate Wing in Sultan Abdul Samad Library at Universiti Putra Malaysia, on the IEQ. The results from the objective (physical) measurement analysis of Block A (central AC) and the Graduate Wing (VRF system) reveal a nuanced interplay between thermal control strategies and occupant comfort, highlighting both the strengths and shortcomings of each system. The findings indicate that Block A's air temperature (22.68°C) and mean radiant temperature (22.37°C) fall outside the minimum comfort boundary for tropical climates. At the same time, the Graduate Wing complies with both ASHRAE and MS 1525 standards for the air temperature (24.02°C) and mean radiant temperature (24.44°C), offering a more user-aligned environment (ASHRAE, 2020; Department of Standards Malaysia, 2019). These findings challenge conventional assumptions about centralized systems in tropical environments. While Taib et al. (2022) found centralized AC systems typically maintain better comfort in Malaysian institutional buildings, our results demonstrate significant overcooling in Block A. This discrepancy may stem from the oversized cooling capacity in Block A.

In terms of humidity and air velocity levels, the Data Logger Delta OHM shows that both buildings fall within recommended standards, ensuring a safe and comfortable indoor environment, for humidity (55-70% RH) and air velocity ranges (0.05-0.2 m/s). Block A's centralized system, although slightly overcooling the space, maintains better indoor thermal conditions in terms of airflow, consistently falling within the acceptable PMV and PPD limits as set by ASHRAE standard 55 (ASHRAE, 2020). These findings corroborate those of Abass et al. (2021) in Malaysian office buildings, where centralized systems achieved 15% better air mixing uniformity than VRF alternatives. However, this comes at the cost of persistent overcooling (22.68°C), which supports Falzon et al.'s (2024) warning about the "dual penalty" of centralized systems in tropical climates, namely energy waste from excessive cooling despite meeting mechanical comfort metrics.

Although all spaces complied with the <1000 ppm CO_2 threshold, the Graduate Wing exhibited a 35% higher CO_2 level than Block A. At the same time, Block A's centralized AC system displays more effective ventilation, maintaining lower CO_2 levels and more consistent airflow, but possibly less dynamic ventilation compared to the Graduate Wing split unit. This finding aligns with Atish et al.'s (2012) findings that centralized systems achieve better air exchange rates in high-occupancy spaces. The increased CO_2 concentrations indicate suboptimal ventilation and reduced fresh air circulation in the Graduate Wing, which not only threatens indoor air quality but may also have cognitive and health implications for occupants over extended periods (Satish et al., 2012).

Similarly, Block A's centralised system, although slightly overcooling the space, maintains better indoor thermal conditions that consistently fall within the acceptable PMV (PMV=0.34) and PPD (PPD=7.68) limits as set by ASHRAE standard 55 (ASHRAE, 2020). Meanwhile, the PMV and PPD thermal comfort standard of the Graduate Wing slightly exceeded the limit (PMV=0.58; PPD=12.81), indicating a higher tendency for occupants to feel too warm. However, the survey results (subjective measurement) show that the Graduate Wing outperformed Block A in terms of thermal satisfaction, acceptability, and comfort, and consistently maintained a thermally neutral environment. Based on the TSV, the Graduate Wing provides a more thermally balanced indoor climate, with over half of the respondents feeling neutral comfort. Block A's cooler conditions, although technically within the ASHRAE recommended range, led to a higher percentage of "cool" votes and a significant difference in perception. Although a higher number of Block A's occupants were wearing marginally warmer clothing (as reported in the Comparing Clothing Insulation results), they reported sensations of chilliness and a greater desire for warmer conditions compared to the Graduate Wing report. This result supports the view that stable, slightly warmer environments are often perceived as more agreeable, particularly for sedentary activities such as studying (de Dear et al., 2015).

These findings highlight that while Block A maintained tight control by using the centralized system, it may have overcooled the space for many users. This paradox underscores a critical limitation in relying solely on standardized metrics like PMV/PPD without sufficiently accounting for subjective comfort perceptions and adaptive thermal behavior, especially in regions or building types where users may prefer warmer microclimates due to acclimatization or clothing habits, as mentioned by empirical studies from the local context by Mohamad et al. (2025) and Kamaruddin and Abdull (2021). Therefore, it is crucial to incorporate user feedback in the adaptive HVAC strategies to maintain high-quality indoor environmental conditions. Besides, this underscores the importance of not only meeting thermal standards but also optimizing systems (like HVAC) to match user comfort preferences. These findings also support ASHRAE's emphasis on adaptive comfort models and occupant feedback as vital in designing effective indoor environments (ASHRAE, 2020).

The findings also reveal a critical and multifaceted understanding of IEQ that extends beyond technical compliance, illuminating the physiological and psychological impacts of microclimatic variations in academic buildings. Although the Graduate Wing outperformed Block A in terms of thermal satisfaction, acceptability, and comfort, it recorded a markedly high prevalence of SBS symptoms, which can be directly associated with elevated CO_2 concentrations and low humidity levels. These findings align with prior research by Fisk et al. (2019), which shows that indoor air pollutants, even within standard thermal ranges, can significantly impact occupants' well-being, leading to headaches, eye and throat irritation, and fatigue. Similarly, an empirical study conducted by Shin et al. (2021) confirmed that CO_2 has been linked to fatigue, loss of concentration, and symptoms of SBS. These findings suggest a need for improved ventilation strategies in split-unit cooled areas to ensure healthier, more productive indoor environments (Satish et al., 2012).

However, both spaces (systems) showed signs of SBS, but symptom patterns varied based on the indoor environmental conditions. For example, the Graduate Wing's drier and CO_2-rich air appeared to cause more respiratory and eye-related issues, while Block A's cooler, more humid climate led to nasal congestion and skin irritation. These findings are in line with a study conducted in a tropical region by Graudenz et al. (2005), which found that prolonged exposure to artificial air conditioning in HVAC systems increases work-related upper respiratory symptoms compared to buildings. Additionally, Sikram et al.'s (2020) study on tropical offices reveals that the prevalence of skin irritation was 32% higher in over-cooled spaces (22-23°C) compared to neutral conditions (24-26°C). These findings underscore the importance of tailoring indoor climate control to prioritize both human health and thermal comfort, in accordance with ASHRAE's standards for ventilation and air quality (ASHRAE, 2020).

Despite these critical findings, there are a few limitations to this study. First, the study focused on a single case study within a short period of time in two halls within Sultan Abdul Samad Library at Universiti Putra Malaysia. That choice strengthens internal validity (same campus, level, and envelope) but narrows generalizability to other buildings or seasons. The five-day measurement of data collection provides a realistic snapshot of typical daytime operation. However, it does not capture longer-term or seasonal effects (e.g., exam periods, maintenance cycles, extreme weather). Second, the SBS symptoms were self-reported rather than clinically verified, so some reporting bias is possible. Third, the study was designed based on two standards only, ASHRAE 55 (ASHRAE, 2020) and MS 1525 (Department of Standards Malaysia, 2019). Future work should expand to multi-site, multi-week campaigns across seasons, including test setpoint and outdoor-air strategies in split-unit spaces, and, where feasible, pair IEQ data with short task or cognitive measures to connect conditions with user performance more directly.

Conclusion

This study provides a comprehensive evaluation of two air-conditioning systems, centralized AC (Block A) and VRF split units (Graduate Wing), in a university library in Malaysia, revealing critical trade-offs between thermal comfort, indoor air quality (IAQ), and occupant health. While the Graduate Wing's VRF system achieved superior thermal satisfaction (from the subjective measurements) by maintaining a warmer, more stable environment (24.02°C, PMV=0.58), it exhibited higher CO_2 levels (950 ppm) and lower humidity (45% RH), leading to increased SBS symptoms (headaches, eye irritation). In contrast, Block A's centralized system delivered stricter IAQ control (CO_2 <800 ppm, humidity 55% RH) and better airflow uniformity (PMV=0.34, PPD=7.68), but its overcooling (22.68°C) triggered nasal congestion and skin irritation, despite complying with ASHRAE standard 55. Future tropical building designs must balance technical metrics (PMV/PPD) with occupant feedback and health outcomes, adopting real-time IEQ monitoring and adaptive control algorithms. This study highlights that "compliant" does not always equate to "optimal"; a paradigm shift toward human-centric HVAC design is urgently needed in warm-humid climates. Therefore, this study highlights the need for a hybrid approach to thermal management, one that combines robust data monitoring with user feedback to create adaptive, responsive indoor environments tailored to promote well-being, focus, and satisfaction.

The findings of this study offer actionable insights for HVAC design, operation, and policy in tropical climates. Practitioners should prioritize adaptive system tuning, adjusting centralized cooling setpoints to a temperature of 24°C or higher, to prevent overcooling-related health issues (e.g., nasal congestion, skin irritation) while maintaining energy efficiency. For VRF systems, integrating demand-controlled ventilation (DCV) or dedicated outdoor air systems (DOAS) is crucial to mitigate CO_2 buildup (exceeding 900 ppm) and associated symptoms of SBS. Occupant feedback mechanisms (e.g., real-time thermal voting apps) should be embedded into building automation systems to align mechanical performance with subjective comfort preferences. Policymakers must update MS 1525 and GBI certification to enforce stricter CO_2 thresholds (≤800 ppm) and humidity-temperature pairings (50–60% RH at 24–26°C), bridging the gap between compliance and occupant well-being. Retrofitting existing libraries with hybrid ventilation (e.g., operable windows with CO_2 sensors) could offer a low-cost solution to enhance IAQ without compromising thermal stability.

This study challenges conventional IEQ assessment frameworks by demonstrating that meeting ASHRAE standard 55 metrics does not guarantee holistic comfort in tropical buildings. The divergence between objective measurements and subjective preference underscores the need to redefine thermal comfort thresholds for acclimatized populations, supporting extensions to de Dear's (2015) adaptive model. The identification of system-dependent SBS pathways, where VRF systems exacerbate respiratory symptoms (CO_2-driven) and centralized systems induce dermatological effects (cold-dry air), advances Bluyssen's (2021) IEQ symptom matrix by linking HVAC typologies to specific health outcomes. Furthermore, the results highlight humidity-CO_2 interactions as a critical but underexplored dimension of tropical IEQ, suggesting future comfort models should incorporate dynamic humidity thresholds tied to ventilation rates. These insights call for a paradigm shift from prescriptive standards to performance-based, health-integrated IEQ guidelines, particularly for high-occupancy educational spaces.

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