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Classroom indoor air quality and its association with sick Building syndrome (SBS) symptoms in a Malaysian university setting

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This study aimed to investigate the association between indoor air quality (IAQ) parameters and the prevalence of Sick Building Syndrome (SBS) symptoms among university students in different types of classrooms. The research responds to growing concerns about environmental health risks in educational settings and seeks to identify key IAQ predictors of SBS symptoms. A cross-sectional study was conducted among 205 students at a Malaysian public university. An online questionnaire adapted from the Indoor Air Quality Industry Code of Practice (ICOP-IAQ) 2010 was used to assess SBS symptoms. Simultaneously, IAQ monitoring was carried out in selected lecture halls (LHs) and tutorial rooms (TRs) using calibrated instruments to measure $PM_{2.5}$, PM_{10}, temperature, relative humidity, carbon monoxide (CO), carbon dioxide (CO_2), total bacterial count, and fungal count. Comparisons were made between the classrooms. Significant differences were observed between LHs and TRs for $PM_{2.5}$, PM_{10}, temperature, relative humidity, CO, and bacterial counts. SBS symptoms were more prevalent in LHs (70.2%) than in TRs (56.6%). In LHs, CO, PM_{10}, relative humidity, and fungal count were significantly associated with SBS symptoms, while in TRs, only CO_2 showed a significant association. Multivariate analysis identified CO, PM_{10}, and fungal count as significant predictors in LHs (AOR = 4.7; $p < 0.001$), and CO_2 in TRs (AOR = 2.7; $p = 0.003$). IAQ parameters are significant contributors to SBS symptom prevalence among university students, with differences influenced by classroom type and ventilation design. These findings emphasize the urgency of IAQ interventions in academic institutions.

Keywords Classroom environment, University students, Particulate matter, Carbon dioxide, Fungal exposure

Indoor air quality (IAQ) refers to the condition of air within and around buildings, particularly as it relates to the health, comfort, and cognitive performance of occupants[1]. According to the Department of Occupational Safety and Health Malaysia, IAQ encompasses physical, chemical and biological indicators[2]. Inadequate IAQ has been consistently linked to a wide spectrum of adverse effects, including respiratory symptoms, headaches, fatigue, and reduced work and academic performance[3,4].

One of the most common health complaints associated with poor IAQ is Sick Building Syndrome (SBS), a collection of non-specific symptoms such as eye irritation, headache, dizziness, and dry throat that tend to improve upon exiting the affected environment[5]. Although SBS is not a formally recognized medical condition, its impact on well-being, cognitive function, and productivity has been widely acknowledged, especially in occupational and educational settings[6,7]. Although SBS is not a formal medical diagnosis, it is recognized as a public health concern, especially in institutional settings.

Educational institutions are particularly susceptible to IAQ-related issues, as students spend long hours in enclosed classrooms. Numerous studies have emphasized the negative effects of poor indoor environments on academic performance, including reduced attention span, impaired memory, and physical discomfort due to prolonged occupancy, densely packed classrooms, limited ventilation, and the presence of heat-retaining materials and furnishings[8,9]. While a substantial body of research has assessed IAQ in primary and secondary schools[9,10], there is a notable gap in studies focusing on tertiary education settings in Malaysia, particularly in relation to SBS symptomatology.

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Environmental stressors such as overcrowding, fluctuating temperatures, insufficient ventilation, and limited air circulation remain prevalent in Malaysian university classrooms. These conditions not only diminish comfort but also elevate the risk of SBS. Moreover, most existing Malaysian studies have either focused on specific pollutants or relied on subjective reports without robust spatial and temporal monitoring. For instance[11], reported a high prevalence of SBS-related symptoms in anatomy laboratories, including headache, dry throat, and fatigue. These symptoms are exacerbated by poor ventilation and prolonged indoor exposure.

This study addresses a critical gap in the Malaysian context by examining the association between IAQ parameters and SBS symptoms among students in two types of university classrooms, which are lecture halls (LHs) and tutorial rooms (TRs). Moreover, this research captures the IAQ exposure experience of typical classroom-based learning environments in higher education. By employing a multi-parameter approach with real-time IAQ monitoring and validated SBS symptom assessment tools, this research provides new insights into how classroom type, environmental conditions, and student health outcomes intersect. Aligned with Sustainable Development Goal 3 (Good Health and Well-being), this study seeks to inform institutional strategies that promote healthy learning environments, thereby enhancing student wellness, comfort, and academic performance in Malaysian universities.

Methodology

Study design, location and participants

This cross-sectional study was conducted from October to November 2023, coinciding with the dry season. The participants were selected among undergraduate students at a faculty at a public Malaysian university. The data collection period was timed to coincide with the start of a new academic semester to ensure optimal classroom occupancy. This timing allowed for consistent IAQ monitoring during active teaching hours when classrooms were most heavily used.

Two types of classrooms, LHs and TRs were purposively selected for this study as they represent the most commonly used teaching spaces in the selected university and possess distinct characteristics relevant to indoor environmental quality (IEQ). These distinctions include significant differences in room volume, seating capacity, occupancy density, ventilation design, and typical usage patterns. This comparative approach enabled an assessment of how varying spatial and structural classroom environments influence IAQ parameters and the prevalence of SBS symptoms among students.

In terms of environmental context, most classrooms were located on elevated floors away from direct outdoor pollution sources. No unusual outdoor air pollution events, such as haze, were recorded during the monitoring period. Records from the Department of Environment indicated that daily air quality remained in the moderate range, and no rainfall or strong wind events occurred that could have significantly affected IAQ during data collection. LHs are large-capacity teaching spaces with a mean floor area of approximately 758.3 m^2. These spaces are designed to accommodate up to 200 students and are furnished with fixed cushioned seating and carpeting. Each LH is equipped with four wooden doors and no windows, creating a fully enclosed indoor environment. Centralized air conditioning is used for temperature control and ventilation. Cleaning and janitorial services are conducted daily between 7:00 and 8:00 a.m. by the university's facility management unit.

TRs, in contrast, are smaller classrooms averaging 65.7 m^2 in floor area, typically used for small group classes involving up to 30 students. Furthermore, TRs are equipped with a movable wall panel that offers a flexible solution for accommodating more students by combining spaces for larger groups. Therefore, sometimes two TRs are used for one class if the students are more than 30. Each TR is fitted with two solid-core doors, and similar to LHs, does not have windows. All rooms rely on centralized air conditioning systems for thermal regulation. The doors in both room types are generally kept closed during class sessions to maintain indoor comfort and reduce noise from outside.

A total of 205 undergraduate students were recruited using a convenience sampling method, targeting those attending scheduled classes during the data collection period. Eligible participants included male and female students from all six undergraduate programs in the faculty. They were also among those who had been enrolled at the faculty for at least six months and attended the classrooms for a minimum of five hours per week at the faculty. These inclusion criteria ensure adequate exposure to classroom air quality conditions. Students with pre-existing respiratory or dermatological conditions such as asthma, sinusitis or eczema were excluded to minimize confounding in symptom reporting. Exclusion criteria included smokers of all types and those who refused to complete the questionnaire.

Sick building syndrome (SBS) symptoms assessment

SBS symptoms were assessed using a standardized, validated self-administered questionnaire adapted from the Malaysian Industry Code of Practice on Indoor Air Quality (ICOP-IAQ 2010). This tool has demonstrated strong internal consistency in prior university-based studies in Malaysia, with a Cronbach's alpha of 0.84[7]. Students were categorized as SBS-positive if they reported two or more symptoms occurring at least once per week over the past month, in line with established definitions used in SBS-related research[7]. Symptoms that improved upon leaving the classroom were considered indicative of SBS. This frequency-based approach allowed for clear distinction between acute SBS-related symptoms and incidental discomfort.

All participants were enrolled in academic programs that required attendance in both LHs and TRs as part of their weekly schedules. SBS symptoms questionnaires were distributed to students present in the monitored classrooms on the same day. Only those students who were confirmed to be physically present during the IAQ measurement session were invited to complete the SBS questionnaire. Therefore, each respondent had exposure to both classroom types during the study period, allowing within-subject comparison of SBS symptom reporting. This uniform exposure structure helps minimize confounding due to individual differences and strengthens the inference that SBS differences are likely related to environmental characteristics rather than respondent characteristics.

Indoor air quality (IAQ) measurement

IAQ measurements were conducted in the selected six classrooms (three LHs and three TRs) using real-time monitoring equipment over a full academic day (8:00 a.m. to 5:00 p.m.), excluding a 1-hour lunch break (1:00 p.m. to 2:00 p.m.). Each classroom was monitored for a single full day. The three LHs (LH-A, LH-B and LH-C) were measured on October 30, October 31 and November 1, 2023, respectively. Meanwhile, the three TRs (TR-A, TR-B and TR-C) were measured on November 6, November 7 and November 8, 2023, respectively. Due to limitations in the availability of real-time instruments and time constraints, continuous monitoring over multiple days was not feasible. The selected day reflected a typical class schedule and was not associated with any anomalous campus events, ensuring representative conditions for routine occupancy. The monitoring adhered to the recommended practices outlined by the Malaysian ICOP-IAQ 2010, including appropriate calibration, positioning, and recording intervals for each IAQ parameter. The IAQ parameters measured included physical, chemical, and biological parameters. Physical indicators measured were temperature, relative humidity, and air velocity. Chemical indicators included carbon monoxide (CO), carbon dioxide (CO_2), total volatile organic compounds (TVOC), particulate matter ($PM_{2.5}$, PM_{10}) and ultrafine particles (UFP). Biological indicators consisted of total bacterial and fungal counts.

Monitoring was carried out in the presence of both lecturers and students to reflect actual classroom conditions during occupancy. Student presence during IAQ monitoring was determined using official class attendance lists. Only these students were included in the analysis of SBS symptoms to maintain alignment between exposure and outcome. While this approach may not fully capture individual variations such as late arrivals or absences, it provides a practical and reasonable estimate of student presence during monitored sessions. All instruments were placed on a stable platform approximately 1.1 to 1.3 m above the floor to represent the typical breathing zone of seated students. Equipment was positioned centrally in the classroom, at least 1 m away from walls, doors, windows, or active ventilation outlets to avoid direct influence from airflow sources.

Measurements were obtained at 1-hour intervals using calibrated instruments, which are the Q-Trak IAQ Monitor (TSI USA, Model 7565) for temperature, relative humidity, CO, and CO_2; the VelociCalc Multifunction Ventilation Meter (TSI USA, Model 9565) for air velocity; the Handheld VOC Monitor (RAE Systems, PpbRAE 3000) for TVOC; the DustTrak II Aerosol Monitor (TSI USA, Model 8532) for $PM_{2.5}$ and PM_{10}; the P-Trak Ultrafine Particle Counter (TSI USA, Model 8525) for ultrafine particles; and the Duo SAS High Volume Microbial Air Sampler (International PBI, Italy, Model 360) for microbial counts.

While classroom floor areas were known, actual occupancy headcounts during IAQ monitoring were estimated based on class schedules and typical attendance. Therefore, precise occupancy density calculations may be subject to variability. Occupancy density (persons/m^2) was calculated by dividing the number of occupants by the floor area of each classroom. Although this approach offers a practical proxy for estimating classroom occupancy, it may not account for individual variations such as student absenteeism, late arrivals, or unscheduled class changes. Therefore, the occupancy figures used in the analysis represent an estimated maximum occupancy rather than real-time presence.

In addition, air velocity measurements were specifically taken at the center of each classroom to represent the general air movement within the occupied space. Additional measurements were taken near supply and return air grilles, where feasible, to assess localized airflow patterns, adhering to manufacturer guidelines for accurate readings. All classrooms in this study were served by a centralized Heating, Ventilation, and Air Conditioning (HVAC) system, typical of institutional buildings in Malaysian universities. While the exact specifications of airflow rates and filtration mechanisms were not available, the classrooms received uniform conditioned air through ceiling diffusers without individual room controls. No natural ventilation (e.g., openable windows) was available during the monitoring period.

Quality control and assurance

All instruments underwent factory calibration by their respective manufacturers. Furthermore, pre-deployment calibration or zeroing procedures were performed before each measurement session in accordance with the manufacturer's standard operating procedures. Calibration certificates for all instruments were verified prior to the commencement of the study. Sampling adhered strictly to ICOP-IAQ 2010 spatial protocols, including recommended distances from walls, doors, and floors. The Duo SAS microbial sampler was sterilized between uses with alcohol swabs to prevent cross-contamination. All questionnaires were checked for completeness onsite, and standardized instructions were provided to respondents to enhance response validity. Students were informed that they had the right to refuse to answer any question or to withdraw from the study at any point without penalty. Only questionnaires that were fully completed and submitted with informed consent were included in the final analysis.

Data analysis

Data collected were analyzed using the Statistical Package for the Social Sciences (SPSS) Version 27 and Microsoft Excel Version 2503. Descriptive statistics were performed to summarize and organize the data. Normality of continuous variables was assessed using the Shapiro-Wilk test, with a $p > 0.05$ indicating a normal distribution. Although parametric tests are generally robust to moderate deviations from normality when the sample size is large ($n \geq 30$), non-parametric tests were used for non-normally distributed variables as determined by the Shapiro-Wilk test ($p < 0.05$), to maintain a conservative approach in the analysis of skewed environmental exposure data. Univariate, bivariate, and multivariate analyses were conducted to address each research objective.

For the purpose of association analysis between IAQ parameters and SBS symptoms, continuous IAQ variables were categorized into two groups (high vs. low) using the median value as the cut-off point. This approach was adopted because the data were not normally distributed for several parameters, and the median provides a robust measure of central tendency that is less sensitive to outliers. By dichotomizing the variables based on the median, we were able to perform chi-square and logistic regression analyses to identify significant predictors of SBS symptoms.

Ethical concern

This study was approved by the Ethics Committee for Research Involving Human Subjects of Universiti Putra Malaysia (JKEUPM), with approval reference number JKEUPM–2023–398. All methods were performed in accordance with the relevant guidelines and regulations, including the Declaration of Helsinki. Written informed consent was obtained from all participants prior to questionnaire administration and IAQ monitoring.

Moreover, participation in this study was entirely voluntary and did not interfere with the educational process between lecturers and students. Consent forms were given to be read and signed by them, which were written in both Malay and English language and in simple terms which can be easily understood by the respondents. In the consent forms, there was an explanation of why the study is being done and why the respondents have been asked to participate. There was also a description of what would happen in the course of the study in sequence, with enough detail for the subject to gain a clear idea of what to expect. The consent form also indicated that the respondents had the right to withdraw from the study at any time. Besides that, the respondents were assured of the confidentiality of the findings.

Results

Sociodemographic information

Table 1 presents the socio-demographic characteristics of the respondents. The majority of students were female (66.9%), while 33.2% were male. Most participants were of Malay ethnicity ($n = 107$), and all were single undergraduate students aged between 19 and 24 years. The most represented age group was 22 years (41.5%). In terms of academic programs, the highest proportion was enrolled in the Environmental and Occupational Health with Honors (35.1%), followed by Dietetics with Honors (18.0%), Biomedical Sciences with Honors (15.1%), Medicine (15.1%), Nutrition and Community Health with Honors (11.7) and Nursing (4.9%).

Classroom information

Figures 1 and 2 illustrate the usage patterns and occupancy levels of the classrooms included in the study. Of the six available LHs and twenty TRs at the faculty, three classrooms from each category were selected based on high frequency of student usage during the preliminary site survey.

Figure 1 presents the distribution of classroom population sizes. In LHs (Fig. 1a), most students (69.3%) attended classes with 31–60 students, followed by 21.5% in 61–90 student classrooms, and smaller proportions in other size categories. For TRs (Fig. 1b), the trend was similar, with 57.6% of respondents in 31–60 student

Variable	n (%)
Gender	
Male	68 (33.2)
Female	137 (66.9)
Age	
19	4 (2.0)
20	29 (14.1)
21	48(23.4)
22	85 (41.5)
23	36 (17.6)
24	3 (1.5)
Ethnicity	
Malay	107 (52.5)
Chinese	55 (26.8)
Indian	42 (20.5)
Others	1 (0.5)
Course	
Biomedical Sciences with Honors	31 (15.1)
Dietetics with Honors	37 (18.0)
Nutrition and Community Health with Honors	24 (11.7)
Environmental and Occupational Health with Honors	72 (35.1)
Nursing	10 (4.9)
Medicine	31 (15.1)

Table 1. The socio-demographic information of the respondents. N = 205.

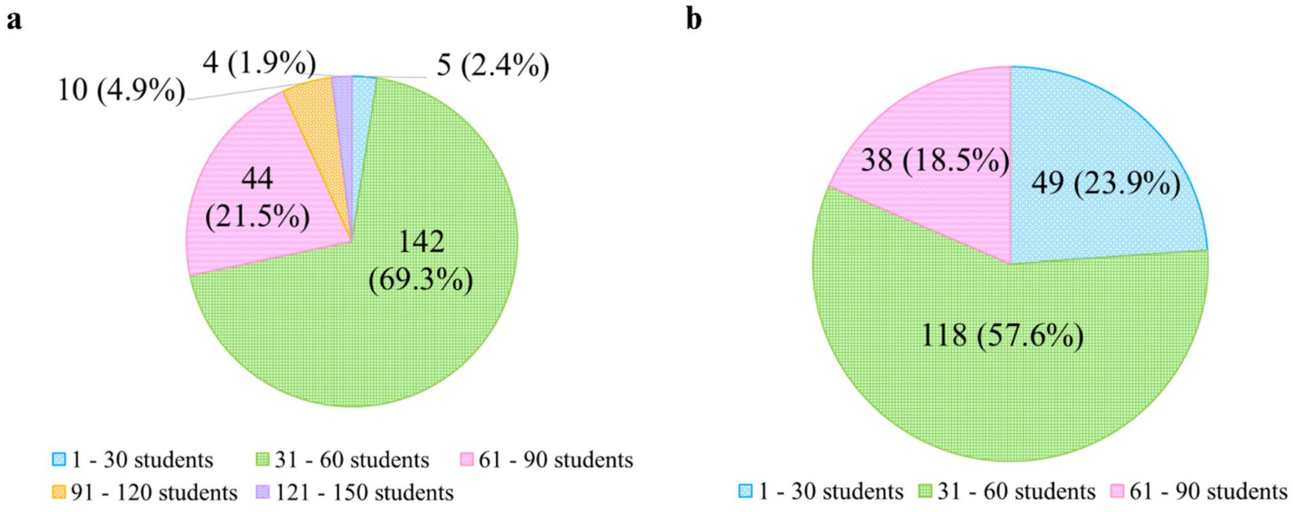

Fig. 1. Distribution of classmates in **(a)** Lecture Halls and **(b)** Tutorial Rooms.

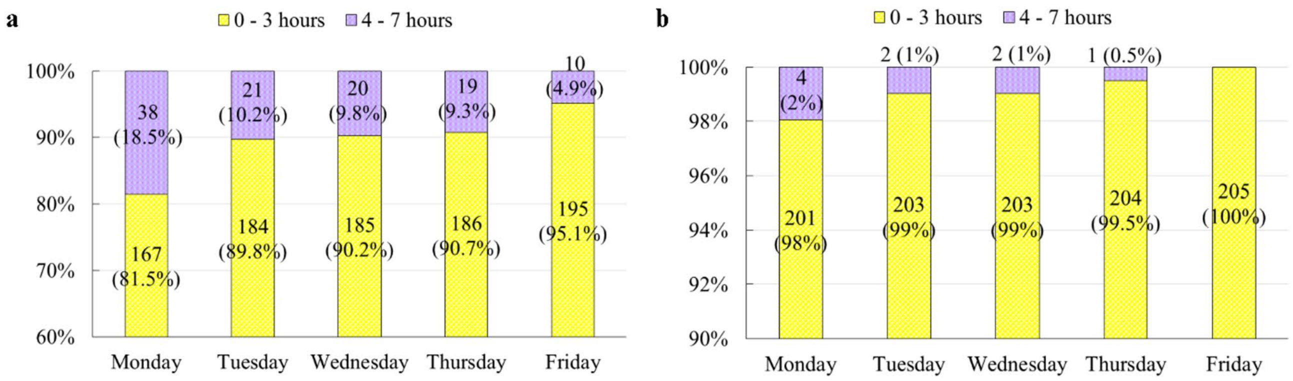

Fig. 2. Total hours spent in **(a)** Lecture Halls and **(b)** Tutorial Rooms.

rooms, 23.9% in smaller classrooms (1–30 students), and 18.5% in classes with 61–90 students. As shown in Fig. 2a, a majority of students reported spending 0–3 h per day in LHs throughout the week, with Friday (95.1%) showing the highest proportion and Monday (81.5%) the lowest. Notably, Monday had the greatest proportion of students (18.5%) spending 4–7 h, suggesting heavier scheduling at the beginning of the week. In contrast, TRs (Fig. 2b) were consistently used for shorter durations, with 98–100% of students reporting 0–3 h of use per day, indicating lighter use and possibly more flexibility in TR scheduling.

Together, these findings confirm that both classroom types were primarily used for shorter daily durations and generally accommodated moderate-sized groups. These usage profiles provide essential context for interpreting the temporal and spatial variability of indoor air quality observed in this study.

Comparison of IAQ measurements between LHs and TRs

Table 2 presents the comparison of IAQ parameters measured in LHs and TRs. IAQ measurements were subsequently evaluated against ICOP-IAQ 2010 guideline limits except $PM_{2.5}$, which has no specific guideline value under ICOP-IAQ 2010. As the Shapiro-Wilk test indicated non-normal data distribution, Mann-Whitney U test was applied. Significant differences between LHs and TRs were observed in $PM_{2.5}$ ($p<0.001$), PM_{10} ($p<0.001$), temperature ($p=0.002$), relative humidity ($p<0.001$), CO ($p<0.001$), and total bacterial count ($p=0.016$). The median levels of $PM_{2.5}$ and PM_{10} were notably higher in LHs compared to TRs. Although carbon dioxide (CO_2) levels did not differ significantly between room types ($p=0.172$), concentrations exceeded the recommended limit of 1000 ppm in TRs (median = 1133.22 ppm). Additionally, the relative humidity in LHs (median = 74.82%) surpassed the ICOP-IAQ 2010 acceptable range of 40–70%.

The temporal and spatial variation of IAQ parameters across LHs and TRs is presented in Fig. 3. Although the measurements were not performed concurrently across all classrooms, all data was collected during a typical academic week, following a consistent monitoring protocol and time schedule under comparable weather conditions. IAQ data were collected at 1-hour intervals over an 8-hour period, excluding lunch hour, in a single day. This interval was selected to balance data resolution with logistical feasibility during active classroom sessions, minimizing disruption to teaching. While this frequency provides a representative profile of daily IAQ

Variables	Locations and Area	Min	Max	Mean	Median	SD	IQR	z	p	ICOP-IAQ 2010	ICOP-IAQ 2010 Compliance
$PM_{2.5}$(μg/m^3)	**LH;** 758.3 m^2	18	52	34	34	9	13	−3.587	**< 0.001***	N/A	N/A
	TR; 65.7 m^2	2	23	11	11	5	6				N/A
PM_{10}(μg/m^3)	**LH;** 758.3 m^2	24	81	51	52	14.6	19	−3.580	**< 0.001***	150 μg/m^3	Yes
	TR; 65.7 m^2	4	44	17	13	12	19				Yes
CO (ppm)	**LH;** 758.3 m^2	0.46	1.33	0.92	0.92	0.27	0.45	−3.373	**< 0.001***	10 ppm	Yes
	TR; 65.7 m^2	0.50	0.78	0.62	0.62	0.08	0.07				Yes
TVOC (ppb)	**LH;** 758.3 m^2	0	0	0	0	0	0	0.000	1.000	3000 ppb	Yes
	TR; 65.7 m^2	0	0	0	0	0	0				Yes
Temperature (°C)	**LH;** 758.3 m^2	22.44	24.70	23.51	23.59	0.54	0.22	−3.046	**0.002***	23–26 °C	Yes
	TR; 65.7 m^2	22.62	26.35	24.36	23.79	1.41	2.87				No
Relative Humidity (%)	**LH;** 758.3 m^2	66.31	80.16	75.15	78.01	5.65	11.77	−3.363	**< 0.001***	40% – 70%	No
	TR; 65.7 m^2	62.80	77.52	69.36	69.29	3.66	3.13				No
Air Velocity (m/s)	**LH;** 758.3 m^2	0.08	0.20	0.17	0.18	0.03	0.04	−1.947	0.052	0.15–0.50 m/s	No
	TR; 65.7 m^2	0.09	0.29	0.19	0.20	0.05	0.05				No
CO_2(ppm)	**LH;** 758.3 m^2	392.78	1919.22	803.60	664.73	393.40	400.37	−2.120	0.075	1000 ppm	No
	TR; 65.7 m^2	479.00	2113.17	1005.83	902.25	436.79	422.37				No
Total bacterial count (cfu/m^3)	**LH;** 758.3 m^2	8	68	38	39	21	37	−2.402	**0.016***	500 cfu/m^3	Yes
	TR; 65.7 m^2	48	312	171	179	111	208				Yes
Total fungal count (cfu/m^3)	**LH;** 758.3 m^2	38	198	96	63	69	131	−1.845	0.065	1000 cfu/m^3	Yes
	TR; 65.7 m^2	92	214	156	162	55	107				Yes

Table 2. IAQ measurement in each of type of classrooms. *Significant at $p < 0.05$; N/A = Not Applicable; SD = Standard Deviation; IQR = Interquartile Range.

fluctuations, it may limit the detection of rapid or transient changes in indoor air parameters. Due to the lack of meaningful variation in certain parameters, TVOC, bacterial count, and fungal count were excluded from trendline visualization but included in tabular analysis. The remaining IAQ parameters are illustrated using trendlines to reveal trends across space and time. To facilitate trendline interpretation, the selected LHs and TRs were labeled as follows: LH-A, LH-B, and LH-C refer to the three selected LHs, while TR-A, TR-B, and TR-C denote the three selected TRs monitored during the study.

Figure 3(a) displays the diurnal variation of $PM_{2.5}$ concentrations (μg/m^3) across the six monitored classrooms. Concentrations in LH-A generally showed a decreasing trend from a peak at 8:00 a.m., while LH-B and LH-C maintained relatively stable, elevated levels throughout the day, with LH-C exhibiting the highest overall concentrations among the lecture halls. In contrast, the TRs (TR-A, TR-B and TR-C) consistently presented lower $PM_{2.5}$ concentrations compared to the LHs (LH-A, LH-B and LH-C), typically remaining below 15 μg/m^3 across the measurement period. TR-A and TR-C showed minor fluctuations, while TR-B remained relatively constant.

Figure 3(b) illustrates the diurnal variation of PM_{10} concentrations (μg/m^3) in the same six classrooms. Similar to $PM_{2.5}$, LH – A began with a high concentration at 8:00 a.m., followed by a noticeable decrease over the morning hours before stabilizing at lower levels in the afternoon. LH – B and LH – C generally exhibited higher and more sustained PM_{10} levels throughout the day, with LH-C again demonstrating the highest concentrations among all rooms for most of the measurement period. The TRs (TR-A, TR-B and TR-C) consistently maintained lower PM_{10} concentrations compared to the LHs (LH-A, LH-B and LH-C), generally staying below 20 μg/m^3. TR-B showed the most stable pattern among the TRs, while TR-A and TR-C presented slight variations during the day.

The trendline for CO concentrations as displayed in Fig. 3(c) presents its diurnal variation across the six monitored classrooms. LH-C generally exhibited the highest CO concentrations throughout the day, showing an increasing trend from 8:00 a.m. to a peak around 3:00 p.m., followed by a slight decrease. LH-B displayed fluctuations, including a peak at 12:00 p.m., while LH-A showed an initial increase followed by a decrease after 10:00 a.m., before stabilizing at lower levels. The TRs (TR-A, TR-B and TR-C) consistently maintained lower CO concentrations compared to the LHs (LH-A, LH-B and LH-C), with levels generally remaining below 0.8 ppm across the measurement period. TR-A, TR-B, and TR-C showed relatively stable patterns, with minor variations throughout the day.

The trendline of indoor temperature (°C) as shown in Fig. 3(d) illustrates its diurnal variation across the six monitored classrooms. TR-C consistently maintained the highest temperatures among all classrooms, generally staying above 26.0 °C throughout the measurement period. LH-A and TR-A exhibited similar initial temperatures at 8:00 a.m., with LH-A showing a decline after 10:00 a.m. and TR-A remaining relatively stable before a slight decrease in the afternoon. LH-B, LH-C, and TR-B generally displayed temperatures between approximately 23.0 °C and 24.5 °C. Overall, most classrooms showed relatively stable temperature profiles across the school day, with minor fluctuations observed.

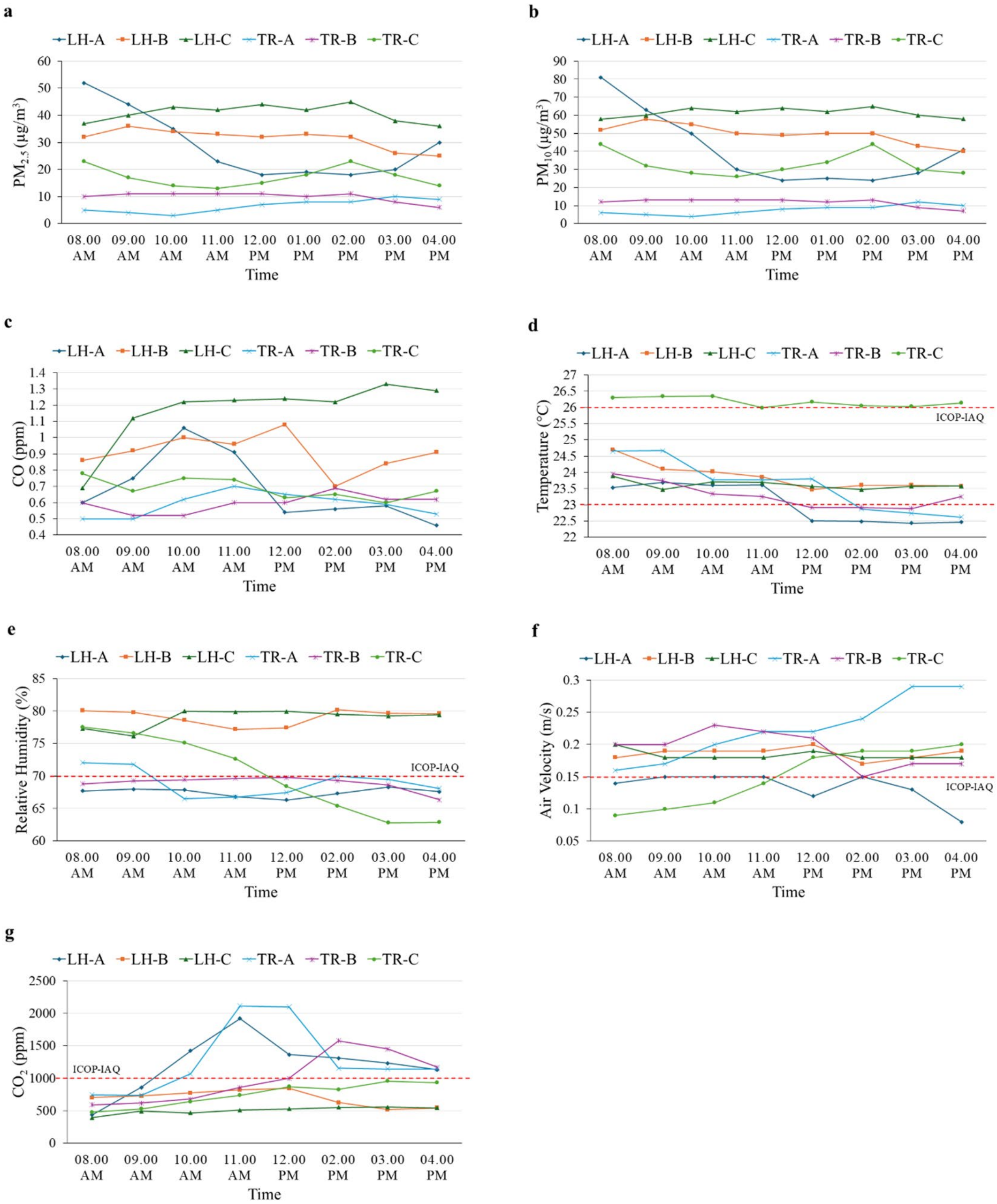

Fig. 3. Trendlines showing spatial and temporal variation in indoor air quality parameters across lecture halls (LH-A, LH-B, LH-C) and tutorial rooms (TR-A, TR-B, TR-C) from 8:00 a.m. to 4.00 p.m. (excluding lunch hour). **(a)** $PM_{2.5}$ (µg/m^3): $PM_{2.5}$ levels were generally higher in lecture halls, particularly in LH-C, exhibiting the highest median concentration across the day. In contrast, tutorial rooms maintained lower concentrations throughout the day, with TR-A showing the lowest $PM_{2.5}$ levels during most time points. **(b)** PM_{10} (µg/m^3): PM_{10} levels were generally higher in lecture halls, particularly in LH-C, exhibiting the highest median concentration across the day. In contrast, tutorial rooms maintained lower concentrations throughout the day, with TR-A showing the lowest PM_{10} levels during most time points. **(c)** CO (ppm): CO levels were generally higher in lecture halls, particularly in LH-C, which exhibited the highest median concentration and persistent elevation throughout the day. In contrast, tutorial rooms maintained lower CO concentrations, with TR-B showing the lowest levels during most time points. **(d)** Temperature (°C): TR-C consistently recorded the highest temperatures across the day. Conversely, LH-A maintained the lowest and most stable temperatures, particularly in the afternoon sessions. **(e)** Relative humidity (%): LH-B and LH-C exhibited consistently elevated relative humidity levels across most time points. In contrast, LH-A recorded the lowest relative humidity levels throughout the day. **(f)** Air velocity (m/s): Tutorial rooms, particularly TR-A, consistently recorded higher air velocity throughout the day. In contrast, lecture halls showed lower and more stable air movement, with LH-A recording the lowest median air velocity. **(g)** CO_2 (ppm): TR-A recorded the highest CO_2 level, while LH-C consistently maintained lower CO_2 concentrations across all time points.

The trendline for relative humidity (%) as illustrated in Fig. 3(e) shows the diurnal variation in moisture levels in the air across the six monitored classrooms. LH-B consistently exhibited the highest relative humidity levels, generally staying around 80% throughout the day. LH-C showed relatively high initial humidity levels, which then declined gradually throughout the day. LH-A maintained levels between approximately 66% and 68%, showing minor fluctuations. The TRs generally displayed lower relative humidity values compared to the LHs. TR-A and TR-B maintained relatively stable levels, typically ranging from 66% to 72%, while TR-C showed a gradual decrease in relative humidity over the measurement period. Overall, relative humidity levels in most classrooms remained relatively stable, with some rooms exhibiting gradual changes throughout the day.

The indoor air velocity (m/s) trendline, as shown in Fig. 3(f) depicts its diurnal variation across the six monitored classrooms. TR-A generally exhibited the highest air velocities, showing a notable increase in the afternoon hours and reaching the highest levels among all rooms by 3:00 p.m. TR-B also showed fluctuations, including a peak at 10:00 a.m. LH-A maintained relatively low air velocities throughout the day, with a significant decrease observed towards the end of the measurement period. LH-B and LH-C generally exhibited stable air velocity profiles, with values remaining between approximately 0.15 m/s and 0.20 m/s for most of the day. TR-C displayed an increasing trend in air velocity from 8:00 a.m., reaching levels comparable to some LHs in the afternoon. Overall, air velocity patterns varied across the different classroom types, with some showing more dynamic changes than others.

The trendline of CO_2 concentrations (ppm) as displayed in Fig. 3(g) presents its diurnal variation across the six monitored classrooms. TR-A exhibited the most dynamic pattern, showing a sharp increase from 8:00 a.m. to a peak exceeding 2000 ppm around 11:00 a.m. and 12:00 p.m., followed by a significant decrease in the afternoon. LH-A also displayed an increasing trend in the morning, reaching high concentrations before declining. TR-B showed a steady increase in CO_2 concentrations throughout the morning, peaking around 2:00 p.m. In contrast, LH-B, LH-C, and TR-C generally maintained lower CO_2 concentrations, typically remaining below 1000 ppm for most of the measurement period. LH-C and TR-C showed relatively stable patterns, while LH-B experienced a slight increase in the morning followed by a decrease in the afternoon. Overall, CO_2 concentrations in some classrooms showed distinct peaks, while others remained comparatively stable.

Prevalence of sick Building syndrome (SBS) symptoms among students in different classroom types

Table 3 presents the prevalence of SBS symptoms among students in LHs and TRs. Of the 205 students assessed per classroom type, 70.2% of students reported experiencing at least one SBS symptom in LHs, compared to 56.6% in TRs. The difference in symptom prevalence between the two classroom types was statistically significant ($p = 0.004$). Figure 4 provides a breakdown of individual SBS symptoms reported in both classroom types. The most frequently reported symptom was fatigue, affecting 90.7% of students in LHs and 76.6% in TRs. This was followed by feeling heavy-headed, reported by 83.4% of LH users and 66.8% of TR users. The least frequently reported symptom in both settings was nausea, at 4.4% in LHs and 5.9% in TRs. Most SBS symptoms showed significant differences between classroom types, except for headache ($p = 0.112$), nausea ($p = 0.502$), and cough ($p = 0.104$), which did not differ significantly between LHs and TRs.

Association between IAQ parameters and SBS symptoms

The association between IAQ parameters and SBS symptoms was examined separately for LHs and TRs, as presented in Tables 4 and 5. All IAQ parameters were dichotomized using their median values for categorical analysis. In LHs, significant associations were observed for several IAQ parameters. Among chemical parameters, elevated carbon monoxide CO (≥ 0.93 ppm) and PM_{10} (≥ 39 μg/m³) concentrations were strongly associated with SBS symptoms ($p < 0.001$), with both showing an odds ratio (OR) of 4.01. Among physical parameters, relative humidity was also significantly associated with SBS symptoms (OR = 2.4, $p = 0.047$). Among biological parameters, elevated total fungal counts (≥ 63 cfu/m³) were significantly linked to SBS symptoms (OR = 4.0, $p < 0.001$), while higher total bacterial counts (≥ 39 cfu/m³) were paradoxically associated with lower odds of SBS (OR = 0.4, $p = 0.003$).

In contrast, only one IAQ parameter, CO_2 concentration was significantly associated with SBS symptoms in TRs (Table 5). Students exposed to higher CO_2 levels (≥ 1133.22 ppm) were 2.5 times more likely to report SBS symptoms (95% CI = 1.36–4.41, $p = 0.003$). Other parameters, including CO, particulate matter, air velocity, temperature, humidity, and microbial counts, did not show statistically significant associations in TRs.

Main predictors of SBS symptoms among students

Table 6 presents the significant predictors of SBS symptoms after adjusting for confounding variables using multiple logistic regression analysis, after adjusting for potential confounders including gender, age, and ethnicity. The model identified that, among students in LHs, high levels of CO, PM_{10}, and total fungal count were

Classrooms	Prevalence of SBS Symptoms N (%)		OR (95% CI)	χ^2	*p*
	Yes	No			
LHs	144 (70.2)	61 (29.8)	181 (1.21–2.72)	8.24	**0.004***
TRs	116 (56.6)	89 (43.4)			

Table 3. Comparison of SBS symptoms between different types of classrooms. $N = 410$, *Significant at $p < 0.05$.

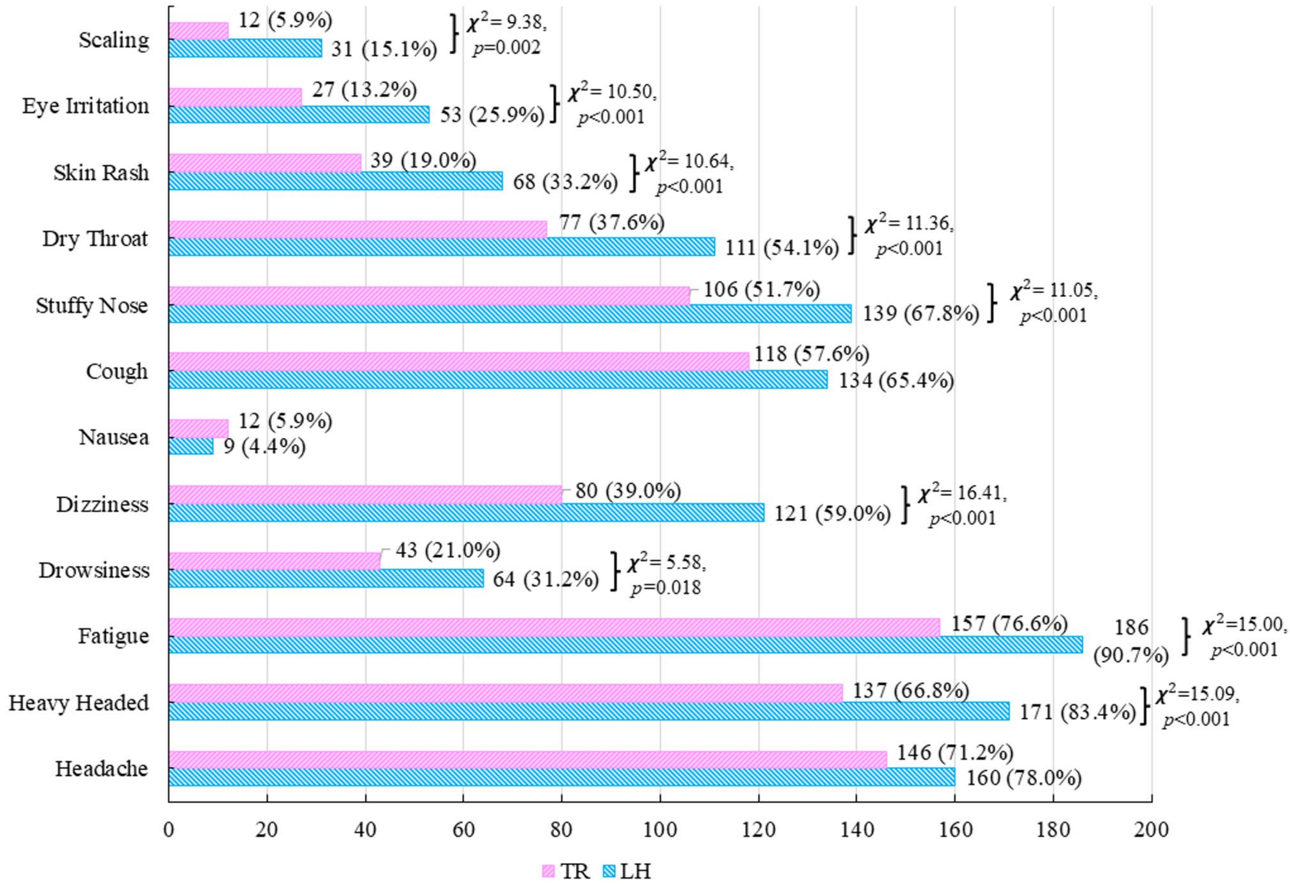

Fig. 4. Prevalence of SBS symptoms, stratified for different types of classrooms.

significantly associated with increased odds of experiencing SBS symptoms. CO was the strongest predictor, with a regression coefficient (B) of 1.55, $p < 0.001$, adjusted odds ratio (AOR) = 4.7, and a 95% confidence interval (CI) of 2.27–9.78. These results suggest that elevated concentrations of these specific indoor air pollutants in LHs are significantly associated with a higher likelihood of SBS symptoms among students. On the contrary, no significant predictor was identified in TRs after adjusting for confounding variables.

Discussion

This study was conducted to assess the association between IAQ and SBS symptoms among students using two types of classrooms, which were LHs and TRs at a Malaysian public university. The results confirmed significant differences in IAQ parameters and SBS symptom prevalence between classroom types, with several environmental factors emerging as predictors of SBS, particularly in LHs.

The socio-demographic profile of the respondents (Table 1) reflects a typical undergraduate population in Malaysian health science faculties, with most students aged 19 to 24 and a majority being female. This aligns with student demographic trends reported by[12]. The largest proportion of respondents were enrolled in the Bachelor of Science in Environmental and Occupational Health with Honors, likely due to their familiarity with environmental health topics and increased willingness to participate in IAQ-related research. While this may have improved questionnaire engagement and comprehension, it also introduces the possibility of response bias, as students with prior exposure to IAQ issues might report symptoms more readily or with greater awareness. To mitigate this, all participants, regardless of academic background had received standardized instructions and information about the study's purpose. Moreover, the questionnaire was self-administered anonymously, and symptoms were evaluated using a frequency-based criterion to reduce the influence of subjective reporting.

Patterns of classroom usage (Figs. 1 and 2) revealed greater student occupancy in LHs, which were structurally larger and more enclosed than TRs. Each LH had four doors, no windows, and was equipped with fixed, cushioned seating arranged in tiered rows. These structural and furnishing features could be associated with pollutant retention and reduce air circulation. All LHs were serviced by centralized air-conditioning systems and cleaned daily in the early morning hours. One of the LHs (LH-C) was situated within 300 m of a major car park, potentially increasing infiltration from outdoor pollutants such as vehicle emissions. In contrast, TRs were considerably smaller instructional spaces. Each TR had two doors, no windows, movable chairs with flip-up desks, allowing for more flexible room arrangements. Like LHs, TRs were centrally air-conditioned and cleaned daily. However, their compact size, limited ventilation surfaces, and high occupant density could be factors in elevated CO_2 levels during peak usage hours. This architectural and functional distinction between LHs and

Variables	Prevalence of SBS ($N = 205$)		OR (95% CI)	χ^2	p
	Yes (%)	No (%)			
Chemical Parameters					
CO_2					
High (≥ 664.73 ppm)	38 (26.4)	12 (24.0)	0.7 (0.33–1.42)	1.05	0.306
Low (< 664.73 ppm)	106 (73.6)	49 (80.30)			
CO					
High (≥ 0.92 ppm)	28 (19.4)	30 (49.2)	4.0 (2.09–7.68)	18.68	**< 0.001***
Low (< 0.92 ppm)	116 (80.6)	31 (50.8)			
$PM_{2.5}$					
High (≥ 34 μg/m³)	106 (73.6)	49 (80.3)	1.5 (0.70–3.04)	1.05	0.306
Low (< 34 μg/m³)	38 (26.4)	12 (19.7)			
PM_{10}					
High (≥ 39 μg/m³)	28 (19.4)	30 (49.2)	4.0 (2.09–7.68)	18.68	**< 0.001***
Low (< 39 μg/m³)	116 (80.6)	31 (50.8)			
Physical Parameters					
Air Velocity					
High (≥ 0.18 m/s)	106 (73.6)	49 (80.3)	1.5 (0.70–3.04)	1.41	0.306
Low (< 0.18 m/s)	38 (26.4)	12 (19.7)			
Relative Humidity					
High (≥ 78.01%)	110 (76.4)	54 (88.5)	2.4 (1.00-5.73)	3.94	**0.047***
Low (< 78.01%)	34 (23.6)	7 (11.5)			
Temperature					
High (≥ 23.59 °C)	106 (73.6)	49 (80.3)	1.45 (0.70–3.04)	1.41	0.306
Low (< 23.59 °C)	38 (26.4)	12 (19.7)			
Biological Parameters					
Total Bacterial Count					
High (≥ 39 cfu/m³)	78 (80.4)	19 (31.1)	0.4 (0.20–0.72)	9.11	0.003
Low (< 39 cfu/m³)	66 (45.8)	42 (68.9)			
Total Fungal Count					
High (≥ 63 cfu/m³)	28 (19.4)	30 (49.2)	4.0 (2.09–7.68)	18.68	**< 0.001***
Low (< 63 cfu/m³)	116 (80.6)	31 (50.8)			

Table 4. Association between IAQ parameters and SBS symptoms in lecture halls. *Significant at $p < 0.05$.

TRs is suggested to influence IAQ profiles through its effects on air exchange rates, pollutant dispersion, and bioaerosol accumulation. These findings are in line with previous studies highlighting the role of room size, layout, and furnishing materials in shaping IEQ and occupant health outcomes[13].

Consistent with previous research[14,15], the present findings demonstrate that larger occupancy and prolonged classroom time showed a correlation with poorer IAQ, particularly in LHs. Table 2 indicates significant differences in $PM_{2.5}$, PM_{10}, CO, temperature, relative humidity, and bacterial counts between the classroom types. $PM_{2.5}$ levels were notably elevated in LHs, which could be influenced by factors such as higher occupancy and greater surface area for particle resuspension due to occupant movement[16]. While TRs recorded lower particulate matter concentrations, this observation should be interpreted cautiously, as the study did not assess potential contributing factors such as surface cleanliness, outdoor infiltration, or cleaning activities prior to sampling. Interestingly, TRs exhibited higher total bacterial counts than LHs. No signs of water damage, active leakage, or visible dampness were observed during the preliminary walkthrough survey, suggesting that the elevated bacterial levels were unlikely to be due to structural moisture issues. It is possible that limited ventilation, smaller room volume, or closer occupant proximity in TRs could have contributed to the higher microbial loads[17], though further targeted studies are needed to elucidate these mechanisms.

To explore spatial and temporal variations, trendlines were employed to visualize trends in IAQ parameters across classrooms and time. $PM_{2.5}$ and PM_{10} levels were consistently higher in LHs, particularly in LH-A during morning hours. This pattern could indicate early accumulation and potentially less efficient air turnover in these spaces[18]. Interestingly, the trendline revealed a pattern of early morning PM accumulation, particularly in LH-A between 8:00 a.m. and 10:00 a.m. While the precise source cannot be determined based on the walkthrough survey, potential contributors could include cleaning activities prior to occupancy, infiltration of outdoor particles during door opening, or limited overnight ventilation. These possibilities were not directly assessed in this study, as outdoor PM monitoring was not conducted. Future investigations incorporating real-time outdoor air quality measurements and observational audits could clarify whether external pollutants or pre-classroom cleaning practices influence indoor PM levels. Although PM_{10} levels remained below the ICOP-IAQ 2010

Variables	Prevalence of SBS ($N = 205$)		OR (95% CI)	χ^2	*p*
	Yes (%)	No (%)			
Chemical Parameters					
CO_2					
High (≥ 902.25 ppm)	30 (42.3)	41 (46.1)	2.5 (1.36–4.41)	9.08	**0.003***
Low (< 902.25 ppm)	86 (74.1)	48 (53.9)			
CO					
High (≥ 0.62 ppm)	39 (33.6)	23 (25.8)	0.7 (0.37–1.27)	1.44	0.229
Low (< 0.62 ppm)	77 (66.4)	66 (74.2)			
$PM_{2.5}$					
High (≥ 11 µg/m^3)	69 (59.5)	64 (71.9)	1.7 (0.96–3.15)	3.41	0.065
Low (< 11 µg/m^3)	47 (40.5)	25 (28.1)			
PM_{10}					
High (≥ 15 µg/m^3)	39 (33.6)	23 (25.8)	0.7 (0.37–1.27)	1.44	0.229
Low (< 15 µg/m^3)	77 (66.4)	66 (74.2)			
Physical Parameters					
Air Velocity					
High (≥ 0.20 m/s)	71 (61.2)	65 (73.0)	1.7 (0.94–3.12)	3.15	0.076
Low (< 0.20 m/s)	45 (38.8)	24 (27.0)			
Relative Humidity					
High (≥ 69.29%)	86 (74.1)	48 (53.9)	0.4 (0.23–0.74)	9.08	0.103
Low (< 69.29%)	30 (25.9)	41 (46.1)			
Temperature					
High (≥ 23.79°C)	39 (33.6)	23 (25.8)	0.7 (0.37–1.27)	1.44	0.229
Low (< 23.79°C)	77 (66.4)	66 (74.2)			
Biological Parameters					
Total Bacterial Count					
High (≥ 179 cfu/m^3)	86 (74.1)	48 (53.9)	0.4 (0.23–0.74)	9.08	0.103
Low (< 179 cfu/m^3)	30 (25.9)	41 (46.1)			
Total Fungal Count					
High (≥ 162 cfu/m^3)	47 (40.5)	25 (28.1)	0.6 (0.32–1.04)	3.41	0.065
Low (< 162 cfu/m^3)	69 (59.5)	64 (71.9)			

Table 5. Association between IAQ parameters and SBS symptoms in tutorial rooms. *Significant at $p < 0.05$.

Types of classrooms	Variables	B	SE	*p*	AOR	95% CI
LHs	CO	1.55	0.37	**< 0.001***	4.7	2.27–9.78
	Relative humidity	0.56	0.51	0.269	1.8	0.65–4.73
	PM_{10}	1.55	0.37	**< 0.001***	4.7	2.27–9.78
	Total fungal count	1.55	0.37	**< 0.001***	4.7	2.27–9.78
TRs	CO_2	0.98	0.33	**0.003***	2.7	1.38–5.09

Table 6. The significant factors that influenced SBS symptoms among the students. Adjusted factors: Gender, Age, Ethnicity. *Significant at $\boldsymbol{p} < 0.05$; B = regression coefficient, SE = Standard error, AOR = Adjusted Odds Ratio, CI = Confidence Interval.

threshold, their persistent presence across the day could be influenced by several factors, such as resuspension from occupant movement, residual particulate matter from early cleaning activities, or infiltration from outdoor sources[19]. However, without direct measurements of surface dust or outdoor PM levels, definitive conclusions regarding dust accumulation or hygiene practices cannot be drawn and these remain potential contributors requiring further investigation. In addition, despite CO levels being well below the 10 ppm ICOP-IAQ 2010 limit, they were significantly higher in LHs, with LH-C registering peak values during late morning hours. These spikes could be indicative of nearby emissions from vehicle traffic or other outdoor sources, given LH-C's proximity to a car park.

Moving on with physical parameters, temperature readings were generally within the acceptable ICOP-IAQ 2010 range (23–26 °C), but TR-C exhibited higher thermal values (median = 26.3 °C), potentially contributing to occupant discomfort. Minor thermal discomfort, especially in warm climates like Malaysia, has been associated with hindered concentration and amplified perceived fatigue[20]. These effects could potentially compound stress in under-ventilated spaces and influence overall academic performance. Moreover, LHs were generally cooler, with LH-A maintaining the lowest average readings, possibly influenced by better airflow. The measured relative humidity values in both classroom types approached or exceeded the ICOP-IAQ 2010 recommended upper threshold of 70%. In particular, the median relative humidity in LHs (78.01%) was outside the permissible range, while TRs recorded a median value (69.29%) just below the limit. Prolonged exposure to elevated humidity levels may foster microbial proliferation and diminish thermal comfort. Fungal spores such as *Aspergillus* and *Penicillium* thrive in humid, cushioned environments[21]. Without proper dehumidification, these bioaerosols could become airborne, potentially leading to respiratory and skin irritation among occupants. Another physical parameter, air velocity data showed slightly higher values in TRs (median = 0.20 m/s) compared to LHs (0.18 m/s), though this was not statistically significant (p = 0.052). Notably, TR-A had the highest afternoon air velocity, possibly attributed to cross-ventilation via open doors or windows. Enhanced air movement is known to improve thermal comfort, especially in warmer rooms like TR-C[22].

CO_2 concentrations, a crude proxy for occupancy and ventilation effectiveness, revealed a contrasting pattern. While LHs maintained CO_2 levels below ICOP-IAQ 2010 thresholds, TRs frequently exceeded 1000 ppm, with TR-A recording a peak concentration above 2100 ppm around midday (11:00 a.m. to 2:00 p.m.), coinciding with the highest classroom occupancy and prolonged student presence. These elevations are indicative of insufficient fresh air supply and suggest that the existing ventilation within TRs might not be adequately accommodating maximum occupancy. Elevated CO_2 levels are widely recognized as an indirect marker of inadequate ventilation, particularly in compact, enclosed environments like TRs[23]. Rather than being problematic on their own, elevated CO_2 concentrations typically signal insufficient ventilation and a potential decline in overall indoor air quality, which has been associated with impaired student well-being and cognitive function, including reduced attention span and slower response times. These physiological and cognitive effects could be particularly relevant.

Additionally, LHs had an area of 758.3 m^2, whereas TRs had an area of 65.7 m^2. Based on observed occupancy during IAQ monitoring, LHs had an average of 60 students per room (≈ 0.08 persons/m^2), while TRs had approximately 30 students per room (≈ 0.46 persons/m^2). This indicates that TRs had a 5.8 times higher occupant density than LHs. The elevated CO_2 levels in TRs could therefore be associated with the limited volume of air per person and insufficient air exchange. These findings suggest the importance of considering occupancy per unit area when assessing IEQ, as room volume alone does not guarantee adequate ventilation without proportional airflow per occupant.

TVOC, bacterial and fungal count data were excluded from the trendline analysis due to limited variation. TVOC concentrations remained at zero or near-detection limits throughout the sampling period. However, bacterial count differences between classroom types remained significant ($p = 0.016$), indicating the need for future investigation. TRs, which are smaller in size, more enclosed, and typically accommodate higher student density per square meter compared to LHs, might experience reduced air circulation and microbial buildup. These conditions, coupled with a lack of windows and lower air velocity observed in some TRs, may contribute to higher bacterial concentrations despite overall lower particulate levels. This contrast further illustrates the complex interplay between classroom size, ventilation efficiency, and microbial exposure, and highlights the need for more granular IAQ surveillance strategies beyond typical chemical parameters.

One of the most widely reported outcomes of poor IAQ is SBS symptoms. SBS symptoms in this study were significantly more prevalent among students in LHs (70.2%) compared to TRs (56.6%) (Table 3). This finding aligns with the theory that greater occupant density and elevated indoor pollutant concentrations in LHs may be associated with adverse health symptoms[24]. As depicted in Fig. 4, fatigue, dry throat, and dizziness were among the most reported symptoms. These are frequently reported in conjunction with prolonged exposure to indoor pollutants such as volatile organic compounds and airborne fungal spores[15]. Since all respondents used both LHs and TRs during their academic schedules, the observed differences in SBS symptoms are more plausibly related to variations in classroom IAQ, rather than inherent differences within the student population between classroom types. The elevated symptom burden among students in LHs further underscores the potential health considerations associated with prolonged exposure to indoor pollutants. Although SBS is not a formal medical diagnosis, it is recognized as a public health concern, especially in institutional settings.

There were significant associations between SBS symptoms and specific IAQ parameters (Tables 4 and 5). In LHs, CO, PM_{10}, relative humidity, and total fungal count were significantly associated with SBS symptoms. These findings are consistent with an earlier study demonstrating that elevated levels of CO and PM_{10} are associated with a range of adverse health outcomes, including headaches, nausea, and mucosal irritation[25], whereas excess humidity can foster fungal growth, which may be related to exacerbation of respiratory or skin symptoms[26]. Although CO levels were below guideline thresholds (< 10 ppm), their associations with SBS symptoms may indicate poor air exchange or presence of combustion sources nearby. These low CO levels might be co-occurring with other unmeasured indoor contaminants or signal inadequate ventilation. In contrast, within TRs, only CO_2 levels were significantly associated with SBS symptoms. Elevated CO_2 is not only a marker of overcrowding but has been reported to be associated with impaired cognitive performance, fatigue, and contribute to a perception of stuffiness[27]. These results highlight the crucial role of ventilation even in smaller rooms, where pollutant buildup may occur quickly during peak periods.

The final objective of this study involved identifying the main predictors of SBS symptoms after adjusting for potential confounders such as age, gender, and ethnicity using multiple logistic regression (Table 6). High levels of CO, PM_{10}, and total fungal count in LHs emerged as strong independent predictors of SBS symptoms ($p < 0.001$, AOR = 4.7, 95% CI: 2.27–9.78). These findings suggest that students exposed to higher concentrations of any one of these pollutants were approximately 4.7 times more likely to report SBS symptoms compared to those with lower exposures. PM_{10} and fungal contamination were also associated with an increased symptom risk, reinforcing the impact of both chemical and biological pollutants in enclosed, high-occupancy classroom environments. On the contrary, in TRs, only CO_2 was identified as a significant predictor ($p = 0.003$, AOR = 2.7). The lack of other significant predictors in TRs could be related to their smaller occupancy loads, potentially shorter exposure durations, or differing ventilation characteristics.

This study offers several strengths, including the application of a validated SBS symptom questionnaire[7], real-time monitoring of multiple IAQ parameters using calibrated instruments[28], and the inclusion of a clearly defined and relevant student population. These methodological choices enhance the credibility and contextual relevance of the findings.

However, several limitations should be noted. One potential limitation of this study is the timing of data collection, which was conducted at the start of the academic semester. While this approach ensured high classroom occupancy and consistent usage patterns critical for capturing real-time indoor environmental conditions, students may have had limited cumulative exposure to these environments. However, as SBS symptoms are typically acute and transient, resolving shortly after leaving the affected space, the short-term exposure captured in this study remains highly relevant and valid for assessing immediate IAQ-related health effects.

Additionally, there is a temporal mismatch between the short-term IAQ measurements (captured over a single day) and the self-reported SBS symptoms, which reflect experiences over the prior week. This discrepancy may limit the precision of direct exposure-outcome associations. However, such structure is common in cross-sectional IAQ-SBS studies[3,29], particularly where indoor environments exhibit relatively stable patterns under controlled usage and air-conditioning regimes.

Another limitation concerns the temporal and procedural aspects of IAQ measurement. This study employed a 1-hour interval for data collection from 8:00 a.m. to 4:00 p.m., which, while potentially missing very short-term fluctuations, aligns with standard practices in indoor environmental research and provides adequate granularity to observe diurnal IAQ trends during school hours. Previous studies, constrained by logistical and technical factors, have similarly adopted hourly or half-hourly intervals for IAQ profiling in classrooms[4,16]. Furthermore, key IAQ parameters such as CO_2 and particulate matter typically change gradually in naturally ventilated or air-conditioned indoor environments, making this interval suitable for capturing peak exposure periods and trends relevant to SBS symptom onset. However, the study relied on a one-day IAQ monitoring period per classroom, which may limit the ability to detect day-to-day variability in environmental conditions influenced by weather patterns, cleaning schedules, or differing classroom usage. Compounding this, IAQ data were not collected concurrently across all rooms, introducing potential variability due to external environmental factors across days. This limitation was partially addressed by conducting measurements under consistent seasonal conditions during routine teaching sessions to reflect typical indoor conditions.

Conclusion

This study provides compelling evidence that IAQ significantly influences the prevalence of SBS symptoms among university students, with notable differences observed between LHs and TRs, attributed to differences in occupancy patterns, room architecture, and ventilation adequacy. Specifically, CO, PM_{10}, and total fungal counts were identified as key predictors of SBS symptoms in LHs, while elevated CO_2 levels were the primary contributor in TRs. These findings underscore the importance of optimizing indoor environments in educational institutions to safeguard student health.

In the Malaysian context, the Industry Code of Practice on Indoor Air Quality (ICOP-IAQ) 2010 provides acceptable limits for several indoor air pollutants and physical parameters. However, certain limitations remain, such as the absence of a specific standard for $PM_{2.5}$ and the lack of differentiated guidelines for educational institutions. While this study adhered to ICOP-IAQ 2010 for evaluation, the results suggest that current thresholds may not fully capture health risks in high-density academic environments, especially under prolonged exposure.

Moving forward, there is a need to update Malaysia's IAQ regulations to reflect current scientific understanding and the specific needs of modern learning environments. This should include setting limits for $PM_{2.5}$ and introducing IAQ standards tailored specifically for classrooms and educational facilities. To support more meaningful comparisons and enhance public health relevance, future studies should consider categorizing classrooms based on their compliance with the ICOP-IAQ 2010, such as labeling rooms as "compliant" or "non-compliant." Doing so would help bridge research outcomes with regulatory priorities, particularly in light of the Occupational Safety and Health (Amendment) Act 2022, which now covers educational institutions. While this study focused on naturally occurring classroom conditions, future research could incorporate a designated low-exposure control room meeting optimal IAQ standards. This would provide a useful baseline for quantifying relative risks associated with suboptimal classroom environments. Additionally, future research should aim to include longer-term monitoring, a wider variety of institutions, and multiple measurement periods to strengthen the evidence base for revising Malaysia's IAQ policies.

Data availability

The datasets generated or analyzed during the current study, including indoor air quality measurements and anonymized survey responses on Sick Building Syndrome symptoms are not publicly available due to privacy and institutional data governance policies, but are available from the corresponding author upon reasonable request.

Received: 11 June 2025; Accepted: 18 September 2025
Published online: 24 October 2025

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Acknowledgements

The authors would like to express their sincere gratitude to the faculty management for granting permission to conduct this study within the academic premises. Appreciation is also extended to the laboratory officers from the Department of Environmental and Occupational Health for their invaluable technical assistance throughout the research process. Finally, the authors wish to thank all student participants for their voluntary involvement and cooperation during the data collection phase. Portions of this study were presented previously in the abstract form at the 13th Asian Aerosol Conference (Kuching, Malaysia, November 3–7, 2024).

Author contributions

K.N.T.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. N.A.M.R.: Formal analysis, Methodology, Validation, Writing – review & editing. N.F.S.: Formal analysis, Methodology, Project administration, Resources, Supervision, Validation, Writing – review & editing.

Funding

This research was self-funded.

Declarations

Competing interests
The authors declare no competing interests.

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