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Assessment of Thermal Environment and Indoor Air Quality in University Buildings under Tropical Climate Conditions

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Abstract

This study developed mathematical models for assessing the ventilation performance of a university lecture hall using thermal indoor air quality indicators, which focused on heat distribution and contaminant removal effectiveness. Ventilation effectiveness was modelled through the heat distribution effectiveness ratio (Et) and contaminant removal effectiveness ratio (Ec), developed from temperature and CO_2 concentration data collected at the supply, exhaust, and breathing zones. Data measurements of temperature, CO_2 concentration, and air velocity were collected across multiple zones during morning and afternoon lecture periods between February and April to capture variations in occupancy and outdoor conditions. Results revealed significant spatial and temporal variations in temperature (21.4–38.9 °C) and CO_2 levels (456–2673 ppm), with higher values typically occurring in the afternoon due to increased occupancy and reduced outdoor air supply. The evaluated Et values (0–1.2) indicated generally poor heat distribution and limited air mixing, while Ec values (0.1–0.7) suggested suboptimal contaminant removal, despite occasional improvements linked to increased outdoor air circulation. Occupancy-based ventilation analysis showed that outdoor air supply per person frequently fell below ASHRAE recommendations, particularly during peak afternoon periods. CONTAM airflow simulations corroborated the mathematical model developed from experimental results, indicating low infiltration rates during high occupancy. Overall, the findings demonstrate inadequate ventilation performance, leading to thermal discomfort and compromised indoor air quality, and underscore the need for improved ventilation strategies in densely occupied lecture halls.

Keywords: IAQ, Thermal Comfort, Ventilation, Building, Airflow, SBS, ACH.

Introduction

The purpose of Ventilation is to induce and distribute outdoor air within a building to maintain healthy indoor air by dilution and removal of pollutants (Awbi, 2003; Etheridge & Sandberg, 1996). Ventilation rate refers to the amount and quality of outdoor air supplied to a space. However, high rates alone may not ensure good air quality if airflow distribution is uneven or exhaust ventilation is inadequate. Effective air distribution ensures pollutants are efficiently removed. Ventilation performance is assessed using airflow patterns, contaminant distribution, and overall ventilation effectiveness. Air leakage occurs when air infiltrates through the building's foundation, exterior walls, roof, doors, and windows, influenced by airtightness and pressure differences. Ventilation effectiveness measures how long air remains in a space and considers pollutant concentrations in supply, exhaust, and breathing zones. Regulations set limits on air contaminant concentration to ensure safe indoor environments.

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Bastide *et al*. (2007) suggested that natural ventilation is preferable to HVAC systems for maintaining comfort in low-energy buildings. The model they developed incorporates a coefficient dependent on the building to enhance Walton's (1984) and Roldan's (1985) models, particularly for large external openings. Their model improved the representation of turbulent airflow near these large external openings. Their study found that the discharge coefficient alone is insufficient for achieving accurate indoor static pressure and realistic mass flow rates. The enhanced model effectively predicts mass flow in cross-ventilated buildings with improved accuracy compared to Computational Fluid Dynamics (CFD) results.

Evola and Popov (2006) noted in their study of CFD projections and comparative analysis of four turbulence models with experimental data that the RNG method showed the best results, with an error of less than 10% between calculated and expected ventilation rates. This suggests that the RNG model is a reliable tool for studying airflow in and around buildings, particularly for wind-driven natural ventilation. Layeni et al. (2020) assessed the thermal comfort (TC) of a lecture hall using CFD to determine passive ventilation and energy-saving potential. They highlighted the importance of passive ventilation methods on Indoor Air Quality (IAQ) for cost-effective improvements. Designing energy-efficient or Zero Energy (ZE) lecture buildings can reduce expenses, and pre-construction analysis helps optimise designs. Janssens et al. (2009) simulated the performance of various ventilation systems in five dwelling types, considering both standard and improved airtightness. The study examined passive ventilation with passive stacks and mechanical ventilation systems. Carbon dioxide was used as a measure of the IAQ, with its concentration analysed based on occupancy schedules. The results were classified according to the European standard EN 13799, which categorises indoor air quality into four levels based on CO_2 concentration.

Yang et al. (2014) reported that buildings consume about 40% of the worldwide energy and are responsible for over 30% of the global CO_2 emissions, with a significant portion used for thermal comfort. The study reviewed thermal comfort research and its impact on energy efficiency. Their study reported that Predicted Mean Vote (PMV) models perform well in enclosed, air-conditioned spaces; however, they are less effective in naturally/passively ventilated buildings, while adaptive models offer broader comfort temperature ranges (ISO7730: 1994). Alamin et al. (2017) explored the challenge of maintaining indoor thermal comfort while optimising energy management. The study introduced a techno-economic model-based predictive control (MPC) system that utilises the day-ahead price (DAP) to estimate energy use in HVAC systems. This approach ensures high thermal comfort while minimising energy use. The system's performance was tested through simulations in a bioclimatic building room under various scenarios. Results demonstrated that the MPC system effectively maintains comfort levels while dynamically adjusting HVAC usage based on DAP, leading to increased energy savings.

Wang et al. (2014) in their study reported that natural ventilation effectively improves indoor air quality and reduces energy consumption, particularly when indoor temperatures are near outdoor conditions such as during transitional seasons in Germany. Their study analytically modelled heat loss caused by open windows and the ventilation effectiveness of the lecture rooms. They examined the impact of thermal buoyancy on airflow, thermal stratification, and contaminant dispersion in a lecture hall. Displacement ventilation was analysed in terms of CO_2 concentration, air supply temperature, and ventilation flow rate. Thermal comfort analysis conducted evaluated the percentage dissatisfaction and differences in temperature between the ankle and head. They noted in their analysis of the Energy efficiency that optimising the ventilation effectiveness ratio can reduce energy demand. Their study also provided a relationship between heat loss and ventilation effectiveness in classrooms.

Fauzi et al. (2024) in their study of the Breathing Architecture (BA) concept, noted that designing indoor spaces to maintain good IAQ faces challenges due to indoor pollutants. Their study examined correlations between IAQ variables and air pollutants. Through content analysis, key variables identified include air-change rate, space size, relative humidity, and indoor-outdoor temperature, which influence pollutant levels and the effectiveness of the Breathing Architecture. Breathing Architecture (BA) is an architectural framework that allows buildings to function as breathable systems by introducing outdoor fresh air to enhance IAQ and thermal comfort via passive ventilation. This is achieved by drawing in air, exhausting indoor pollutants, and facilitating passive cooling (Khdair & Rumman, 2022). Previous studies have demonstrated that controllable passive ventilation can decrease energy demand (Stavridou, 2015), lower indoor CO_2 concentrations (Muelas et al., 2022), and provide additional benefits that closely align with the objectives of the BA concept. Academic discussion on breathing architecture formally emerged in 2014.

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However, earlier works by Stavridou (2015) in 2011, 2013, and 2015 outlined the fundamental parameters of BA, namely: (i) inspiration and relational reasoning, (ii) initial concept development using Computer-Aided Design (CAD) tools, (iii) analytical refinement of concept aimed at optimising building design and spacial layout, and (iv) building form configuration, shape exploration, and other generative design considerations. Overall, BA primarily depends on passive ventilation strategies to supply outdoor air, assisting buildings to ventilate while maintaining a healthy indoor environment.

Despite its relevance, discourse on the BA concept remains limited, as it was only formally articulated in 2017 by Stavridou (2015), and further studies are required to expand and clarify its theoretical and practical foundations. Moreover, the terminology associated with BA is interpreted differently across the literature, leading to conceptual ambiguity. For instance, von Spreckelsen et al. (2015) describe “breathing” as a biomimetic approach for water harvesting through building façades. It has also been interpreted as an interactive relationship between buildings and their surrounding environment, which aligns with Davidová (2021), who reasons that “breathing” extends beyond air exchange to include interactions with climate, landscape, and other living systems. In contrast, Tiderenczl and Matolcsy (Tiderenczl & Matolcsy, 2000) define “breathing” as facilitating indoor air ventilation to improve energy efficiency and remove contaminants, whereas Park et. al. (2016) characterise it as a building component designed to enhance both ventilation and insulation performance. Kalantar and Borhani (2022) describe “breathing” as the ability of a building façade to absorb outdoor air through wind-driven mechanisms. Accordingly, drawing from (Stavridou, 2015) and (Kalantar & Borhani, 2022), “breathing” is defined as a strategy that utilises airflow characteristics—derived from computational and experimental analyses—to optimise the induction of outdoor air through natural ventilation. This emphasises the need of computational or laboratory analysis in effectively applying the BA concept during the design process.

A substantial body of research has employed computational analysis, particularly CFD, as a tool for improving IAQ through system validation (Calautit et al., 2017; Hsu & Tsai, 2020; Zhang et al., 2022) and strategic decision-making (Layeni et al., 2020; Fikry & Elsayed, 2021; Rajkumar et al., 2022). Related studies that align with the objectives of BA have also utilised CFD-based methodologies. For example, Li et. al. (2021) developed an intelligent ventilation control strategy by coupling CFD with a back-propagation neural network (BPNN) and a particle swarm optimiser (PSO), achieving reductions in air pollutants of up to 6.44% and computational costs of up to 23.53%. Similarly, Yuan et al. (2022) applied CFD to model toxic gas leakage and dispersion to evaluate evacuation strategies, a process comparable to the BA approach of using airflow characteristics to inform design decisions. Nevertheless, comprehensive investigations specifically addressing pollutant behaviour and mitigation opportunities within the implementation of the BA concept remain limited, indicating a clear gap for further research.

Budiakova (2019) examines the architectural design of large lecture halls with a focus on air conditioning system requirements. Proper design is crucial for maintaining indoor air quality, ensuring students' comfort, and enhancing their performance. Maintaining acceptable CO_2 levels is essential for both physiological well-being and academic efficiency. Poor ventilation leads to high CO_2 concentrations, causing fatigue and distraction among students. The study evaluates the lecture hall's architectural and mechanical ventilation design. McNeill et al. (2022) noted that Ventilation is crucial for preserving a good IAQ and preventing the spread of airborne diseases like COVID-19. However, while building-level guidelines exist, room-level ventilation data is often lacking in universities and schools. Their study reviewed methods for measuring ventilation, discussing their benefits and limitations. Their findings highlight common trends and differences, demonstrating how ventilation data can inform decision-making for improved indoor air quality. The Walton model, improved by Roldan, is used for analysing airflow in cross-ventilated buildings, accurately predicting mass flow compared to CFD results. This model provides valuable insights into heat and mass transfer in complex or multi-zone buildings. Wang et al. (2014) also explored natural ventilation as a means to enhance indoor air quality, modelling heat loss from open windows and ventilation effectiveness. Their study identified two key parameters for assessing ventilation effectiveness: the ventilation effectiveness ratio for contaminant removal and for heat distribution. These parameters depend on room airflow patterns, room characteristics, heat and pollutant sources, making them essential for evaluating ventilation performance in the study area of this research.

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Studies have also been carried out on building energy performance combining active and passive ventilation systems to achieve better performance (Wang et al., 2014). Chua et. al. (2013) reviewed various innovative designs of cooling technologies and their energy efficiencies, and also various control strategies capable of reducing cooling energy demand by about 33.33% or lower. Tian et. al. (2020) in their study evaluated the overall IAQ by combining air change effectiveness (ACE) and contaminant removal effectiveness (CRE) across 24 experimental scenarios involving different ventilation strategies, air exchange rates, and pollutant source locations. The results show that displacement ventilation and stratified ventilation outperform mixing ventilation in most cases, and that CRE is a more typical indicator than ACE for representing the overall IAQ.

Uneven distribution of air in a building (lecture hall) is an issue even in buildings with high ventilation rates, which may be as a consequence of insufficient exhaust ventilation and/or concentrated flow at specific locations. Furthermore, inadequate control of temperature, humidity, and air movement within a building may cause occupants to obstruct supply points if the air discharged at these points becomes excessively hot or cold, thereby disrupting the intended air flow patterns. This study examines the ventilation performance of a university lecture hall using thermal indoor air quality indicators, focusing on heat distribution and contaminant removal effectiveness and therefore determines the overall ventilation effectiveness.

Materials and Methods

Study Area and Experimental Facility

The study was carried out in the lecture hall in the mechanical department of Olabisi Onabanjo University, College of Engineering, Ibogun campus, Ifo, Ogun state. The lecture hall was selected because it has the largest ventilated teaching space in the department and accommodates a high student population during lecture hours. The lecture hall has a floor area of approximately 177.21 m^2 and an indoor volume of 620.234 m^3. Ventilation within the space is primarily achieved through natural airflow via windows and doors positioned along the building envelope. The hall operates most of the time without mechanical ventilation systems due to a shortage of power supply, making it suitable for evaluating natural ventilation effectiveness under tropical climatic conditions. Figure 1 shows the lecture hall during a class. The investigation focused on indoor thermal conditions, airflow characteristics, and indoor air quality indicators during lecture periods. The data, such as temperature, CO_2concentration and air flow velocity, are measured.

Measurements and Instrumentation

The indoor environmental measurements were conducted using portable monitoring instruments. Air temperature and air velocity were measured using a digital peak meter/anemometer with an accuracy of ± 0.5°C and 0.5 °C and 0.5% (Figure 2). A TIM10 CO_2 meter was also used to measure the concentration of CO_2 in the hall in parts per million (ppm) (Figure 2).

Figure 1. *Lecture in session in the Lecture hall*

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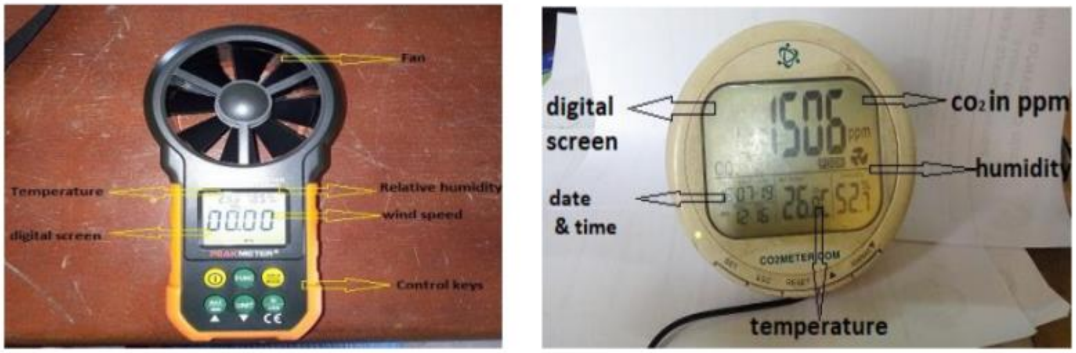

Figure 2: *(a) Digital peak meter* *(b) TIM10 CO_2 meter*

Measurements were obtained from multiple zones within the lecture hall, including

- Window regions,
- Door openings,
- Breathing zone,
- Central occupied zone,
- Ambient outdoor environment

The selected measurement locations enabled evaluation of contaminant transport and thermal distribution within the occupied region of the hall.

Data collection

Environmental data were collected over three months from February to April. Environmental parameters measurements were taken twice daily during lecture periods:

1. Morning session,
2. Afternoon/evening session.

The data collected consists of CO_2 concentration (ppm), Indoor air temperature (°C), Airflow velocity (m/s), and Occupancy level (number of students).

Outdoor environmental conditions, including ambient temperature, wind speed, atmospheric pressure, relative humidity, and dew-point temperature, were obtained for the study and used as boundary conditions for the airflow simulation.

Mathematical Modelling of Ventilation

The ventilation performance of the Lecture hall was modelled using a thermo-fluid and contaminant transport model based on airflow mechanics, contaminant removal effectiveness, thermal comfort, and ventilation efficiency.

The developed model integrates the airflow through openings, CO_2 contaminant transport, and heat balance within the lecture hall. Other parameters integrated are ventilation effectiveness indices, occupancy-dependent ventilation demand, and thermal comfort prediction

Assumptions for the Mathematical Model

The lecture hall ventilation model developed is based on the following assumptions: airflow is transient and incompressible, indoor air is perfectly mixed within each zone, CO_2 generated indoors is mainly from occupants, heat gain is caused by occupants, solar radiation, infiltration, and equipment, airflow through doors and windows follows the power-law relationship, outdoor environmental conditions remain uniform during each measurement period, and ventilation effectiveness depends on the temperature distribution and contaminant transport.

Airflow through Openings

The modified Walton bi-directional airflow model for large openings was used to model the airflow through doors and windows. The airflow induced by pressure differences between indoor and outdoor environmental conditions was estimated with the model. The airflow rate through the openings is expressed by Equation 1:

$$\dot{m} = \rho c_d \frac{s}{2} \sin(\Delta p_{\frac{5}{8}h}) \left|\Delta p_{\frac{5}{18\,h}}\right|^{1/2} + \rho c_d \frac{s}{2} \sin((\Delta p_{\frac{13}{18}h}) \left|\Delta p_{\frac{13}{18\,h}}\right|^{1/2} \qquad 1$$

where m is the airflow rate, C_d is the discharge coefficient, ρ is air density, s is the opening area (m^2), ΔP is the pressure difference across the opening (Pa), and h is the opening height (m). This equation governs passive ventilation through the lecture hall openings.

Artificial Pressure Difference Model Developed Using the Inverse Problem Method

CFD value of the mass flow rate $\dot{m}$ is used. The inverse pressure difference is given by Equation 2:

$$\partial\rho_{CFD} = \sin(\dot{m}_{CFD}) \left(\frac{2\dot{m}_{CFD}}{C_d\ \rho s}\right)^2 \qquad 2$$

Modelling the Building Pressure Coefficient C_B for Each Small Opening in the Walton Model

The mathematical models, Equations 3 and 4, are developed by allowing for the surface pressure of the facade (C_P) and the mass flow rate through ∂P_{CFD}.

$$C_{B,top} = \frac{\partial P_{CFD,top}}{1/2\rho V^2 out(H + \frac{13}{8}h)} + C_p \qquad 3$$

$$C_{B,bottom} = \frac{\partial P_{CFD,bottom}}{1/2\rho V^2 out(H + \frac{5}{18}h)} + C_p \qquad 4$$

Power Law Ventilation Model

The infiltration airflow through cracks and openings follows the CONTAM power-law model (Equations 5 and 6).

Volumetric Airflow Rate

$$Q = C(\Delta P)^n \qquad 5$$

$$F = C(\Delta P)^n \qquad 6$$

where: Q is the volumetric airflow rate (m^3/s), F is the mass airflow rate (kg/s), C is the flow coefficient, ΔP is the pressure difference, and n is the flow exponent (0.65 from CONTAM data). Equation 5 becomes

$$Q = C(1.5)^{0.65} \qquad 5b$$

which is the infiltration into the lecture hall.

CO_2 Mass Balance Model

The indoor CO_2 concentration is governed by a transient contaminant conservation equation.

General CO_2 Balance Equation

$$V\frac{dC_i}{dt} = Q(C_o - C_i) + G \qquad 7$$

Where V is the lecture hall volume (620.235 m^3), C_i and C_o are the indoor and outdoor CO_2 concentrations (ppm), Q is the ventilation airflow rate, and G is the indoor CO_2 generation rate from occupants.

At steady state, Equation 7 becomes:

$$Q = \frac{G}{C_i - C_o} \qquad 8$$

Since occupant density strongly affects afternoon CO_2 values, the generation terms become:

$$G = N_p g_c \qquad 9$$

where N_p is the number of occupants and g_c is the CO_2 generation rate per person.

Hence, Equation 8 becomes,

$$Q = \frac{N_p g_c}{C_i - C_o} \qquad 10$$

This equation directly shows the relationship of the occupancy to the required ventilation rate.

Air Change Rate (ACH)

The ventilation rate in the lecture hall is expressed using air changes per hour (ACH), given below:

$$n = \frac{60Q}{V} \qquad 11$$

where n is the air change rate per hour, Q is the airflow rate (cfm) and V the volume of the lecture hall.

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Ventilation Effectiveness Model

Heat Distribution Effectiveness

The ventilation effectiveness for thermal distribution is given by Equation 12:

$$E_t = \frac{T_{exhaust} - T_{supply}}{T_{breathing} - T_{supply}} \qquad 12$$

where $T_{exhaust}$ is the exhaust air temperature, T_{supply} the inlet air temperature, and $T_{breathing}$ the breathing zone temperature.

E_t greater than 1implies a highly effective ventilation, while a value lower than 0.5 implies poor air distribution. However, an E_t value approximately equal to 1 means there is good air mixing within the hall. From the study, E_t values range from 0 to 1.2, indicating unstable thermal air mixing caused by occupancy fluctuations and inadequate airflow distribution.

Contaminant Removal Effectiveness

$$E_c = \frac{C_{exhaust} - C_{supply}}{C_{breathing} - C_{supply}} \qquad 13$$

where $C_{exhaust}$ is the exhaust CO_2 concentration, C_{supply} is the supply CO_2 concentration, and $C_{breathing}$ is the breathing zone CO_2 concentration. From the study, E_c had a morning peak of 0.5 and an afternoon peak of 0.7, and the minimum value of 0.1. The lower values indicate poor contaminant extraction and short-circuiting airflow patterns.

Empirical Relationship between Temperature and Ventilation Effectiveness

From the data collected from the study, empirical regression models were developed between the supply temperature and ventilation effectiveness.

For the contaminant removal effectiveness model (Equation 14):

$$E_c = aT_s + b \qquad 14$$

where T_s is the supply air temperature and a and b are regression constants. Similarly, for heat distribution model (Equation 15):

$$E_t = cT_s + d \qquad 15$$

Based on the observed trends, an increase in the indoor temperature reduced the ventilation effectiveness. The increase in the indoor temperature is a consequence of high occupant density, which increased the thermal load and CO_2 accumulation.

This implies that E_c is inversely proportional to the product of the number of occupant N_p and the indoor temperature T_i. $E_c \propto 1/N_pT_i$. Also, E_t is directly proportional to the airflow rate Q and inversely proportional to the occupancy N_p, $E_t \propto Q/N_p$.

Thermal Comfort Model

The thermal comfort in the lecture hall is modelled using the Fanger's Predicted Mean Vote (PMV) model as shown in Equation 16.

$$\mathrm{PMV} = [0.0303\exp(-0.036\mathrm{M}) + 0.028\mathrm{L}] \qquad 16$$

where M is the metabolic rate and L is the thermal load. The dissatisfaction percentage is given by the Predicted Percentage of Dissatisfied (PPD), Equation 17.

$$\mathrm{PPD} = 100 - 95 \times \mathrm{EXP}(-0.03353\mathrm{PMV}^4 - 0.219\mathrm{PMV}^2) \qquad 17$$

The observed lecture hall temperatures range was$31.4^oC \leq T \leq 38.9^oC$, indicating thermal discomfort conditions beyond ASHRAE comfort limits.

Integrated Dynamic Ventilation Model

Combining airflow, contaminant transport, and heat transfer yield the complete lecture hall ventilation model given by Equations 18 and 19.

$$m_a c_p \frac{dT_i}{dt} = Q_{glass} + Q_{HVAC} + Q_{vent} + Q_{Conv} + Q_{gain} + Q_{inf} \qquad 18$$

and simultaneously,

$$V\frac{dC_i}{dt} = Q(C_o - C_i) + N_p g_c \qquad 19$$

This coupled model predicts the indoor temperature evolution, CO_2 concentration, ventilation effectiveness and occupant thermal comfort under varying occupancy and environmental conditions.

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Final Developed Ventilation Model for the Lecture Hall

The overall ventilation performance of the lecture hall is therefore represented as:

$$VE = f(Q, \Delta P, N_p, T_i, C_i, V_{wind}, RH) \qquad 20$$

where VE is the ventilation effectiveness, Q airflow rate, ΔP pressure difference, N_p occupancy, T_i indoor temperature, C_i indoor CO_2 concentration, V_{wind} wind speed and RH is the relative humidity.

This gives, using dimensional analysis Equation 21:

$$VE = k\frac{Q}{N_p T_i C_i} \qquad 21$$

where k is an experimentally determined proportionality constant.

The developed model demonstrates that ventilation effectiveness in the lecture hall depends strongly on:

1. Occupancy density
2. Indoor thermal load
3. Natural airflow through openings
4. Pressure-driven infiltration
5. CO_2 accumulation patterns
6. Building geometry and airflow path distribution

The model further confirms that although the airflow rate approached ASHRAE recommendations, ineffective airflow distribution reduced actual ventilation performance inside the occupied zone. Table 1 shows the ASHRAE Standard 62.1-2007 [32] air change rates for Educational spaces.

Table 1: Outdoor Air Requirements for Ventilation in Institutional Facilities
(ASHRAE Standard 62.1-2007)

Application (Education)	Cfm per person	L/S
Classroom	15	8
Auditorium	15	8

CONTAM Simulation

Multizone airflow simulation was performed using CONTAM software developed by the National Institute of Standards and Technology. The indoor air quality and ventilation analysis simulation tool simulated airflow rates, infiltration, and room-to-room airflow rates in the building system (Figure 3). The lecture hall geometry, opening characteristics, pressure coefficients, and weather parameters were incorporated into the simulation environment. The airflow simulation parameters are as shown in Table 2.

Table 2: CONTAM Air flow simulation parameters

Zone Details	Flow Element	Temperature Schedule	Contaminant Data
volume- 620.235 m^3 floor area- 177.21 m^2 temperature- 25(Celsius)	Area- 0. 0302 m^2/m^2 flow exponent- 0.65 discharge coefficient- 1 pressure difference- 1.5pa	12 days(variable)	CO_2-400ppm

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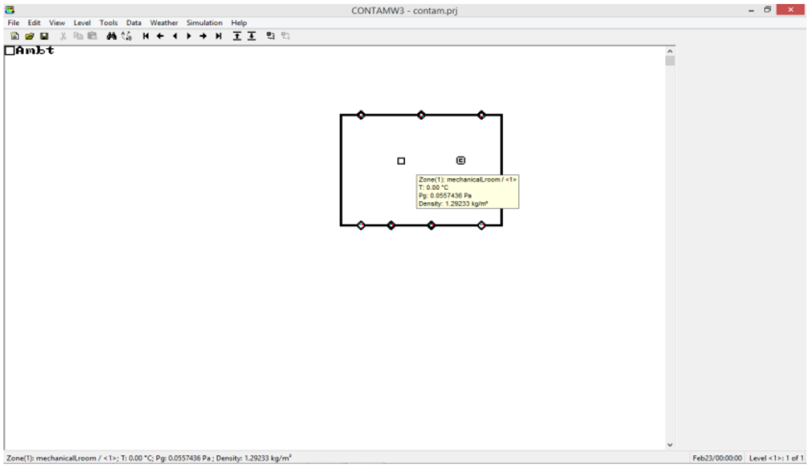

Zone(1): mechanicalLroom / <1>
T: 0.00 °C
Pg: 0.0557436 Pa
Density: 1.29233 kg/m³

Zone(1): mechanicalLroom / <1>; T: 0.00 °C; Pg: 0.0557436 Pa ; Density: 1.29233 kg/m³ Feb23/00:00:00 Level <1>: 1 of 1

Figure 3. The modelled lecture hall for the simulation on CONTAM Interface

Results

The measured CO_2 concentrations within the lecture hall vary significantly with the occupancy level and time of measurement. Lower contaminant concentrations were generally observed during the morning lecture periods, which is a result of lower occupancy, while higher CO_2 accumulation during the afternoon periods is due to increased student population in the lecture and consequently reduced ventilation effectiveness. The average ambient CO_2 concentration in February was approximately 456 ppm, while the average indoor concentration values were as high as 1435 ppm. The indoor CO_2 levels increased further in March, with values between 801 ppm and 1706 ppm during the morning periods and a recorded peak concentration exceeding 2500 ppm in the afternoon at some points within the lecture hall. The increase in contaminant concentration implies inadequate contaminant removal during peak occupancy periods. ASHRAE (2020) IAQ recommendations for indoor CO_2 concentration should be below 1000 ppm, and above this limit indicates inadequate ventilation conditions. Several data collected during this study exceeded this limit, indicating poor IAQ within the lecture hall. The increase in CO_2 concentration was strongly influenced by the increase in student population and inadequate airflow distribution within the lecture hall.

Table 3 presents CO_2 concentrations (ppm) and temperatures (°C) across different zones within the lecture hall where data were collected, including the windows, doors, podium, middle zone, and ambient conditions. Data were collected in the morning and afternoon lecture periods, with fewer students attending lectures in the morning compared to the afternoon periods.

Table 4 shows the separation of the morning and afternoon data to clarify the average values used in calculating the ventilation effectiveness ratio for heat distribution. These values include the supply temperature, exhaust temperature, and temperature in the breathing zone. In Table 5, the morning and afternoon data were separated to clarify the average values used in calculating the ventilation effectiveness ratio for contaminant removal. These values include C_o, C_i, and the breathing zone contaminant concentration. A gradual decrease in temperature values was observed from February to April (Table 6). These values help assess the ventilation effectiveness for heat distribution, providing insights into how efficiently airborne pollutants are removed from the lecture hall. Fluctuating values were observed from February to April (Table 7). These measurements help assess the ventilation effectiveness for contaminant removal, providing insights into how efficiently airborne pollutants are being eliminated from the lecture hall. Table 8 shows the outdoor conditions on the days on which data were collected. Tables 9 and 10 show the ventilation rate in the lecture hall on an occupancy basis, according to ASHRAE standard, which states ventilation (outdoor air) requirements on an occupancy basis, which was developed for the purpose of preventing indoor air quality problems. The developed model from the experimental data collected predicted indoor CO_2 concentrations ranging ,approximately between $840.5ppm \leq C_i \leq 2673.3ppm,$ particularly during the afternoon occupancy peaks. According to ASHRAE standard 62.1 (2007), indoor CO_2 concentrations above 1000 ppm indicate inadequate ventilation, while acceptable classroom ventilation usually maintains concentrations between 600 – 1000 ppm. The present study recorded indoor CO_2 levels between 840 and 2673, which, on average, resulted in poor air quality within the lecture hall, which also was a consequence of high occupancy in the hall. Other studies have also reported similar data with Seppänen *et al.* (1999) presenting CO_2 concentrations between 800 – 3000 and Clements-Croome (2008) with a result of 700 – 2000, which reduced occupant comfort. Satish *et al.* (2012) also presented CO_2 concentrations between 1000 – 2500 and further observed a reduction in cognitive performance. This implies that the developed model agrees strongly with previous classroom ventilation studies as CO_2 concentration increased with occupancy, afternoon lectures produced the worst indoor air quality, and noted that natural/passive ventilation alone becomes insufficient at high occupant density. This implies that the contaminant transport component of the model is validated.

Discussion

Ventilation Effectiveness for Contaminant Removal (E_c)

The study obtained a model result for Ventilation effectiveness for contaminant removal between $0.1 \leq E_c \leq 0.7$, which indicates poor to moderate air mixing within the hall. Similar studies by Awbi (2003), Etheridge & Sandberg (1996) and Mundt (2004) presented results of 0.5 – 1.0, 0.4 -1.2, and 0.6 – 1.4, respectively. The developed model predicts lower E_c values than optimised displacement ventilation systems, which is expected as the lecture hall relied largely on natural ventilation, airflow short-circuiting occurred near openings, and occupant density disrupted contaminant removal. The model results therefore is physically realistic and consistent with naturally ventilated educational buildings.

Heat Distribution Effectiveness (E_t)

The experimental results showed that E_t is between $0 \leq E_t \leq 1.2$, where E_t less than 0.5 indicates poor heat distribution, E_t greater than 1 implies displacement-type effectiveness, and approximately 1 implies adequate thermal mixing and thermal satisfaction within the lecture hall. The results obtained showed that increased occupancy generated substantial internal heat gain, particularly during the afternoon lecture sessions. Similar studies by Li *et al.* (2011) reported E_t range between 0.3 – 0.9 under a cross ventilation situation, while Chen & Glicksman (2003) with a range of 0.6 – 1.1 studied hybrid ventilation system. The lecture hall model developed produced values comparable to naturally ventilated and hybrid building. The periods where E_t tends towards zero imply high thermal condition and poor air distribution, which is what has been observed in crowded classrooms reported in previous studies.

Airflow/Infiltration Model

The developed airflow model used the power-law relationship with n as 0.65, which agrees with established airflow network modelling approaches (CONTAM/NIST standard, 0.65; ASHRAE Fundamentals, 0.60 – 0.70).

Thermal Comfort Analysis

The measured indoor temperatures were $31.4\,^{o}C \leq T_i \leq 38.9\,^{o}C$, however, ASHRAE thermal comfort recommendations for classrooms are approximately $23\,^{o}C \leq T_i \leq 27\,^{o}C$. This indoor temperature range significantly exceed the recommended thermal comfort limits for educational buildings. The elevated temperatures were due to the high occupancy, inadequate airflow circulation, tropical ambient conditions, and limited air exchange effectiveness. The high indoor temperature levels indicate that the available natural ventilation was insufficient to offset internal thermal loads generated by occupants and surrounding environmental conditions. Fanger (1970) stated that the Comfort Zone should be between 22 ^{o}C 26 ^{o}C. The simulated airflow trends are consistent with standard multizone airflow simulations. The transient airflow fluctuations also agree with wind-driven natural ventilation theory.

Outdoor Air Ventilation Rate

The estimated outdoor air percentages varied substantially between morning and afternoon sessions. Morning outdoor air percentages ranged between 20% and 60%, while the afternoon values decreased significantly to between 1% and 17%. The reduced outdoor air contribution during the afternoon sessions indicates insufficient fresh air penetration into the lecture hall under high occupancy conditions. Although the calculated airflow supply approached the ASHRAE requirement of 15 cfm/person, the actual distribution of the outdoor air within the lecture hall remained ineffective. This demonstrates that satisfying nominal airflow requirements alone does not guarantee acceptable indoor air quality if the airflow distribution within the occupied zone is inadequate.

CONTAM Airflow Simulation

The CONTAM simulation results revealed transient airflow infiltration patterns within the lecture hall. In February, infiltration airflow rates increased gradually during the afternoon, reaching approximately 0.17 L/s before decreasing during evening periods. In April, airflow infiltration rates increased slightly to approximately 0.18 L/s, indicating improved outdoor airflow penetration caused by varying weather conditions. The simulation further revealed that the

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airflow distribution within the lecture hall was highly dependent on the wind speed, outdoor temperature, pressure differentials, and opening configuration, as expected. Despite periods of increased infiltration, the airflow rates remained below the ventilation requirement needed for effective contaminant removal under high occupancy conditions. The simulation findings therefore support the experimental observations of inadequate ventilation effectiveness and elevated indoor contaminant accumulation.

Developed Ventilation Model

The mathematical model so developed shows good agreement with previous studies of ventilation and IAQ as shown above. The projected airflow, contaminant concentration, and thermal comfort were consistent with previous studies on naturally/passively ventilated educational buildings. The model successfully estimated the occupancy-driven CO_2 accumulation. It also shows the rate of temperature increase within the occupied zones and the reduction in ventilation effectiveness when the hall is overcrowded. The correlation between the experimental data, analytical data, and CONTAM simulations confirms the suitability of the developed model for evaluating performance in naturally/passive ventilated lecture halls located in the tropics.

Table 3. The average values for the CO_2 concentration and temperature for the zones in the lecture hall.

Date	Time	No. of Students	Measurement	AMB.	WIN.1	WIN.2	WIN.3	WIN.4	WIN.5	PODIUM	F DOOR	B DOOR	MID.1	MID2
23/02/2023	10:30am	109	CO2 (PPM)	456	1435	1187	1008	720	739	683	629	1015	1705	1644
23/02/2023	10:30am	109	TEMP (°C)	26.6	32.2	32.6	32	32.1	32	32	32	32	33	32.7
23/02/2023	2pm	145	CO2 (PPM)	745	1212	1070	1200	1156	1099	1065	1001	1650	1711	1950
23/02/2023	2pm	145	TEMP (°C)	32.7	34	34.1	34.5	34.7	34.3	34	33.5	34	35	35
27/02/2023	11AM	120	CO2 (PPM)	560	1250	1050	1200	987	1600	968	1000	1001	1906	1961
27/02/2023	11AM	120	TEMP (°C)	28	32.6	32	32.4	31.5	32	32	31	32	32.7	33
13/3/2023	10am	160	CO2 (PPM)	685	878	808	854	822	866	801	798	1065	1685	1706
13/3/2023	10am	160	TEMP (°C)	25.9	31.6	31	31.2	32.1	31	31	31	32	32.6	32.8
13/3/2023	1:30PM	250	CO2 (PPM)	985	2035	2506	2511	2618	2621	2016	2008	2718	2738	2881
13/3/2023	1:30PM	250	TEMP (°C)	35	37.1	37	37	36.9	37	37	37	37.9	38	38.3
14/03/2023	11AM	123	CO2 (PPM)	560	1252	1115	1205	987	1600	1067	968	1001	1926	1961
14/03/2023	11AM	123	TEMP (°C)	27.9	32.6	32	32.4	31.5	32.7	32	32.6	32	32	32
14/03/2023	2:45PM	225	CO2 (PPM)	968	2210	2316	2316	2418	2500	2201	2811	2201	2901	2918
14/03/2023	2:45PM	225	TEMP (°C)	34.6	37.1	38.4	37.2	37.1	38.6	37.4	37.1	37.6	39.6	39.8
4/4/2023	8am	149	CO2 (PPM)	465	845	765	963	865	872	782	766	986	1232	1500
4/4/2023	8am	149	TEMP (°C)	26	27.2	27.1	27.6	27.3	27.3	27.1	27.1	27.1	28.2	28.6
4/4/2023	2pm	206	CO2 (PPM)	567	1945	1862	1927	1966	1998	1902	1946	1967	2010	2101
4/4/2023	2pm	206	TEMP (°C)	28.5	30.1	30.1	30	30.2	30.6	30.1	30.2	30	31.6	31.8
12/4/2023	10:50am	135	CO2 (PPM)	768	1250	1050	1200	987	1600	968	1000	1006	1909	1982
12/4/2023	10:50am	135	TEMP (°C)	27.1	32.6	32	32	31.5	32	31	32	32	32.8	33
12/4/2023	3pm	242	CO2 (PPM)	896	2095	2001	2178	2199	2216	1998	1989	2460	2498	2560
12/4/2023	3pm	242	TEMP (°C)	27.6	32.6	36.9	37	36.9	37	36.6	36.2	37	37.6	36.2

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Table 4. The average values of temperature from February to April

Inlet temperature	23-Feb	27-Feb	13-Mar	14-Mar	4-Apr	12-Apr
morning(°c)	31.7	31.9	31.4	32.2	21.4	31.5
afternoon(°c)	34.5	35.9	36.9	37.6	30.2	36
Outlet temperature	23-Feb	27-Feb	13-Mar	14-Mar	4-Apr	12-Apr
morning(°c)	32.2	31.8	31.4	32.3	27.4	32.3
afternoon(°c)	33.9	36.3	37.2	37.6	30.5	36.8
Breathing temperature	23-Feb	27-Feb	13-Mar	14-Mar	4-Apr	12-Apr
morning(°c)	32.6	32.6	32.1	32.6	28.1	32.6
afternoon(°c)	34	36.9	37.8	38.9	31.1	36.9

Table 5. The average values CO_2 concentration from February to April

CO_2 outlet	23-Feb	27-Feb	13-Mar	14-Mar	4-Apr	12-Apr
morning(ppm)	1066.5	1075.3	887.3	1084	840.5	1076.5
afternoon(ppm)	1233.3	1926	2437	2384.5	1930	2136.3
CO_2 inlet	23-Feb	27-Feb	13-Mar	14-Mar	4-Apr	12-Apr
morning(ppm)	822.3	1897.7	847.3	1264	900	1262.3
afternoon(ppm)	115.7	1262.3	2580.7	2411.3	1963.7	2197.7
CO_2 breathing zone	23-Feb	27-Feb	13-Mar	14-Mar	4-Apr	12-Apr
morning(ppm)	1344	1611.7	1397	1651	1171.3	1619.7
afternoon(ppm)	1575.3	2072	2545	2673.3	2006.3	2352

Table 6. The average ventilation effectiveness ratio for heat distribution

E_t values	23-Feb	27-Feb	13-Mar	14-Mar	4-Apr	12-Apr
Morning	0.6	0.1	0	0.3	1.2	0.7
afternoon	1.2	0.4	0.3	0	0.3	0.9

Table 7. The average ventilation effectiveness value for contaminant removal

E_c values	23-Feb	27-Feb	13-Mar	14-Mar	4-Apr	12-Apr
morning	0.5	0.5	0.1	0.5	0.2	0.5
afternoon	0.2	0.2	0.4	0.1	0.7	0.4

Table 8. The average outdoor air (in percent) for both morning and afternoon

Outdoor air (in %)	23-Feb	27-Feb	13-Mar	14-Mar	4-Apr	12-Apr
morning	40	36	20	34	20	60
afternoon	17	20	1	2	3	5

Table 9. The model estimates of the ventilation rate in the lecture hall in the morning.

Date	Zone	Outdoor air % A	Total air supplied (cfm) B	Peak occupancy (no of people) C	$D=\frac{B}{C}$ Total air supply per person D	E=(A/100) D outdoor air supply per person E
23/02	Lecture hall	40	3750	109	34.4	13.76
27/02	Lecture hall	36	3750	120	31.25	11.25
13/03	Lecture hall	20	3750	160	23.4	4.69
14/03	Lecture hall	34	3750	123	30.5	10.37
04/04	Lecture hall	20	3750	152	24.7	4.94
12/04	Lecture hall	60	3750	135	27.8	16.67

Table 10. The model estimates of the ventilation rate in the lecture hall in the afternoon.

Date	Zone	% of OA A	Total air supplied (cfm) B	Peak occupancy (no of people) C	$D=\frac{B}{C}$ Total air supply per person D	E=(A/100) D outdoor air supply per person E
23/02	Lecture hall	17	3750	145	25.9	4.40
27/02	Lecture hall	2	3750	186	20.2	0.40
13/03	Lecture hall	1	3750	250	15	0.15
14/03	Lecture hall	2	3750	225	16.7	0.33
04/04	Lecture hall	3	3750	206	18.2	0.55
12/04	Lecture hall	5	3750	242	15.5	0.78

Table 11. Average values for weather data of study area

Weather Data	High Temperature (^{O}C)	Low Temperature (^{O}C)	Atmospheric Pressure (KPa)	Relative Humidity (%)	Dew point Temperature (^{O}C)	Wind Speed (km/hr)
	32.77	23.55	101.33	73	10.24	11.7

Weather data from Table 11 was used to estimate the weather factors influencing air infiltration over 24 hours, spanning from January 1 to December 31, for the location. Parameters such as pressure, wind speed, and temperature were recorded and applied as boundary conditions in the CONTAM weather simulation to assess contaminant concentration and airflow distribution.

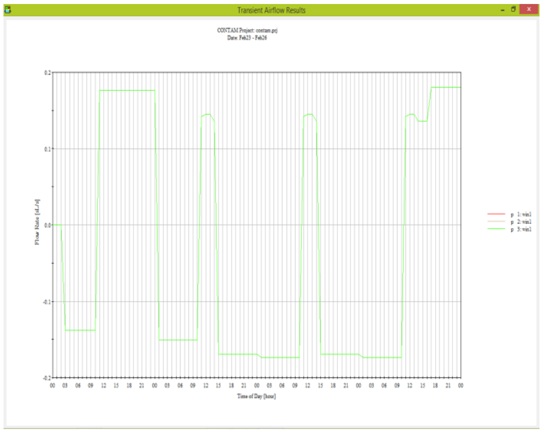

Figure 4. *Airflow simulation graph for February (CONTAM)*

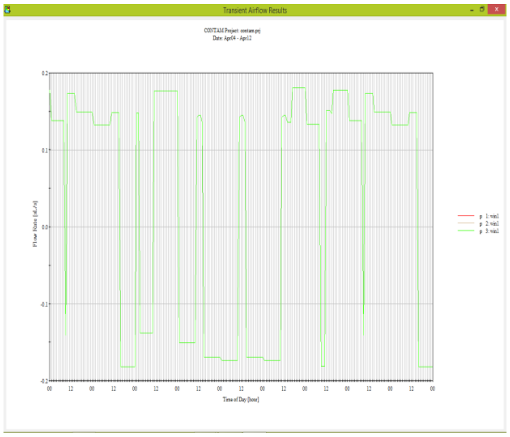

Figure 5. Airflow simulation graph for April (CONTAM)

The simulation result for the airflow rates (Figure 4) shows that higher air infiltration from the ambient into the lecture hall occurs for only very few days in February. The infiltration rate is normal in the morning, increasing to a peak of 0.17 l/s for occupants, which is below the required level, in the afternoon, and then dropping low in the evening. The simulation considered the openings within the hall and the size of the hall, which produced the output values. In Figure 5, the 0000000000000000000graph shows a higher infiltration rate from the ambient to the lecture hall for more days in April. The result shows a transient flow infiltration supply into the lecture hall, and the airflow rate goes high in the afternoon to a peak of 0.18 l/s.

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Conclusion

This study investigated the ventilation performance, IAQ, and thermal comfort conditions of a naturally ventilated lecture hall in the Department of Mechanical at Olabisi Onabanjo University using experimental measurements, mathematical modelling, and CONTAM airflow simulation. The study collected indoor air temperature, CO_2 concentration, airflow characteristics, and occupancy level data for over three months, with measurements taken twice daily, during morning and afternoon/evening lecture hours. A coupled ventilation model integrating airflow mechanics, contaminant transport, thermal comfort analysis, and multizone airflow simulation was developed to evaluate the ventilation effectiveness of the lecture hall. The results revealed that the indoor CO_2 concentration increased significantly with occupant density, particularly during afternoon lecture periods. Measured CO_2 concentrations ranged from approximately 840 ppm to values exceeding 2600 ppm, indicating inadequate contaminant removal under high occupancy conditions. This result surpassed the international recommended IAQ limits for educational buildings, suggesting insufficient ventilation within the lecture hall.

The ventilation effectiveness for contaminant removal (E_c) and heat distribution (E_t) varied between 0.1 and 0.7, and 0 and 1.2, respectively. These results imply that the airflow distribution is unstable, the contaminant extraction is low, and the thermal mixing is uneven within the lecture hall. It is noted that the low ventilation effectiveness values during some periods were as a result of airflow short-circuiting, inadequate air mixing, and the impact of high occupancy levels. The thermal comfort analysis further revealed that the indoor temperatures regularly exceeded acceptable comfort limits. It is known that indoor temperatures in the range of 31.4 °C to 38.9 °C produced high thermal discomfort within the lecture hall, particularly during the afternoon sessions. The PMV-based thermal comfort model confirmed that the existing natural/passive ventilation strategy was highly inadequate to maintain acceptable thermal conditions under tropical climatic conditions.

The CONTAM simulation results revealed that transient infiltration airflow was due to the outdoor weather conditions and pressure differentials between the hall and the outdoor conditions. Even though some infiltration airflow was achieved through openings, windows, and doors, the airflow rates were inadequate for effective contaminant dilution and thermal regulation during periods of high occupancy. The developed mathematical model showed good agreement and has been validated with established ventilation theories, ASHRAE ventilation standards, and previously published studies on natural/passive ventilated classrooms. The model adequately predicted the relationship between the occupancy level, indoor temperature, CO_2 accumulation, and ventilation effectiveness. Generally, the study establishes that even though the lecture hall achieved nominal airflow supply levels close to ASHRAE recommendations, the actual ventilation performance within the lecture hall was highly inadequate. This has been a result of poor airflow distribution and the building design. The study therefore underscores the importance of providing sufficient airflow quantity and also ensuring effective airflow distribution within naturally ventilated educational buildings.

Recommendations

The following recommendations are proposed to improve ventilation effectiveness, indoor air quality (IAQ), and thermal comfort within naturally ventilated lecture halls as an outcome of the findings of the study:

1. Improvement of natural ventilation Design: The arrangement and size of windows and doors to be redesigned to induce cross-ventilation and airflow distribution within the lecture hall. Opposing openings should be intentionally located to reduce airflow short-circuiting and improve contaminant removal effectiveness.
2. Installation of hybrid ventilation systems: Indoor air circulation during periods of high occupancy and high outdoor temperatures require hybrid ventilation systems combining natural ventilation with adequate low-energy mechanical ventilation. Ceiling fans spacing and the installation of air extractor would help improve the ventilation effectiveness of the hall.
3. Continuous indoor air quality monitoring: Continuous monitoring and assessment of the indoor environmental conditions in real-time is required. Monitoring of CO_2, temperature, and relative humidity in real-time would assist to identify periods of inadequate ventilation and implementation of corrective measures promptly.
4. Integration of passive cooling strategies: Incorporating passive cooling methods such as installing solar shading devices, using reflective roofing materials, roof insulation, and consideration of the building

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orientation during design would help to reduce indoor heat gains and improve thermal comfort within the lecture hall.

5. Future research: Future studies should investigate:

- Optimisation of window-to-wall ration for tropical educational building
- Impact of seasonal weather variations on ventilation effectiveness
- Energy-efficient ventilation strategies for university classrooms
- Integration of intelligent ventilation control systems using Model Predictive Control (MPC)

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