



REVEALING THE SPACE CHALLENGES VS INDOOR AIR QUALITY IN ADAPTIVE-REUSED PRESCHOOLS

**Naziah Muhamad Salleh¹, Anisah Ahmad Nahar², Mohd Rodzi Ismail³,
Siti Hamidah Husain⁴, Emma Marinie Ahmad Zawawie⁵**

*^{1,2,3,4}School of Housing, Building and Planning,
UNIVERSITI SAINS MALAYSIA*

*⁵College of Built Environment,
UNIVERSITI TEKNOLOGI MARA (UITM)*

Abstract

The number of preschools has significantly enhanced in recent years, even though numerous preschools are housed in facilities that are not initially intended for such use. Space and indoor Air Quality (IAQ), specifically Carbon Dioxide (CO₂) is regarded as a crucial element influencing the physical growth of children. Therefore, it is crucial to assess the indoor environments of the preschool located in premises that have been renovated and modified from their initial use. Elevated carbon dioxide (CO₂) concentrations in indoor environments may adversely affect children's health and cognitive function. Preschool environments, characterised by high occupancy rates and limited ventilation, are particularly susceptible to poor air quality, which can consequently lead to respiratory issues and diminished learning performance. This study investigates the impact of spaces and ventilation strategies on CO₂ concentration levels in preschool classrooms by examining the occupants activities towards IAQ. The results demonstrated that the CO₂ concentration in the classroom exceeded the recommended 1000 ppm threshold during lesson and group activities but the levels decreased during low-occupancy periods, such as breaks and outdoor activities. Factors such as room size, and occupancy density influenced the increase of CO₂ concentrations. The implementation of exemplary design practices, implementation of hybrid ventilation systems, coupled with thoughtful renovation and ongoing maintenance of preschool facilities, is essential for fostering a high-quality indoor environment within classroom space.

Keywords: Adaptive-reused building, Carbon dioxide, Indoor air quality, Preschool, Classroom, Children

² Corresponding author. Email: anisahahmadnahr@gmail.com

INTRODUCTION

Indoor air quality (IAQ) in educational environments has increasingly been recognised as a crucial determinant of children's physical health, cognitive performance, and academic achievement. Previous studies have highlighted air pollution as a significant environmental concern, demonstrating its adverse effects on both outdoor and indoor air quality in surrounding neighbourhoods (Abdullah et al., 2024; Rashid & Sipahi, 2021). Poor indoor air quality, characterised by inadequate ventilation and elevated carbon dioxide (CO₂) concentrations, may contribute to a range of health problems, including headaches, fatigue, respiratory discomfort, and exacerbated asthma symptoms (Settimo et al., 2024). Since preschool children typically spend approximately eight hours per day in educational facilities (Salleh et al., 2015), maintaining acceptable IAQ levels within classrooms is essential for ensuring their comfort, health, well-being, and learning performance.

In Malaysia, most IAQ studies have been conducted in public schools, where buildings and facilities are generally planned, constructed, and maintained according to standards established by government authorities (Kamaruzzaman & Rasitah, 2011; Hussin, 2011). In contrast, private preschools are often operated by individuals or non-governmental organisations (NGOs), with facilities commonly housed in adaptively reused residential buildings (Kuala Lumpur City Hall, 2010). These buildings were not originally designed for educational purposes, and residential spaces such as bedrooms are frequently converted into classrooms. Consequently, providing an indoor environment that adequately supports children's health and learning remains a significant challenge (Salleh et al., 2016).

Previous research reported that approximately 90% of adaptively reused preschool classrooms accommodated more than 15 occupants per classroom (Salleh et al., 2016). Such occupancy levels may contribute to overcrowding and inadequate ventilation, thereby increasing indoor CO₂ concentrations and potentially compromising classroom air quality. Despite the widespread use of adaptively reused buildings for private preschools, limited studies have examined the relationship between classroom spatial characteristics, occupancy density, ventilation strategies, and indoor CO₂ concentrations. Therefore, this study aims to quantify the spatial characteristics and environmental conditions of adaptively reused private preschool classrooms and to evaluate the effects of different ventilation strategies on classroom CO₂ concentrations.

LITERATURE REVIEW

Adaptive-Reused Preschool in Malaysia

Overall, the enrolment of preschool children aged 4 to 6 years in Malaysia increased substantially from 539,469 in 2000 to 729,043 in 2013 (EPRD, 2001; EPRD, 2014). This rapid growth has placed considerable pressure on the capacity of public preschool facilities provided by the government. Concurrently, preschool education coverage has expanded significantly as part of national efforts to enhance access to early childhood education and strengthen the foundation of compulsory education (MOE, 2001). Consequently, the private preschool sector has emerged as an important provider of early childhood education services. Most private preschools are established and operated by private individuals or organisations and are regulated under the Child Care Centres Act 1984 and its Amendment 2007 (Act 308).

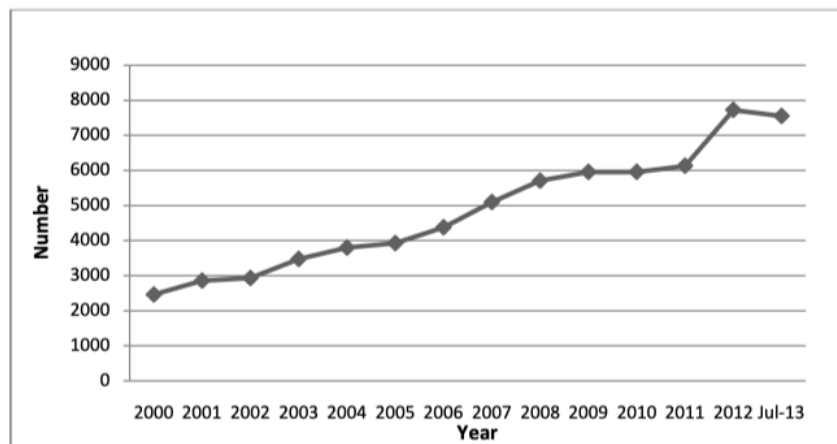


Figure 1: Trends of Private Pre-school in Malaysia from 2000-January 2013
 (Source: EPRD MOE, 2013)

In the Malaysian context, the number of private preschools registered with the Ministry of Education more than doubled between 2000 and January 2013. During the same period, preschool enrolment among children aged 4+ to 5+ years increased from 67% in 2010 to 87% in 2013. This significant growth in enrolment has stimulated the expansion of the private preschool sector despite the concurrent increase in preschool classes provided by public schools under the Tenth Malaysia Plan (2010).

Figure 1 illustrates the rapid growth in the number of private preschools in Malaysia between 2000 and 2013. This upward trend has contributed to the increasing adaptation and reuse of existing premises to accommodate preschool

operations. As demand for preschool education continues to grow, the enrolment capacity of private preschools has expanded in parallel with the availability of suitable educational facilities.

Private preschools play an important role in meeting the growing demand for early childhood education among children aged 4 to 6 years. Many registered private preschools operate in buildings that have undergone adaptive reuse, including residential properties, commercial premises, and institutional buildings. Figure 2 presents the types of buildings occupied by private preschools in Kuala Lumpur following adaptive reuse. The findings indicate that residential buildings within housing developments constitute the most common type of adaptively reused preschool premises.

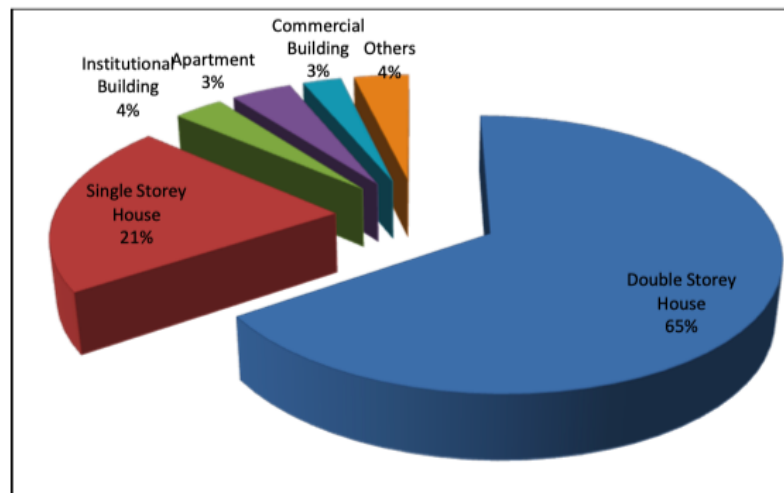


Figure 2: Types of Private Pre-school Premises in Kuala Lumpur
(Source: KL City Council, 2021)

Space Requirements of Preschool Classrooms

The physical environment of educational facilities is an important component of sustainable learning environments; however, its role in supporting sustainability remains underexplored. Recent studies have highlighted that institutional physical environments, particularly classroom space requirements, constitute a major challenge in implementing sustainable preschool ecosystems within the framework of Malaysia's National Preschool Curriculum Standards and broader national sustainability goals (Hashim et al., 2025). In many cases, spatial comfort is compromised in favour of safety requirements and other functional priorities associated with preschool operations (Mansour, 2025).

In addition to building design, the geographical location of preschool facilities can significantly influence indoor air quality (IAQ) conditions (Sarijuddin et al., 2018). In Malaysia, a large proportion of private preschools operate in adaptively reused residential buildings that were originally designed as family dwellings rather than educational facilities. As a result, these buildings often provide limited spatial capacity and inadequate classroom layouts, which may adversely affect children's learning experiences and overall environmental quality (Yoo & Ito, 2022). Preschool environments are of particular concern because children spend a substantial proportion of their time indoors, second only to their homes. Studies have reported that individuals in educational settings may spend up to one-third of their day in enclosed indoor environments (Rahman et al., 2019).

Occupancy density is another important factor influencing IAQ in preschool classrooms. Naziah et al. (2016) reported that approximately 90% of surveyed adaptively reused preschool classrooms accommodated more than 15 occupants per classroom, exceeding the recommended capacity limits for preschool facilities. High occupancy levels can increase the accumulation of indoor pollutants, particularly carbon dioxide (CO₂), as pollutant generation is closely related to the number of occupants within an enclosed space (Horr et al., 2016). Consequently, overcrowded classrooms may experience reduced air quality and diminished thermal comfort, potentially affecting children's health and learning performance.

Several standards and guidelines have established minimum space requirements for educational facilities. The Uniform Building By-Laws (UBBL, 2016) specify a minimum floor area of 2 m² per person, which permits approximately seven students in a typical classroom of the size examined in this study. In addition, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends a maximum occupancy of 50 persons per 100 m² for classroom environments. International standards provide even more stringent requirements. For example, Serbian regulations stipulate that preschool facilities should allocate between 6 and 9 m² per child, depending on the facility's overall capacity. For children aged 3 to 7 years, indoor activity spaces should provide between 2.5 and 3.75 m² per child, while facilities for children aged 1 to 3 years should allocate between 3.3 and 5.0 m² per child (Lee & Chang, 1999). Furthermore, classroom spaces should be sufficiently flexible to accommodate a range of educational activities and future adjustments in response to changing childcare demands. Such flexibility is essential to ensure that preschool environments remain functional, adaptable, and supportive of children's developmental needs (Lee & Chang, 1999).

Carbon Dioxide Concentration in Classroom

Although numerous studies have investigated indoor air quality (IAQ) in institutional buildings, relatively few have focused on preschool environments (Nahar & Salleh, 2019; Almeida et al., 2016; Kapalo et al., 2018). Maintaining good IAQ is particularly important because individuals spend most of their time indoors, and children are more vulnerable to air pollution due to their higher respiratory rates and developing physiological systems (Settimo et al., 2024; Nahar & Salleh, 2019).

Carbon dioxide (CO₂) is commonly used as an indicator of ventilation adequacy because human respiration is the primary indoor source of CO₂ in occupied spaces. Although CO₂ itself is not considered a major indoor pollutant, elevated concentrations may indicate inadequate ventilation and have been associated with reduced cognitive performance and adverse respiratory effects (Mainka et al., 2018). According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and Malaysia's Industry Code of Practice (ICOP), indoor CO₂ concentrations below 1,000 ppm generally indicate acceptable ventilation conditions.

Previous studies have reported elevated CO₂ concentrations in educational settings, particularly in densely occupied classrooms. Kapalo et al. (2018) found that classroom CO₂ levels frequently exceeded recommended standards during teaching activities, especially in rooms with high occupancy rates. Similarly, Zawawi et al. (2019) demonstrated that ventilation performance significantly influenced IAQ in air-conditioned classrooms equipped with mechanical ventilation systems. These findings highlight the importance of effective ventilation strategies in maintaining acceptable indoor air quality and providing a healthy learning environment for preschool children.

Adaptive Reuse Policy Implications for Sustainable Preschool Development

Adaptive reuse has emerged as an important planning strategy for optimising existing building stock, reducing urban development pressures, and supporting sustainable community development. In Malaysia, the increasing demand for preschool education has encouraged the conversion of residential and commercial buildings into educational facilities, particularly within urban areas where land availability is limited. The National Physical Plan Fourth Edition (NPP-4) promotes sustainable spatial development through the efficient utilisation of existing built environments and community facilities, while the *Garis Panduan Perancangan Tadika dan Taska* provides planning guidance on the location, accessibility, and physical requirements of preschool facilities (Department of Town and Country Planning Peninsular Malaysia [PLANMalaysia], 2021, 2017). These policy initiatives support adaptive reuse as a practical approach to expanding preschool provision. However, existing planning guidelines primarily

focus on land use compatibility, accessibility, safety, and service provision, with limited emphasis on indoor environmental quality (IEQ) performance, ventilation adequacy, and occupant health.

The need to strengthen environmental performance criteria is further reinforced by the aspirations of the Thirteenth Malaysia Plan (RMK13) 2026–2030, which prioritises environmental sustainability, public health, and quality of life (Ministry of Economy, 2025). These objectives are also aligned with Sustainable Development Goal (SDG) 3 (Good Health and Well-being), SDG 4 (Quality Education), and SDG 11 (Sustainable Cities and Communities) (United Nations, 2015). Nevertheless, literature addressing adaptive reuse in educational settings suggests that buildings originally designed for residential occupancy may not adequately support the ventilation and spatial requirements associated with preschool activities. Consequently, there is a need for greater integration of indoor environmental performance standards within adaptive reuse policies and preschool planning guidelines to ensure that educational accessibility is achieved without compromising children's health and learning outcomes.

RESEARCH METHODOLOGY

The study was carried out in four classrooms located in the Penang area, due to the progress development and density of enrolments. All the preschools are private preschools and are entirely managed by the owner. The selection of preschools is based on the number of children per year, population density, and number of seats and applications.

The study continuously refers to schools by labeling them with the development scheme and the road where the buildings are situated. Table 1 indicates the case studies labeled for each classroom are tagged with numbers and Figure 4(a) and 4 (b) the photo of the case studies. Figure 5 indicates the dense indoor environment in case study P2-R2

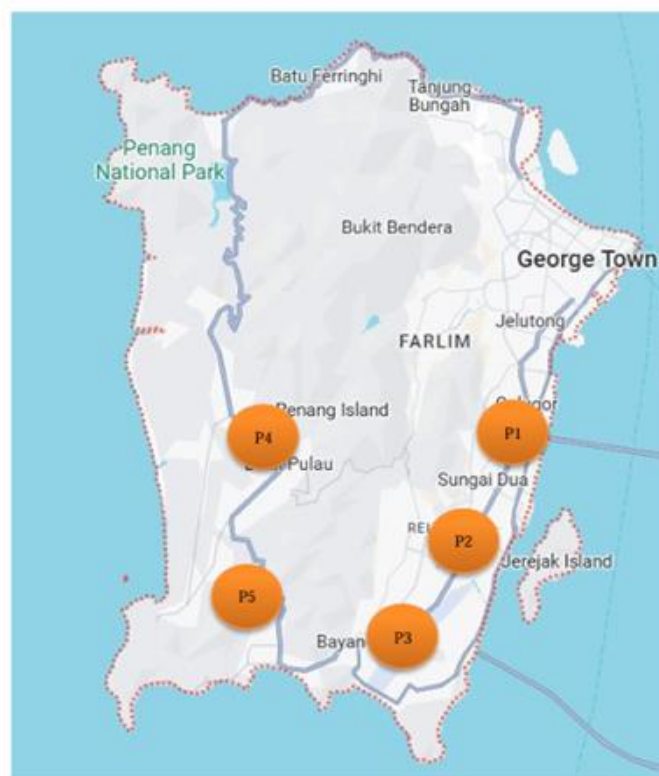


Figure 3: The Location of preschools involved in a field study

Table 1: Case studies for this research

<i>Pre-schools</i>	P1		P2		P3		P4	
<i>Classroom/case study</i>	R1	R2	R1	R2	R1	R2	R1	R2
<i>Type of building</i>	Double-storey detached house							
<i>Age of the building</i>	20 years		25 years		12 years		20 years	
<i>Location</i>	Roadside with less traffic		Roadside with less traffic		Roadside with less traffic		Roadside with heavy traffic	
<i>Surrounding details</i>	Urban, residential, commercial area		Urban, Residential (rock quarry about 1 km from the location)		Urban, residential, commercial area		Urban, residential, commercial area	
<i>Constructional activity</i>	No		No		No		No	No

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Distance from main road	20m		300m		100m		100m	100m
Operation Hour	8am-5pm		7am-3pm		8am-5am		8am-5am	
Maximum pupils' capacity per classroom	16	19	17	16	16	19	19	20
Monitoring Period	4 days	4 days	4 days	4 days	4 days		4 days	4 days
Ventilation status	Natural ventilation with ceiling fan, windows open		Natural ventilation with ceiling fan, windows open		Air conditional with ceiling fan, door open		Air-conditional	Air-conditional
Number of ceiling fan	1	1	1	1	1		1	1
Classroom area(m²)	22.1	14.00	17.08	13.06	23.65		15.47	15.57
Classroom volume (m³)	66.3	36.4	44.41	33.96	66.22		39.70	40.48
Window Size(m²)	2.88	2.88	2.88	2.16	2.88		2.88	2.88
Door	1 (exit)		2 (exit)	1 (exit)	1 (exit) 1 (washroom) 2 (panel sliding door)		1 (exit)	1 (exit)



(a) (b)
Figure 4: Case study building (a) Case study P1 and (b) Case Study P2



Figure 5: Indoor Environment Case Study P2-R2

Sampling Method

The monitoring study aimed to identify CO₂ concentration levels in preschools. The measurements were taken for CO₂ concentration, RH, T, and airflow to enhance the understanding of classroom conditions. The equipment used in the field measurement is BABUC A, TSI IAQ model 7525, Hot Wire CFM Thermo-Anemometer, measuring tape, and laser distance. All equipment used for measurement must ensure it works in good condition. Due to limited instruments, TSI IAQ model 7525 was used to measure only indoor carbon dioxide, humidity, and temperature. The log interval of the concentration data was set at every 60 seconds. Then, the recorded data were downloaded to a PC via USB and opened in Microsoft window to specific software provided along with TSI IAQ model 7525.

The optimal sampling point was typically at the center of the classroom or next to a chair, provided it was away from windows or ventilation and heating systems. the same point was used for measuring CO₂ levels, humidity, temperature, and airflow. To ensure consistency, the same sampling points were used across all classrooms in the 4 schools. The samplers were positioned at a height of approximately 1meter.

The Measurement protocols

The measurement was done for three days in each classroom for a few reasons :

- 1) Three as the optimal sample size, which allows us to verify the mean and frequency of the data to determine the valid minimum and maximum results

- 2) Sampling could be repeated if the instrument fails to measure, as the measurement logging should occur at every one-minute interval during the measurement for at least eight hours per day.
- 3) The measurement devices should be placed at least one meter away from any wall, half a meter from bookshelves, out of reach of children, and 0.5 meters away from the air supply, which is not directly beneath it.
- 4) The measurement devices are consistently positioned at the height equivalent to the children's breathing zone, roughly one meter from the floor, since the pre-school's activities are usually energetic, causing children to move around frequently.

Analysis Indicator Occupancy Density and Ventilation Performance Indicators

To evaluate the adequacy of classroom space and its potential influence on indoor air quality, three spatial indicators were calculated: occupancy density (pupils/m²), floor area per child (m²/pupil), and air volume per child (m³/pupil). These indicators were benchmarked against established space standards and ventilation-related literature. The Uniform Building By-Laws (UBBL) recommend a minimum allocation of 2 m² per occupant, while the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommends a maximum occupancy density of 50 persons per 100 m², equivalent to 2 m² per person. In preschool settings, Lee and Chang (1999) further suggest a provision of 2.5–3.75 m² per child for indoor activity spaces. Classrooms providing less than 2 m² per pupil and exhibiting air volumes below 3 m³ per pupil were considered more susceptible to elevated CO₂ accumulation due to limited dilution capacity and reduced ventilation effectiveness. Therefore, occupancy density and air volume per child were employed as proxy indicators of ventilation performance and indoor environmental adequacy within the adaptively reused preschool classrooms, enabling a comparative assessment of the relationship between spatial constraints and indoor CO₂ concentrations.

Table 2: Ventilation Adequacy Classification Based on Available Air Volume per Child

Air Volume per Child (m ³ /pupil)	Ventilation Adequacy
> 4.0	Good
3.0 – 4.0	Moderate
2.0 – 3.0	Poor
< 2.0	Critical

To facilitate comparison among classrooms, an indicative ventilation adequacy classification was developed based on the calculated air volume available per child (Table 2). The classification was derived from the distribution

of observed classroom volumes and occupancy densities within the present study and is intended as a comparative indicator rather than a regulatory benchmark.

ANALYSIS AND DISCUSSION

CO₂ concentration measurements were conducted continuously during classroom activities and break periods to evaluate indoor air quality under different ventilation strategies. The investigated classrooms employed either split-unit air conditioning (AC) or natural ventilation (NV). Figure 6 illustrates the fluctuation of indoor CO₂ concentrations over time, enabling a comparison of ventilation performance between the two classroom conditions.

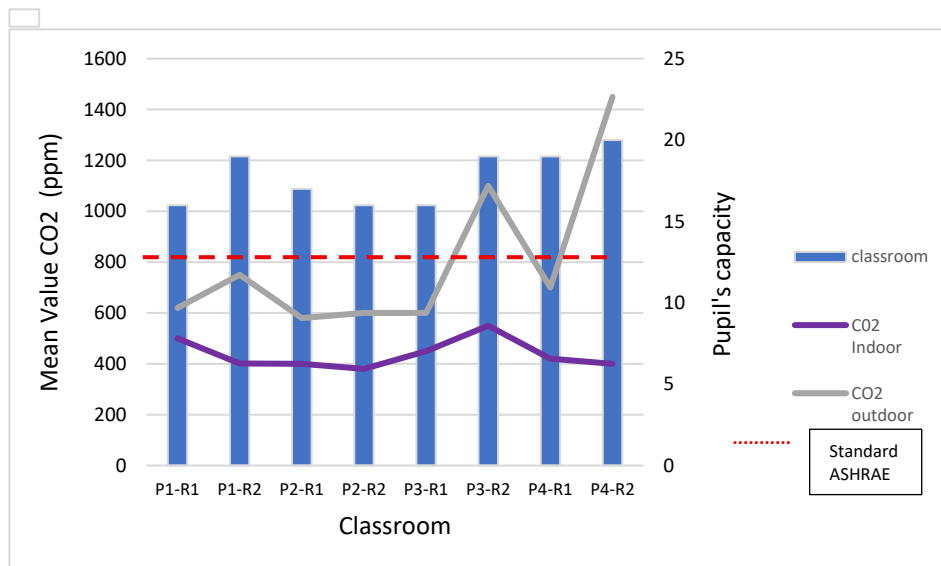


Figure 6: Mean Carbon Dioxide, CO₂ Concentration, and Occupants between Preschool Classroom

Figure 6 compares indoor and outdoor CO₂ concentrations across classrooms P1-R1 to P4-R2 and relates these measurements to maximum occupancy levels. Indoor CO₂ concentration, outdoor CO₂ concentration, and occupant density are presented to evaluate ventilation performance. The ASHRAE and ICOP recommended CO₂ limit is included as a reference benchmark for assessing indoor air quality conditions within the classrooms.

CO₂ Concentrations Exceeding Recommended Limits

As shown in Figure 6, indoor CO₂ concentrations varied considerably across the sampled classrooms and frequently exceeded the ASHRAE and ICOP recommended limit of 1,000 ppm. The highest concentration was recorded in

classroom P2-R1, reaching approximately 1,200 ppm, indicating inadequate ventilation during occupancy periods. Elevated CO₂ levels were generally associated with higher classroom occupancy, particularly in P2-R1 and P3-R1, suggesting that increased occupant density contributed to the accumulation of indoor CO₂.

In contrast, outdoor CO₂ concentrations remained relatively stable throughout the monitoring period, ranging between 400 and 500 ppm. These values were substantially lower than the corresponding indoor concentrations and exhibited minimal variation. The findings indicate that fluctuations in indoor CO₂ levels were primarily influenced by internal factors, particularly occupant density and ventilation effectiveness, rather than changes in outdoor environmental conditions.

Occupancy Density and Indoor CO₂ Concentration

Classroom occupancy was found to be a key factor influencing indoor CO₂ concentrations. The highest CO₂ levels were recorded in classrooms P2-R1 and P3-R1, which accommodated 22 and 20 pupils, respectively. This finding suggests that increased occupant density contributed to the accumulation of indoor CO₂, indicating that the existing ventilation systems were insufficient to maintain acceptable air quality under high-occupancy conditions. Overcrowded classrooms may therefore experience reduced ventilation effectiveness, leading to poorer indoor air quality, occupant discomfort, and potential adverse effects on health and learning performance, consistent with previous studies.

Occupancy Density and Ventilation Performance Indicators of Adaptive-Reused Preschool Classrooms

Table 3 indicates the occupancy density and ventilation performance indicators of adaptive-reused preschool classrooms for this study. Occupancy density varied considerably among the investigated classrooms, ranging from 0.68 to 1.36 pupils/m². Classrooms P1-R2, P4-R2, P2-R2, and P4-R1 recorded the highest occupancy densities, all exceeding 1.20 pupils/m². The floor area available per child ranged from only 0.74 to 1.48 m²/pupil, which is substantially lower than the 2 m²/person minimum requirement recommended by the Uniform Building By-Laws (UBBL).

Similarly, air volume per child ranged from 1.92 to 4.14 m³/pupil. Classrooms P1-R2, P4-R2, P4-R1, and P2-R2 exhibited the lowest air volume per occupant, indicating a higher likelihood of rapid CO₂ accumulation. Although several classrooms had relatively high window-to-floor area ratios (16–21%), elevated occupancy densities reduced the effectiveness of natural ventilation. The findings suggest that classroom volume and occupancy density were more influential than window provision alone in determining ventilation performance

and indoor CO₂ concentrations. These results support the observed exceedance of the 1,000 ppm CO₂ threshold in several classrooms and confirm that adaptively reused preschool classrooms often experience inadequate ventilation under high-occupancy conditions. These findings suggest that inadequate space allocation and limited air volume per occupant contributed to reduced ventilation effectiveness.

Table 3: Occupancy Density and Ventilation Performance Indicators of Adaptive-Reused Preschool Classrooms

Classroom	Area (m ²)	Volume (m ³)	Maximum Occupancy (Pupils)	Occupancy Density (Pupils/m ²)	Floor Area per Child (m ² /pupil)	Air Volume per Child (m ³ /pupil)	Window-to-Floor Ratio (%)	Ventilation Type
P1-R1	22.10	66.30	16	0.72	1.38	4.14	13.03	Natural Ventilation
P1-R2	14.00	36.40	19	1.36	0.74	1.92	20.57	Natural Ventilation
P2-R1	17.08	44.41	17	1.00	1.00	2.61	16.86	Natural Ventilation
P2-R2	13.06	33.96	16	1.23	0.82	2.12	16.54	Natural Ventilation
P3-R1	23.65	66.22	16	0.68	1.48	4.14	12.18	Air-Conditioned
P3-R2	23.65	66.22	19	0.80	1.24	3.49	12.18	Air-Conditioned
P4-R1	15.47	39.70	19	1.23	0.81	2.09	18.62	Air-Conditioned
P4-R2	15.57	40.48	20	1.28	0.78	2.02	18.50	Air-Conditioned

Influence of Ventilation on CO₂ Concentration

The observed variations in CO₂ concentrations highlight the influence of ventilation effectiveness on classroom air quality. Natural ventilation, which relies on airflow through windows, doors, and other openings, can adequately dilute indoor pollutants in classrooms with lower occupancy levels. However, its performance is highly dependent on occupancy density and outdoor environmental conditions.

In contrast, mechanical ventilation systems, including air-conditioning and air-handling units, are designed to provide more consistent indoor air quality control. Nevertheless, elevated CO₂ concentrations may still occur when such systems are inadequately sized, poorly maintained, or unable to meet ventilation demands in highly occupied classrooms. These findings suggest that both occupancy density and ventilation effectiveness are critical factors in maintaining acceptable indoor CO₂ levels in preschool classrooms. Figure 7 illustrates the variation in indoor CO₂ concentrations throughout the school day. The x-axis represents the monitoring intervals, while the y-axis indicates CO₂ concentration

(ppm). The dashed reference line denotes the ASHRAE recommended limit of 1,000 ppm.

The results show substantial fluctuations in CO₂ concentration during classroom activities, with levels exceeding the recommended threshold at several intervals. The highest concentration was recorded at C5 (10:30 a.m.), reaching approximately 2,700 ppm, nearly three times the recommended limit. This peak coincided with periods of intensive classroom activities and high occupancy, suggesting that the natural ventilation system was unable to provide sufficient fresh air to offset the increased CO₂ generated by occupants.

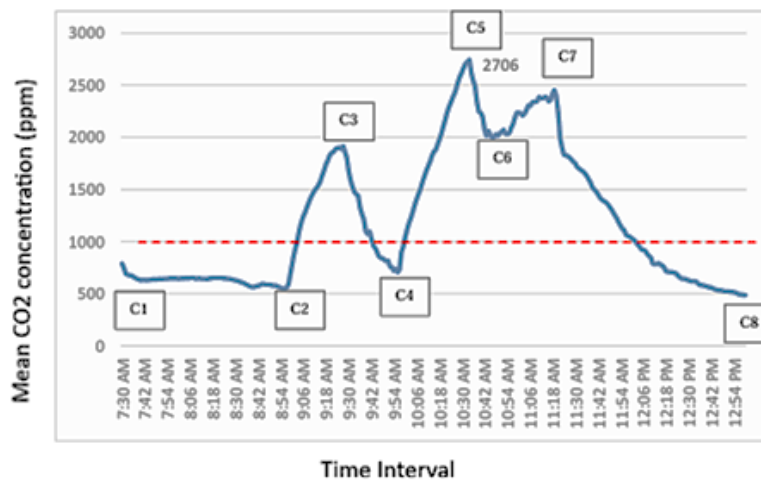


Figure 7: CO₂ Concentration Level and Occupant Density in Naturally Ventilated Classroom (P2-R1)

Following the peak period, CO₂ concentrations declined from C5 to C6, likely due to reduced occupancy and increased air exchange. A gradual decrease was subsequently observed from C6 to C8, indicating an improvement in ventilation effectiveness and indoor air quality. These findings suggest that naturally ventilated classrooms may experience inadequate ventilation during periods of high occupancy and intensive activities, resulting in elevated indoor CO₂ concentrations.

CONCLUSION

The results demonstrate a clear relationship between classroom occupancy, spatial constraints, and indoor CO₂ concentrations, highlighting the limitations of natural ventilation in maintaining acceptable indoor air quality during periods of high occupancy and intensive classroom activities. CO₂ concentrations frequently

exceeded the recommended ASHRAE and ICOP threshold of 1,000 ppm, particularly during lessons and group activities when occupancy levels were highest. In contrast, CO₂ concentrations declined during breaks and outdoor activities, indicating that natural ventilation was more effective when occupancy density was reduced. These findings suggest that natural ventilation alone may be insufficient to provide adequate air exchange under high-occupancy conditions, resulting in suboptimal indoor air quality. Classrooms providing less than 2 m² per pupil and exhibiting air volumes below 3 m³ per pupil demonstrated higher susceptibility to elevated CO₂ concentrations.

Preschool classrooms located in adaptively reused buildings face additional challenges in maintaining acceptable IAQ. Many of these facilities operate in former residential buildings that were not originally designed for educational purposes, resulting in limited classroom space and high occupancy density. Compared with typical office environments, preschool classrooms often accommodate substantially higher occupant densities, leading to the rapid accumulation of CO₂ and other indoor pollutants. Furthermore, activity-based learning environments require designated functional zones, such as reading, art, and science areas, which may increase furniture density and obstruct airflow, creating poorly ventilated areas within the classroom.

Based on the findings, several key observations can be made:

1. Indoor CO₂ concentration is strongly influenced by classroom volume and occupancy density.
2. Ventilation through the opening of windows and doors significantly reduces indoor CO₂ concentrations during breaks and after classroom sessions.
3. Many preschool classrooms exceeded the recommended CO₂ threshold (>1,000 ppm) during occupied periods, indicating that existing classroom space and occupancy levels may not adequately support acceptable indoor air quality.
4. Elevated CO₂ concentrations were associated with inadequate ventilation and high occupant density.
5. Natural ventilation alone was insufficient to maintain acceptable IAQ during periods of high occupancy and intensive classroom activities.

To improve indoor air quality in adaptively reused preschool classrooms, several measures should be considered. Hybrid ventilation strategies that combine natural and mechanical ventilation could provide more effective air exchange and maintain CO₂ concentrations within acceptable limits during peak occupancy periods. Additionally, classroom occupancy limits should be aligned

with available floor area and ventilation capacity. Regular monitoring of CO₂ concentrations is also recommended to support evidence-based ventilation management and ensure a healthier learning environment. Implementing these measures would enhance indoor environmental quality, improve occupant comfort, and support the health and learning performance of preschool children. The paper reveal an important policy gap in the regulation of adaptively reused preschool buildings in Malaysia. While adaptive reuse is recognised as a sustainable planning approach that supports efficient land use and the provision of community facilities, current planning and approval mechanisms largely focus on land-use compatibility, building safety, and operational licensing, with limited emphasis on indoor environmental performance. Existing planning frameworks, including National Physical Plan Fourth Edition (NPP-4) and Garis Panduan Perancangan Tadika dan Taska, provide guidance on preschool location, accessibility, and physical planning requirements but offer limited provisions relating to indoor air quality, ventilation effectiveness, occupancy density, and post-occupancy environmental monitoring. Furthermore, the aspirations of Thirteenth Malaysia Plan (RMK13) 2026–2030 emphasise environmental sustainability, public health, and quality of life but do not explicitly address IAQ performance in adaptively reused educational facilities.

Given that many classrooms in this study exceeded the recommended CO₂ threshold despite complying with existing planning and operational requirements, greater attention should be given to performance-based environmental assessment in adaptive reuse projects. Future planning approvals should incorporate minimum ventilation requirements, occupancy-space standards, and periodic IAQ monitoring, particularly for preschool facilities converted from residential buildings. Strengthening coordination between planning authorities, local governments, public health agencies, and educational regulators would also improve regulatory enforcement and post-occupancy compliance. Such measures would support the objectives of RMK13 and contribute to the achievement of Sustainable Development Goal (SDG) 3: Good Health and Well-being, SDG 4: Quality Education, and SDG 11: Sustainable Cities and Communities by ensuring that adaptive reuse practices promote both educational accessibility and healthy learning environments.

ACKNOWLEDGEMENT

This work was supported by project Grant: Project (1001/PPBGN/8016035) supported by Universiti Sains Malaysia.

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Received: 15th May 2026. Accepted: 6th June 2026