International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Research Article)

Impact of window and door openings on carbon dioxide concentration, temperature, and energy consumption during the heating season in bedrooms

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International Journal of Science and Research Archive, 2025, 14(01), 1695-1703

Publication history: Received on 16 December 2024; revised on 23 January 2025; accepted on 26 January 2025

Article DOI: https://doi.org/10.30574/ijsra.2025.14.1.0264

Abstract

The study investigates the interplay between ventilation, CO_2 concentrations, indoor temperatures, and energy consumption in residential bedrooms during the heating season in Dhaka. Using a mixed-methods approach, including post-occupancy surveys, field measurements, and window and door opening ventilation strategies, the research analyzes the impact of window configurations, behavioral practices, and natural ventilation on indoor air quality and thermal comfort. Key findings reveal significant reductions in CO_2 levels with optimized ventilation practices, improved indoor temperatures, and enhanced energy efficiency. The study emphasizes the importance of integrating sustainable ventilation strategies in urban residential design to balance air quality, occupant comfort, and energy consumption. Recommendations are proposed for optimizing ventilation in resource-constrained tropical climates.

Keywords: Window and Door Openings; Bedroom; Ventilation; Carbon Dioxide; Temperature; Energy Consumption

1. Introduction

The role of ventilation in maintaining acceptable CO_2 levels is especially crucial during the heating season, as windows and doors are often kept closed to retain warmth, thereby limiting the influx of fresh air (Seppänen & Fisk, 2004). Insufficient ventilation under such conditions can result in elevated CO_2 concentrations, which negatively impact cognitive performance, sleep quality, and thermal comfort (Satish et al., 2012). Achieving a balance between thermal comfort and energy efficiency is particularly challenging in bedrooms, where adequate ventilation is critical for maintaining sleep quality (Hummelgaard et al., 2007).

The interaction between window and door openings and indoor environmental conditions is complex. Studies have shown that the strategic use of natural ventilation can effectively control indoor temperatures, improve air quality, and reduce energy consumption (Corgnati et al., 2009). However, understanding the effects of ventilation on energy consumption during the heating season is essential for designing sustainable building systems and minimizing carbon footprints (Pérez-Lombard et al., 2008).

Furthermore, inadequate ventilation is not just a concern in residential settings but also in other indoor environments, such as classrooms. Numerous studies have documented that poor ventilation in classrooms reduces students' comfort, performance, and attendance while increasing negative health symptoms (e.g., Bakó-Biró et al., 2012; Daisey et al., 2003; Gaihre et al., 2014; Haverinen-Shaughnessy et al., 2011; Mendell et al., 2014; Wargocki et al., 2002; Wargocki & Wyon, 2013). Recent cross-sectional studies in schools in Denmark and other regions have revealed that classroom air quality is often characterized by CO_2 concentrations exceeding 1000 ppm, the maximum recommended by current guidelines

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and building codes (Energistyrelsen, 2014; ISO 15251-2007). This issue is particularly prevalent in classrooms where ventilation is achieved through manual window openings, especially during the heating season in temperate regions (Clausen et al., 2014; Santamouris et al., 2008; Shendell et al., 2004; Stabile et al., 2016; Toftum et al., 2015Gao et al., 2014; Hellwig et al., 2009; Rosbach et al., 2016).

However, global air conditioning demand is expected to rise 33-fold by 2100 due to urbanization and increasing incomes in developing nations (Henly, 2015). In tropical regions, air conditioning dominates energy use, particularly in tall buildings (Mohanty, 2013). Natural ventilation offers an energy-efficient solution by utilizing wind and thermal pressure through controllable openings (Rofail, 2006). Properly managed operable windows can reduce energy consumption, but require careful design and environmental consideration (Daly, 2002).

Bangladesh's rapidly growing energy demand, with industry consuming 47.8%, residential 30.5%, and transportation 11.5% (JICA, 2015), highlights the urgency of improving building energy efficiency. Dhaka's poor thermal performance, characterized by single-glazed windows lacking solar shading, exacerbates energy consumption challenges (Ahmed, 1994; Mourshed, 2011). Passive strategies, such as natural ventilation, can significantly reduce cooling loads and improve indoor air quality, with window size and proportion being critical factors (Ahmed et al., 2011; Tariq, 2016). Immediate measures are essential to enhance building resilience to climate change and ensure sustainable urban growth. This highlights the need to investigate the interaction between ventilation strategies, CO_2 levels, and energy consumption across various settings to develop effective solutions.

1.1. Aims and Objectives

The primary aim of this study is to examine the impact of window and door openings on CO_2 concentration, indoor temperature, and energy consumption in residential bedrooms. It seeks to assess how natural ventilation strategies can enhance indoor air quality, thermal comfort, and energy efficiency during the heating season.

- To measure the effect of window and door openings on CO_2 concentrations in residential bedrooms during the heating season, with a focus on how different opening strategies influence indoor air quality.
- To analyze the impact of window and door openings on indoor temperature and thermal comfort, examining how changes in ventilation affect the room temperature, particularly in relation to external weather conditions (e.g., outdoor temperature).
- To evaluate the energy consumption associated with different window and door opening practices, considering the heat loss due to natural ventilation and its effect on heating demand.

How can effective and energy-efficient ventilation solutions optimize thermal comfort, enhance indoor air quality, and reduce energy consumption in bedrooms located in temperate zones?

2. Literature Review

Table 1 literature based

Study	Reference	Findings	Methods
Wargocki et al. (2002)	Wargocki et al., 2002	CO_2 concentrations reduced with window opening, but frequent openings were not observed in cold weather.	Field measurements in classrooms; analysis of CO_2 levels with varying window opening conditions.
Wyon et al. (2010)	Wyon et al., 2010	Students and teachers more likely to open windows when the room is warm, not when CO_2 levels are high, possibly due to sensory fatigue or adaptation.	Experimental study in classrooms with manual window openings; CO_2 level monitoring.
Stabile et al. (2016)	Stabile et al., 2016	Manual window openings reduced CO_2 but increased energy consumption in bedrooms due to heat loss.	Laboratory and field studies; monitored temperature, CO_2, and energy usage in bedrooms with different window opening strategies.
Toftum et al. (2015)	Toftum et al., 2015	Reducing CO_2 concentrations with window openings led to a decrease in room	Field study in classrooms; CO_2 and temperature monitoring with manual and automatic ventilation.

		temperature below 20°C, affecting thermal comfort.	
Gao et al. (2014)	Gao et al., 2014	Natural ventilation in bedrooms led to higher CO_2 concentrations in winter, especially in rooms with poor window openings and insulation.	Cross-sectional study across buildings with natural ventilation; CO_2 measurements in various room conditions.
Mourshed (2011)	Mourshed, 2011	Single-glazed windows and poor solar shading contributed to excessive heat loss, increasing energy consumption during the heating season.	Energy simulation modeling; analysis of thermal performance in residential buildings in Dhaka.
JICA (2015)	JICA, 2015	Energy consumption for heating in residential buildings was high, exacerbated by poor ventilation and inefficient window usage.	Energy consumption analysis of residential buildings in Dhaka; focus on heating energy demands.
Fabiet et al. (2013)	Fabiet et al., 2013	Opening windows reduced CO_2 but often led to thermal discomfort when indoor temperatures dropped below 18°C.	Experimental study in residential bedrooms; analysis of CO_2 levels and indoor temperatures during window opening.
Griffiths and Efthekari (2007)	Griffiths and Efthekari, 2007	Behavioral changes such as window opening reduced CO_2 but increased energy consumption during heating season.	Survey of occupant behaviors and energy usage in residential buildings with varying window-opening practices.
Stabile et al. (2016)	Stabile et al., 2016	Window opening reduced CO_2 but also increased heating energy demand, particularly in poorly insulated bedrooms.	Field measurements in residential settings; monitoring CO_2, temperature, and energy consumption with window-opening actions.
Gao et al. (2016)	Gao et al., 2016	Mechanical ventilation achieved the highest air-change rates, while natural ventilation and window openings were less effective during the heating season.	Comparative study of ventilation systems (mechanical vs. natural) in classrooms and residential rooms.
Hellwig et al. (2009)	Hellwig et al., 2009	Poorly ventilated rooms during the heating season led to high CO_2 concentrations; automated systems or controlled window openings helped manage IAQ better.	Field study; evaluation of ventilation systems and their impact on CO_2 concentrations in residential bedrooms.
Dutton and Shao (2010)	Dutton and Shao, 2010	Cold weather discouraged window openings in bedrooms, leading to reduced ventilation and higher CO_2 concentrations.	Experimental study on temperature, CO_2 levels, and window opening behavior in bedrooms during winter months.
Peddie & Rofail (2011)	Peddie & Rofail, 2011	Integrated natural ventilation in tall buildings could provide thermal comfort, but requires careful planning of window sizes and ventilation openings.	Design and modeling study for residential buildings with integrated natural ventilation principles.
Mohanty (2013)	Mohanty, 2013	High reliance on air conditioning in tropical climates increased energy consumption; window openings as an alternative were not sufficiently effective.	Analysis of air conditioning usage and alternative natural ventilation in tropical climate buildings.

3. Materials and Method

This study employed a mixed-method approach, combining post-occupancy surveys with field measurements to assess bedroom performance during May 2023, a period characterized by hot and dry weather. Each bedroom had a floor area of 19 m^2 and a volume of 76 m^3. The actual occupancy of the bedrooms during the study ranged from 2 to 5 individuals.

The bedrooms were constructed with brick walls, acoustic ceilings, and linoleum floors, featuring uniform interior layouts. These included overhead windows, façade windows providing outdoor views, and two doors—one leading to a hallway and the other to a balcony. The placement of windows on opposite walls facilitated manual cross-ventilation.

As part of the study, façade windows were upgraded in selected bedrooms. Bedrooms with mechanical ventilation or automatic window systems received these upgraded windows, while the reference room and another without automated systems retained their original manually operated windows. Heating was provided by water-filled radiators located beneath the façade windows and water-filled convectors positioned below the overhead windows, both regulated by manually adjustable thermostats.

3.1. Measurements

A measurement station was installed in each bedroom to record CO_2 concentration, temperature, and relative humidity (RH). Each station consisted of a Vaisala CO_2 transmitter (model GMW22, range: 0–5000 ppm ± 100 ppm + 2% of reading) connected to an Onset HOBO data logger (model U12-012, signal range: ±2 mV ± 2.5% of reading). The data logger also monitored temperature (range: -20 to 70 °C, ±0.35 °C within 0 to 50 °C) and RH (±2.5% from 10% to 90% RH). Measurements were recorded at 5-minute intervals from May 7 to June 2, 2015.

The stations were placed approximately 1.5 meters above the floor near the whiteboard, away from windows. During a separate intervention study in the heating season, additional measurement stations were positioned at the back of the classrooms, showing similar CO_2 concentrations due to well-mixed air caused by pupil movement and temperature differences between their surfaces and surrounding air.

Window and door opening events were recorded using Onset HOBO State U9 data loggers with binary outputs. These devices captured the open/closed state and the timing of events for all operable windows and doors. Electricity use by the systems in bedrooms S3, S4, and S5 was logged, while energy meters were installed on radiators, convectors, and water-to-air heating coils in S3. Although bedrooms S7 and S8 were added after retrofit installations, energy meters were not installed in these rooms.

The study also included a simulation of energy use across different climate zones based on the school's geometry and material properties. Heat transfer coefficients (U) and external wall areas (A) were used to compute UA factors, which were applied to adjust heating energy use.

3.2. Data Processing

CO_2 concentration, air temperature, and the opening states of windows and doors were integrated into a common dataset, recorded in 5-minute intervals. Data for CO_2 concentration and temperature were aggregated for occupied times, However, the analysis of window and door states since they influenced bedroom conditions.

Due to the event-based functionality of the loggers, some recorded high-frequency events caused by slightly ajar windows or doors affected by air pressure variations. These instances were corrected to reflect closed states .The analysis covered the full measurement period, including both occupied and unoccupied times.

3.3. Data Analysis

The impact of retrofits on classroom CO_2 concentration and temperature was analyzed using analysis of variance (ANOVA). Separate models assessed the effects of ventilation type on CO_2 concentration and temperature, adjusting for the measurement week, weekday, and lesson within a day.

CO_2 concentrations were log-transformed to address distribution skewness, and Duncan's Multiple Range Test was used for pairwise comparisons. Residuals were verified to follow a normal distribution.

The binary states of windows and doors were compared between classrooms using logistic regression. For each window or door, the processed open/closed data were aligned with corresponding CO_2 and temperature readings every 5 minutes. Logistic regression analysis used classroom, CO_2 concentration, and temperature as explanatory variables and compared bedroom S3 to other rooms. Wald's test was employed for pair wise comparisons among other bedrooms; unpaired t-test was applied to evaluate differences in CO_2 concentrations in S3 between periods when window "winH" was open versus closed.

4. Results and Discussion

Figure 1 presents box plots of the CO_2 concentrations and air temperatures recorded in each bedroom. The bedrooms with mechanical ventilation (S3) and automatic window control paired with a fan (S4) exhibited significantly lower CO_2 concentrations compared to the other bedrooms ($p < 0.01$, ANOVA). In S3 and S4, the median CO_2 concentration remained below 1000 ppm and showed less variation, as indicated by smaller interquartile ranges. No significant differences in CO_2 concentrations were observed among bedrooms S5, S7, and S8.

The analysis also revealed significant two-factor interactions ($p < 0.01$), indicating that CO_2 concentrations varied both between lessons within a day and across days within a week. The mean CO_2 concentration (6:30–7:40 AM) was 510 ppm (range: 475–802 ppm) across all bedrooms. Temperature analysis indicated that bedroom S8, which used visual CO_2 feedback, had significantly higher temperatures than the other bedrooms ($p < 0.01$, ANOVA). The higher temperatures were likely due to elevated radiator thermostat settings. In S8, the median temperature exceeded the recommended maximum heating season temperature of 24°C (ASHRAE 55–2013; ISO 15251-2007).bedroom S3 exhibited higher temperatures than bedrooms S4, S5, and S7 ($p < 0.01$, ANOVA). However, temperatures in S4, S5, and S7 were generally within the recommended thermal comfort range of 20°C to 24°C (ASHRAE 55–2013; ISO 15251-2007), with occasional lower readings in S4.

Figure 1 illustrates the average CO_2 concentration and temperature profiles for the five days during the third measurement week, alongside external temperatures. CO_2 variability during the day was lower in S3, S4, and S5 than in bedrooms without dedicated ventilation systems. Although peak CO_2 concentrations in S4 and S5 were lower, the ventilation flow rate could not consistently maintain CO_2 levels below 1200 ppm. Temperature variations between bedrooms were evident, but the fluctuation within each bedroom during the day was minimal.

Windows and doors varied across bedrooms during the measurement period, as shown in Figures1. S4 and S5, equipped with automatic window-opening systems, experienced many frequent, short-duration window-opening events. However, manual window operation in these rooms occurred only 5% of the time. Conversely, windows were rarely opened in the reference bedroom (S7) and the bedroom with visual CO_2 feedback (S8).

In bedroom S3, which had a mechanical ventilation system, one window (WinH) remained open throughout the latter half of the measurement period. While this did not significantly affect the bedroom temperature, it did lead to a notable reduction in CO_2 concentration. Median CO_2 levels dropped from 989 ppm during the closed-window period to 664 ppm when the window was open ($p < 0.05$, t-test).

The external doors in bedrooms with dedicated ventilation systems (S3, S4, and S5) were generally opened less frequently than in classrooms S7 and S8 ($p < 0.05$, logistic regression). Events with both doors open simultaneously were more common in S7 and S8, as expected. The external door to the balciny was open only 1% to 2% of the time in bedrooms S3, S4, and S5, compared to 31% and 33% in S7 and S8, respectively.

In S4, the entrance door was open for 47% of the occupied time, primarily during the second half of the measurement period.

Figure 1 highlights the differences in window-opening patterns across bedrooms. In bedrooms without automatic window control (S3, S7, and S8), the façade windows were open for less than 15% of the occupied period, including breaks. By contrast, bedrooms with automatically controlled windows (S4 and S5) showed significantly higher window-opening durations, with windows open for 44% to 71% of the occupied time.

In S4, the combination of frequent window openings and an fan contributed to lower indoor temperatures and reduced CO_2 concentrations. This indicates an increased supply of cold outdoor air due to the frequent operation of the automatic windows.

In the bedroom with visual feedback (S8), windows WinH and Win2 were opened more frequently than in the reference bedroom (S7), a statistically significant difference ($p < 0.05$, logistic regression). This suggests that the CO_2 visual feedback influenced window-opening. However, the CO_2 concentration in S8 did not show a significant improvement compared to the reference bedroom(S7).

Table 2 summarizes the energy consumption by the systems in the retrofitted bedrooms during the period from May 7 to June 2. The heating energy use was adjusted to account for differences in the thermal transmittance (UA) of the bedrooms using the correction factors listed in Table 2.

In bedrooms with automatic window controls and either a fan (S4) or heat recovery units (S5), the heating energy included contributions from both the radiator under the façade windows and the convector below the overhead windows. For the classroom with the mechanical ventilation system (S3), the heating energy also accounted for the water-based heating coil.The fans in the mechanical ventilation system, fans, and heat recovery units.

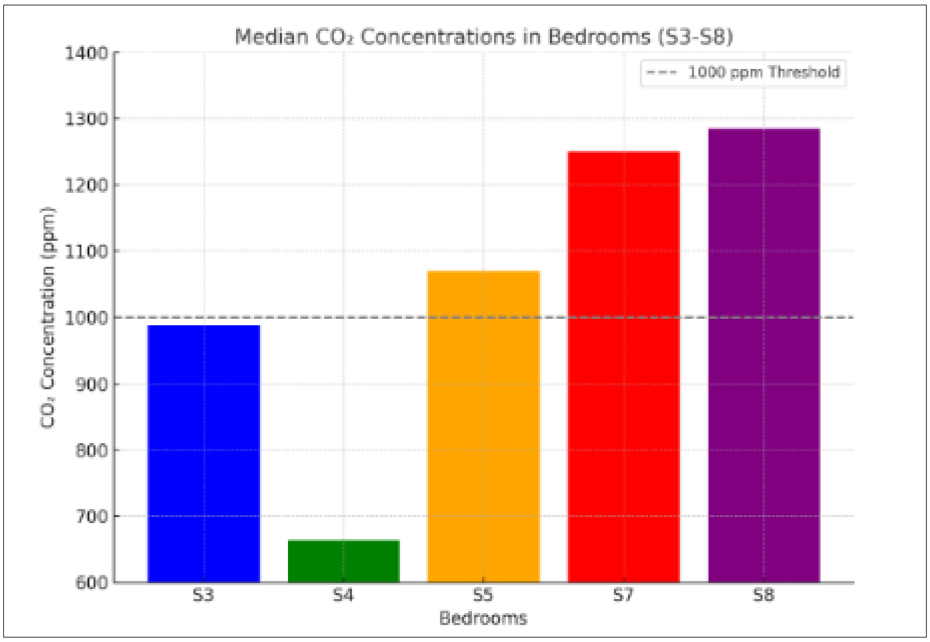

Figure 1 Median CO_2 concentrations for bedrooms S3, S4, S5, S7, and S8

Table 2 Energy Use in Sub-Metered Bedrooms (S3, S4, S5)

Bedrooms	System Type	Electricity Use (kWh)	Measured Heating Use (kWh)	Correction Factor	Corrected Heating Use (kWh)
S3	Mechanical Ventilation System	6.7	346	1	346*
S4	Fan	6.2	135	1.02	172
S5	Hybrid with Heat Recovery Units	4.9	89	1.11	107

4.1. Window Opening Patterns

In bedroom S4, equipped with automatic window opening and a fan, façade windows were open 71% of the occupied time, resulting in lower CO_2 concentrations. Bedroom S5, which had automatic window opening with heat recovery units, saw windows open for only 44% of the time. Despite reduced window opening, the heating energy consumption in S5 was lower due to the efficiency of heat recovery units.

4.2. CO_2 Concentration and Ventilation

bedroomS3, with a mechanical ventilation system, had the lowest CO_2 concentration despite limited window openings (4%–15% of the occupied time). However, a malfunctioning valve in the ventilation system resulted in higher indoor temperatures, invalidating meaningful energy consumption comparisons with S4 and S5.

The study used CO_2 concentrations as a proxy for ventilation effectiveness. Lower CO_2 levels implied better ventilation and indoor air quality, though ventilation rates were not directly measured.

4.3. Energy and Temperature Dynamics

In S4, the median indoor temperature was approximately 1°C lower than in S5 due to differences in heating system design and operation. The heating energy use was higher in S4 due to more frequent window opening and lack of heat recovery units.

4.4. Impact of Visual Feedback Displays

In bedroom S8, the presence of a visual feedback device led to slightly longer window-opening periods compared to the reference bedroom (S7). However, this did not significantly reduce CO_2 levels, possibly because occupants stopped paying attention to the display after prolonged exposure. The study suggested that more engaging or attention-grabbing feedback mechanisms, such as animated or auditory alerts, might improve effectiveness.

4.5. Manual Window Operation

Consistent with previous studies (e.g., Gao et al. 2014; Wargocki and Da Silva 2014), the study found low motivation manually open windows during the heating season due to cold outdoor temperatures causing drafts. The average outdoor temperature during the study was around 3°C.

4.6. Cross-Ventilation

Cross-ventilation events, where windows or doors on opposite sides were simultaneously open, were rare. Window-opening periods were often clustered within specific time slots, limiting the potential for effective natural ventilation.

5. Conclusion

With a visual CO_2 feedback display in the bedroom, windows were opened for a greater portion of the occupied time. However, this did not significantly reduce CO_2 concentrations, even with manual window opening.

In a bedroom equipped with automatic window opening and a fan, windows were open for 68% of the occupied time, resulting in significantly lower CO_2 concentrations compared to the bedroom with only manual window and door opening.

In another bedroom with automatic window opening and heat recovery units, windows were open for 49% of the occupied time. However, this did not lead to significantly lower CO_2 concentrations compared to the bedrooms with manual window opening.

The lowest CO_2 concentrations were observed in the classroom with a mechanical ventilation system and in the bedroom with automatic window opening and a fan.

Temperature levels did not differ significantly between the bedroom without any retrofit and those with automatic window opening, remaining within the recommended thermal comfort range. However, bedrooms with a visual CO_2 feedback display or a mechanical ventilation system showed significantly higher temperatures than others. This may have been caused by radiator thermostat settings and a malfunctioning valve in the mechanical ventilation system, which likely supplied air at an excessively high temperature.

Compliance with ethical standards

Funding

The author(s) did not receive any financial support for the research, authorship, or publication of this article.

Disclosure of conflict of interest

The author(s) declare that there are no competing interests.

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