EVALUATION OF INDOOR AIR QUALITY IN LOW-RISE AND HIGH-RISE APARTMENT UNITS IN HANOI, VIETNAM

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Abstract - Indoor environmental quality during the operational phase of residential buildings plays a critical role in ensuring long-term occupant health and comfort. As part of the CAMaRSEC research project, a year-long measurement campaign of indoor microclimate conditions was conducted in 49 apartment units located within 15 high-rise residential buildings in Vietnam. Key parameters examined included temperature, relative humidity, indoor CO_2 concentrations, window orientation, and floor level. Apartments situated on lower floors and higher floors with naturally ventilated living rooms were selected to assess and compare indoor environmental quality by analysing thermal–humidity conditions, bioclimatic comfort, and temporal variations across units. Results reveal small differences in indoor microclimate conditions between low-rise and high-rise units. The high-rise units also show slightly higher indoor CO_2 concentrations due to prolonged periods of door-closing and tight seals. Based on these findings, the study proposes targeted recommendations aimed at improving indoor air quality.

Key words - Microclimate; thermal comfort; apartment units; high-rise residential buildings; indoor air quality (IAQ); environmental monitoring.

1. Introduction

In recent years, major urban centers in Vietnam have witnessed a proliferation of high-rise residential developments, a strategic response to the multifaceted challenges of urban planning, construction density, and escalating housing demand. Longitudinal data from the national housing and population censuses reveal that the proportion of apartment-style dwellings in urban Hanoi rose from 16.6% in 2009 [1] to 23.0% in 2019 [2], underscoring a decisive shift toward vertical densification in the face of rapid urbanization and land scarcity. As these high-rise structures become the definitive typology of the Hanoi cityscape, research focus has increasingly pivoted toward Indoor Environmental Quality (IEQ) - specifically Indoor Air Quality (IAQ) - during the operational phase. Given its profound implications for occupant health, thermal comfort, and long-term well-being, IAQ represents a critical research frontier. This is particularly salient within the humid subtropical climate (C_{wa}) [3] of Northern Vietnam, where indoor microclimatic parameters - such as ambient temperature, relative humidity, and the efficacy of natural ventilation - are subject to significant fluctuations driven by seasonal transitions, specific architectural configurations, and adaptive occupant behaviors.

Despite an extensive body of international literature regarding the indoor microclimate of high-rise residential buildings [4, 5], longitudinal empirical studies in Vietnam remain sparse, particularly those utilizing large sample sizes and extended monitoring periods to capture seasonal variations comprehensively. In high-rise structures, the vertical position of an apartment may induce significant disparities in microclimatic conditions, specifically regarding temperature gradients, humidity levels, and thermal comfort profiles between low- and high-floor cohorts. However, both global and domestic scholars have yet to fully address this phenomenon.

Consequently, this paper focuses on a comparative analysis of the IAQ between low-floor apartments (levels 2^{nd} –7^{th}) and high-floor apartments (levels 24^{th} –50^{th}). These categories were prescribed in Circular 06-2021 of the Ministry of Construction (Vietnam). To ensure objectivity, the analysis is restricted to living rooms operating without air-conditioners. By examining hygrothermal fluctuations and bioclimatic comfort indices across seasons, the study elucidates the magnitude of microclimatic divergence between the two floor groups during representative climatic extremes: July (hot season) and January (cold season). Additionally, annual indoor CO_2 concentrations were analyzed to evaluate ventilation performance.

The findings not only provide an empirical foundation for assessing IAQ in Hanoi's high-rise housing but also offer architectural design and operational recommendations aimed at enhancing occupant comfort and long-term health.

2. Materials and methods

2.1. The monitoring campaign to collect IAQ data

The CAMaRSEC project investigates indoor environmental conditions in Vietnam's rapidly growing housing sector: modern high-rise apartments, aiming to analyze changing lifestyles, rising comfort demands, and energy consumption under extremely hot and humid climate conditions. The comprehensive survey campaign consists of a year-long monitoring campaign across 49 apartments situated within 15 high-rise buildings in Hanoi, detailed on-site physical and IAQ measurements, along with targeted thermal comfort surveys. Detailed information regarding the location, characteristics, floor levels, and representativeness of the apartment buildings is described in detail in the project information [6]. Ultimately, the collected environmental and behavioral data will support simulation studies to develop climate-adapted materials and sustainable building designs. Outcome data of the project were distributed on Mendeley Data through a CC BY 4.0 creative common license [7]. For the purposes of this specific analysis, the authors focused exclusively on the IAQ data retrieved from living rooms. Key monitored parameters included air temperature, relative humidity (alongside related microclimatic variables), and indoor CO_2 concentrations, while accounting for influential factors such as window orientation and floor level. To facilitate a comparative assessment, the sample was categorized into low-floor units (2nd–7th levels) and high-floor units (8th–50th levels). These apartments were characterized by mixed-mode living spaces, where occupants modulate thermal comfort through a combination of natural ventilation, electric fans, or mechanical cooling. By analyzing data from these spaces during both the hot and cold seasons, this study elucidates the impact of vertical building height on indoor environmental quality.

2.2. Data source description and selection criteria for case-study apartments

This study utilized a dataset comprising: (1) building and occupant information, (2) long-term indoor and outdoor environmental measurements collected from 49 residential apartments in Hanoi, Vietnam.

The investigated residential high-rise buildings were constructed between 2010 and 2018. Basic information on the buildings and apartments included floor plans, year of construction, and window orientation. On weekdays, approximately 80% of occupants reported leaving their homes between 6:30 and 7:30 and returning between 17:00 and 18:00. Electric fans were identified as the most preferred cooling strategy among occupants, followed by split-type air conditioners, while window opening was the least favored option due to the typically higher outdoor temperatures under hot-humid climatic conditions. Indoor environmental parameters, including air temperature, relative humidity, and CO_2 concentration, were monitored in 2021 [6].

Table 1. *Apartment survey information*

Low-floor units (3^{rd} – 6^{th})	High-floor units (18^{th} – 37^{th})
AP45 – L6 – SE	AP8 – L37 – SE
AP2 – L4 – SW	AP36 – L34 – SW
AP47 – L3 – NE	AP37 – L18 – NE
AP48 – L4 – NW	AP11 – L37 – NW

Note: Apartment name - level - window orientation

For the evaluation of IAQ in low and high-rise apartments in Hanoi, four living rooms in low-floor groups and four in high-floor groups, all with similar window orientations, were selected, as summarized in Table 1. For the living room facing Northeast, we only have data for the 18^{th} floor, instead of from the 25^{th} floor upwards. These are apartments with living rooms that simultaneously meet four criteria: floor level, room orientation, room function, and natural operating conditions (no mechanical cooling).

2.3. IAQ assessment tools and standards

Regarding indoor humidity, most standards in developed countries (e.g., ASHRAE and CIBSE) adopt a threshold of 60% (approximately 12 g of water vapor per kilogram of dry air) as the maximum acceptable relative humidity for thermal comfort. However, this limit is frequently exceeded under the hot-humid climatic conditions of Vietnam. Therefore, in this study, the bioclimatic comfort zone established and proposed for Vietnam (see [8]) was used for a more accurate assessment. The biological comfort zones on the bioclimatic chart for Vietnamese are shown in Figure 1.

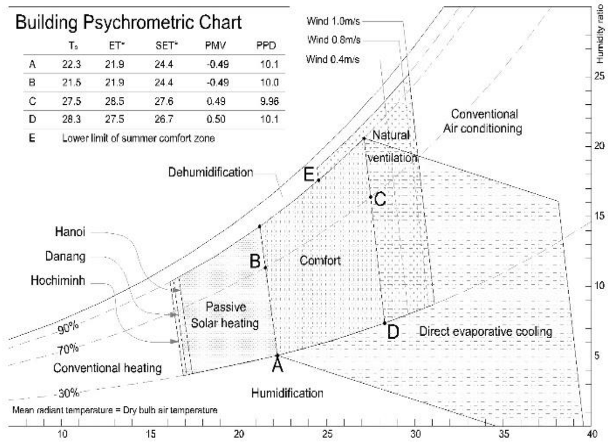


Figure 1. *Bioclimatic chart applied to Vietnamese people [8]*

Indoor CO_2 was monitored in terms of concentration (ppm) within the buildings as an indicator of ventilation performance and IAQ. CO_2 levels below 1000 ppm were considered acceptable, in accordance with established guidelines by TCVN 13521:2022 [9]. Indoor CO_2 monitoring data also indirectly helps us predict window opening and closing behavior, as well as the impact of wind on IAQ.

3. Findings and analysis

3.1. Descriptive Statistics

This study investigates the indoor hygrothermal performance of low-floor and high-floor apartments in Hanoi during two representative months: January (winter) and July (summer). Descriptive statistical analysis was first conducted to provide an overview of the key characteristics of indoor temperature and relative humidity for each group (low-floor vs. high-floor apartments). To compare the variability and distribution ranges of these parameters between the two groups, boxplot diagrams were employed.

Winter indoor microclimate (January):

- Thermal stability (see Figure 2): While both low- and high-floor apartments share a similar median temperature of approximately 20.0°C to 20.2°C, low-floor units exhibit a wider dispersion (Paired T-test returns a p-value of 0). The temperature in low-floor apartments drops to a minimum of 16.7°C, whereas high-floor apartments demonstrate greater thermal stability with a narrower range 17.5 °C - 22.5 °C.

- Humidity patterns (see Figure 3): High-floor apartments experience slightly higher relative humidity, peaking at a maximum of 85.0% compared to 81.0% in low-floor units. Conversely, low-floor units display a broader humidity fluctuation, with minimum values dropping to 40.5%.

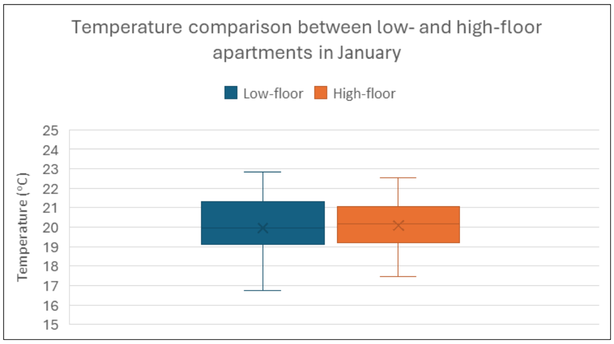


Figure 2. *Temperature comparison between low- and high-floor apartments in January 2021, Hanoi*

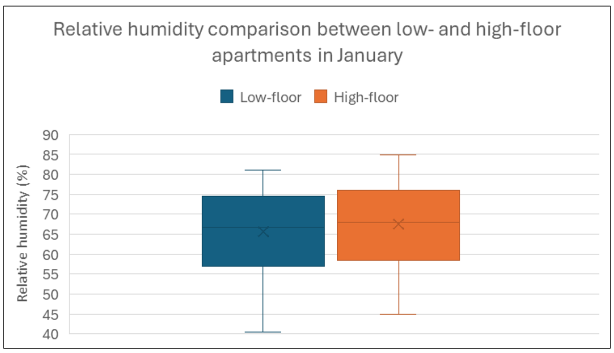


Figure 3. *Relative humidity comparison between low- and high-floor apartments in January 2021, Hanoi*

Figure 4. *Temperature comparison between low- and high-floor apartments in July 2021, Hanoi*

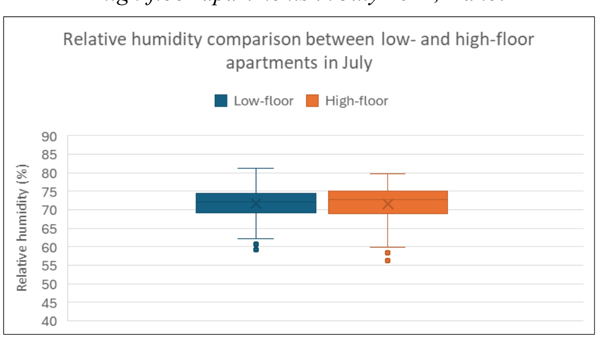


Figure 5. *Relative humidity comparison between low- and high-floor apartments in July 2021, Hanoi*

Summer indoor microclimate (July):

- Homogeneous heat stress (see Figure 4): In July, the median temperatures for both apartment groups converge at around 31.7°C (Paired T-test returns a p-value of 0.49, which means no difference between two groups). The Interquartile Range (IQR) remains highly concentrated (0.7 °C - 0.8 °C), indicating a consistently hot indoor environment. High-floor apartments skew slightly towards higher upper whiskers, reaching a maximum of 33.2°C.

- Anomalies in relative humidity (see Figure 5): Median relative humidity stabilizes between 72.0% and 72.5% for both floor levels. Notably, statistically significant negative outliers were observed in both groups (dropping to 59.0% for low-floor and 56.0% for high-floor), which are likely attributable to abnormal user behaviour or special weather conditions.

3.2. Thermal comfort evaluation

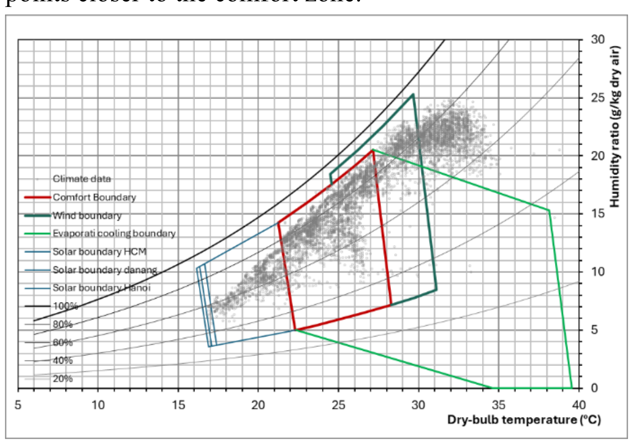
The figures (from 6 to 13) illustrate the distribution of climate data points (grey markers), which are predominantly concentrated within a temperature range of 25°C to 35°C and at relatively high levels of relative humidity (RH), typically exceeding 60–80%.

Role of comfort boundaries:

- Baseline comfort zone: This zone represents the range in which occupants experience optimal thermal comfort without the need for mechanical intervention. However, the majority of the grey data points (observed conditions) lie outside this zone, predominantly to the right (indicating higher temperatures) and above (indicating higher humidity levels).

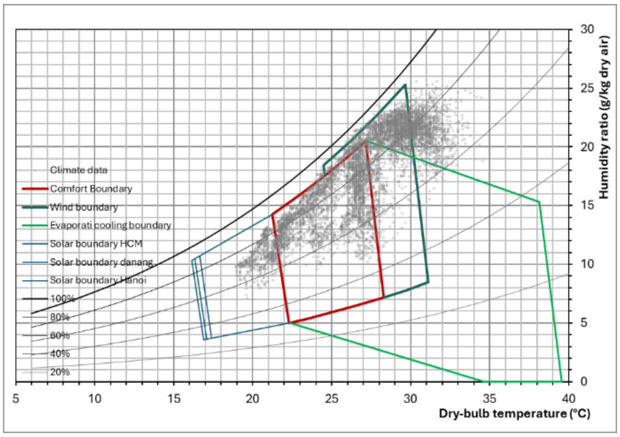
- Ventilation zone: This serves as the most effective passive strategy for these apartments. With the presence of air movement, the comfort zone is significantly extended toward higher temperature conditions.

- Evaporative cooling zone: This strategy is effective under hot and dry air conditions, helping to shift the data points closer to the comfort zone.



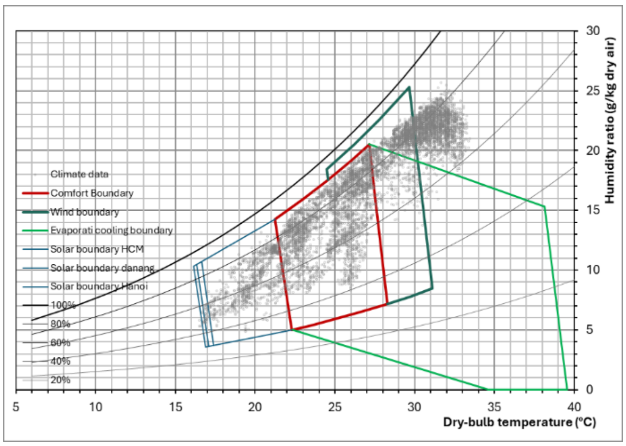
Total comfort hour, all strategies	6089	8760	69.51%	69.52%	30.48%
High humidity zone total hour:	1	8760	0.01%		
Comfort zone total hour:	3361	8760	38.37%		
Ventilation zone total hour:	1711	8760	19.53%		
Solar heating zone total hour:	984	8760	11.23%		
Evaporative cooling zone total hour:	386	8760	4.41%		
Overlap	353				

Figure 6. *Bioclimatic chart of AP45 – L6 – SE*



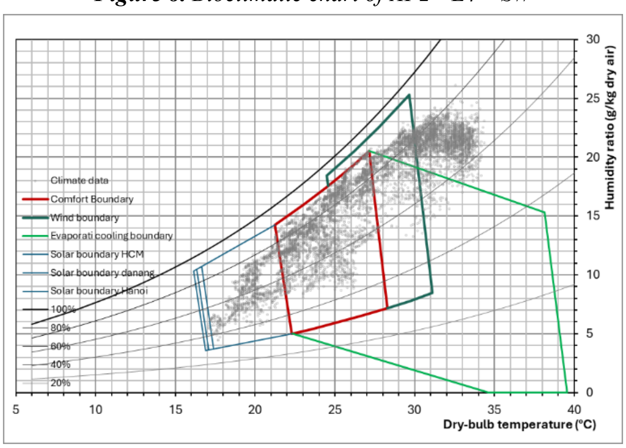
Total comfort hour, all strategies	7180	8760	81.96%	82.58%	17.42%
High humidity zone total hour:	54	8760	0.62%		
Comfort zone total hour:	3706	8760	42.31%		
Ventilation zone total hour:	2715	8760	30.99%		
Solar heating zone total hour:	694	8760	7.92%		
Evaporative cooling zone total hour:	606	8760	6.92%		
Overlap	541				

Figure 7. *Bioclimatic chart of AP8 - L37 – SE*



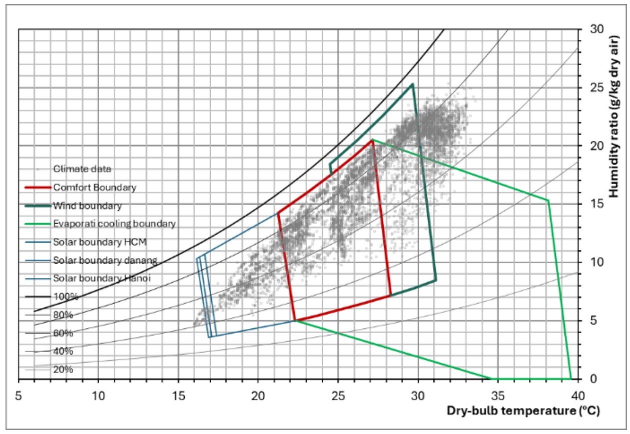
Total comfort hour, all strategies	6106	8760	69.70%	69.70%	30.30%
High humidity zone total hour:	0	8760	0.00%		
Comfort zone total hour:	3588	8760	40.96%		
Ventilation zone total hour:	1489	8760	17.00%		
Solar heating zone total hour:	1006	8760	11.48%		
Evaporative cooling zone total hour:	522	8760	5.96%		
Overlap	499				

Figure 8. *Bioclimatic chart of AP2 - L4 – SW*



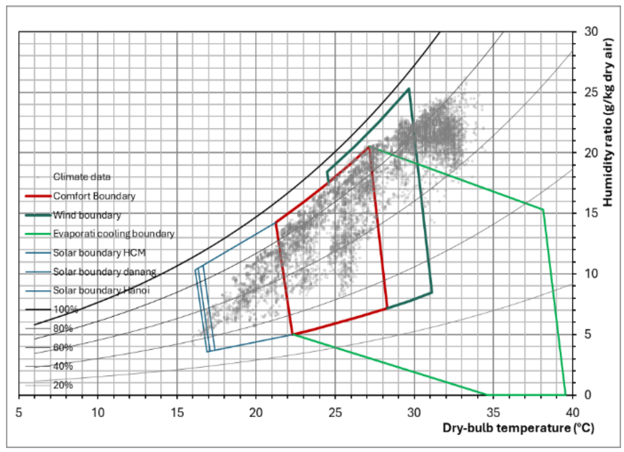
Total comfort hour, all strategies	5932	8760	67.72%	67.72%	32.28%
High humidity zone total hour:	0	8760	0.00%		
Comfort zone total hour:	3583	8760	40.90%		
Ventilation zone total hour:	1228	8760	14.02%		
Solar heating zone total hour:	991	8760	11.31%		
Evaporative cooling zone total hour:	653	8760	7.45%		
Overlap	523				

Figure 9. *Bioclimatic chart of AP36 - L34 – SW*



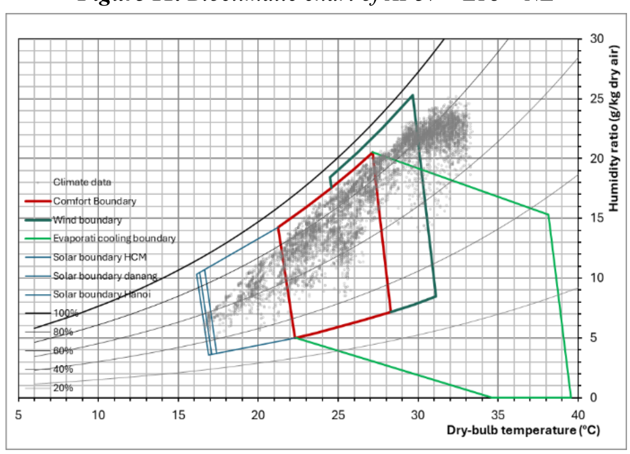
Total comfort hour, all strategies	6415	8760	73.23%	73.23%	26.77%
High humidity zone total hour:	0	8760	0.00%		
Comfort zone total hour:	3651	8760	41.68%		
Ventilation zone total hour:	1610	8760	18.38%		
Solar heating zone total hour:	978	8760	11.16%		
Evaporative cooling zone total hour:	799	8760	9.12%		
Overlap	623				

Figure 10. *Bioclimatic chart of AP47 – L3 – NE*



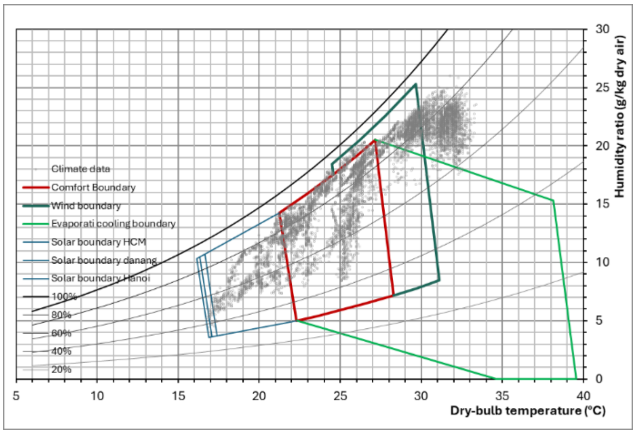
Total comfort hour, all strategies	5892	8760	67.26%	67.26%	32.74%
High humidity zone total hour:	0	8760	0.00%		
Comfort zone total hour:	3420	8760	39.04%		
Ventilation zone total hour:	1438	8760	16.42%		
Solar heating zone total hour:	984	8760	11.23%		
Evaporative cooling zone total hour:	556	8760	6.35%		
Overlap	506				

Figure 11. *Bioclimatic chart of AP37 – L18 – NE*



Total comfort hour, all strategies	6090	8760	69.52%	69.52%	30.48%
High humidity zone total hour:	0	8760	0.00%		
Comfort zone total hour:	3639	8760	41.54%		
Ventilation zone total hour:	1571	8760	17.93%		
Solar heating zone total hour:	830	8760	9.47%		
Evaporative cooling zone total hour:	609	8760	6.95%		
Overlap	559				

Figure 12. *Bioclimatic chart of AP48 – L4 – NW*



Total comfort hour, all strategies	6230	8760	71.12%	71.39%	28.61%
High humidity zone total hour:	24	8760	0.27%		
Comfort zone total hour:	3527	8760	40.26%		
Ventilation zone total hour:	1550	8760	17.69%		
Solar heating zone total hour:	1136	8760	12.97%		
Evaporative cooling zone total hour:	247	8760	2.82%		
Overlap	230				

Figure 13. *Bioclimatic chart of AP11 - L37 – NW*

Analysis of bioclimatic diagrams shows that passive design strategies demonstrate a significant contribution to extending thermal comfort in the studied apartments. The baseline comfort zone accounts for approximately 38.37% to 42.31% of the total annual hours, reflecting the inherent thermal performance of the buildings without intervention. This result is quite similar to that of our previous research [5]. Air cooling (ventilation, fans) has the potential to play a significant role in extending comfort time, especially in high-rise apartments. Regarding overall comfort rates, relatively high averages are achieved, ranging from 67.26% (AP37) to 81.96% (AP8) over a total of 8,760 hours per year. Ventilation or air circulation can further increase passive comfort time by 14.2% to 31.0%. Importantly, for high-rise apartments, natural ventilation is the easiest and least expensive measure, and the air at higher levels is also less polluted.

Regarding humidity specifically, the apartments showed relatively stable humidity levels (below 90%), mostly between 60% and 90%. This is a familiar and acceptable humidity range for Vietnamese people.

One noticeable sign is that for a significant period, the temperature and humidity in all surveyed apartments were excessively high, exceeding the capabilities of passive design. During that period, active solutions (air conditioning) should have been considered.

The data reveals a distinct correlation between floor level and the efficiency of passive cooling, particularly regarding natural ventilation. High-floor units (18th – 37th) generally exhibit a higher potential for natural ventilation. For instance, AP8 (Level 37) utilizes ventilation to achieve comfort for 30.99% of the year, which is substantially higher than the ventilation contribution in low-floor units. Consequently, AP8 achieves the highest total comfort rate at 81.96%. Low-floor units (3rd – 6th) show a more stabilized but slightly lower total comfort range, peaking at 73.23% (AP47). While their ventilation potential is lower (ranging from 17.00% to 19.53%) compared to the best-performing high-floor unit, they compensate with a notable contribution from evaporative cooling, which reaches up to 9.12% in unit AP47.

Orientation plays a critical role in the efficacy of solar heating and ventilation strategies. South-East (SE) orientation appears most favorable for maximizing the total comfort hours in both high and low zones. AP8 (High-floor, SE) and AP45 (Low-floor, SE) leverage a balanced mix of strategies to maintain high environmental quality. North-West (NW) and South-West (SW) orientations: Units with these orientations, such as AP36 (SW) and AP37 (NE), report some of the lowest total comfort percentages, approximately 67%. This suggests that higher solar heat gain (for NW/SW) or exposure to cold winter winds (for NE) may reduce the effectiveness of passive comfort zones.

3.3. Average indoor CO_2 concentrations

The monitoring data reveals distinct characteristics in the distribution and extreme values of indoor CO_2 levels between the low- and high-floor apartments in Hanoi, 2021 (Figure 14). Both groups exhibit nearly identical baseline conditions. The minimum recorded values are practically a match (405 ppm for low-floor vs. 406 ppm for high-floor), hovering near fresh outdoor air levels. The medians are also remarkably close-510 ppm for both groups-indicating that for the vast majority of the monitored timeframe, indoor air quality regarding CO_2 is highly comparable.

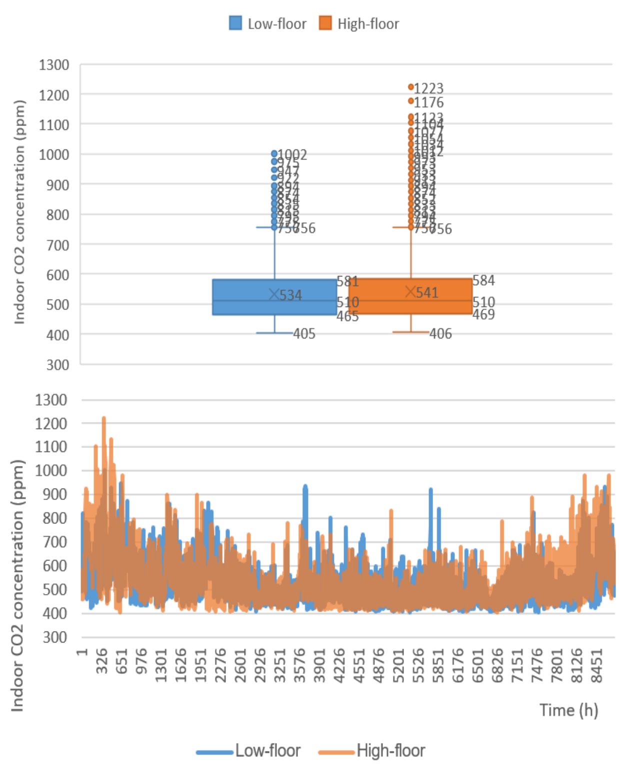


Figure 14. *CO_2 concentration comparison between low- and high-floor apartments in Hanoi, 2021*

The mean CO_2 concentration is slightly higher in high-floor apartments (541 ppm) compared to low-floor apartments (534 ppm). The paired T-test showed that this difference, although small, was statistically significant (p=0). The most significant discrepancy lies in the extreme values. High-floor apartments recorded a peak outlier of 1,223 ppm and a dense cluster of data points exceeding 1,000 ppm. In contrast, low-floor apartments peaked lower, at 1,002 ppm, with fewer extreme spikes. High-rise buildings experience significantly higher wind speeds at upper levels. This often deters occupants from opening windows due to drafts, whistling noises, or safety concerns, leading to reduced natural ventilation and a reliance on recirculation mode. Another hypothesis is that modern high-rise apartment construction tends to be more airtight on upper floors to withstand structural wind loads. Higher airtightness traps metabolically generated CO_2 much faster if active ventilation is absent.

According to ASHRAE standards 62.1, CO_2 concentrations exceeding 1000 ppm are associated with drowsiness and impaired cognitive function. It also serves as a "warning" that the system lacks fresh air, and is the threshold at which body odor and indoor pollutants begin to accumulate to a level that is unpleasant for most people entering the room.

4. Conclusion

This paper evaluated the IAQ between low-floor apartments (levels 2nd –7th) and high-floor apartments (levels 24th –50th) in mixed-mode living rooms (with opening windows, or using electric fans, without air-conditioner). Descriptive statistical analysis was conducted to provide an overview of the key characteristics of indoor temperature and relative humidity for each group (low-floor vs. high-floor apartments) in Hanoi during two representative months: January (winter) and July (summer). Indoor CO_2 levels between the low- and high-floor apartments in Hanoi, 2021 were evaluated. A Vietnamese hygrothermal condition was considered and passive design strategies (including natural ventilation, solar radiation heating, and evaporative cooling) were evaluated.

Based on the empirical evidence from descriptive statistical analysis of indoor temperature and relative humidity for each group (low-floor vs. high-floor apartments) in Hanoi during two representative months, the following conclusions are drawn. Firstly, high-floor units provide enhanced stability against ground-level cold drafts in winter but are more susceptible to cumulative solar gain and overheating in summer due to increased exposure. Secondly, related to seasonal humidity variance, Winter exhibits a higher degree of humidity variance across floor levels compared to the relatively homogeneous humid conditions of summer. Finally, about anthropogenic impact, the presence of sharp humidity drops in July, particularly in high-floor units (56.0%), suggests that residents on higher floors may rely more heavily on mechanical cooling/dehumidification to counteract solar heat gain.

A Vietnamese hygrothermal condition was considered from bioclimatic charts of 8 apartments. Overall comfort ratios were relatively high, ranging from 67.26% (AP37) to 81.96% (AP8) out of the total 8,760 hours per year. Overall, passive design strategies are capable of maintaining thermal comfort for approximately two-thirds of the year without the need for mechanical cooling. Among these, natural ventilation emerges as the key determinant, particularly for high-rise apartments with southeast orientations. However, a notable proportion of time - ranging from approximately 17% to 32% annually - remains outside the comfort range, during which occupants may experience thermal discomfort. This indicates the necessity for supplemental active systems or further improvements in the building envelope to enhance overall indoor environmental performance.

While the average emission profiles (median) are similar across both apartment types, high-floor residences in Hanoi face a slightly higher risk of CO_2 accumulation at hazardous concentrations. Therefore, the implementation of indoor CO_2 monitoring systems is essential for diagnosing ventilation efficiency and enhancing overall indoor air quality (IAQ) within residential units.

Due to data limitations, demographic characteristics and household usage behavior were not included in the study, even though they could influence the assessment results.

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