ORIGINAL ARTICLE

Balancing Affordability and Comfort: Exploring Residential Factors in Thermal Comfort Assessment of Urban Low-cost Flats in Kuala Lumpur

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ABSTRACT

Introduction: Most affordable residential buildings in Kuala Lumpur are primarily multi-story structures designed to maximize space utilization. The objective of our study is to evaluate the thermal comfort and identify the factors that affect the levels of heat exposure in these buildings during the Southwest monsoon season. **Materials and methods:** We employed multistage sampling to recruit 55 units from three affordable apartments (low-cost flat) in Kuala Lumpur. Wet-bulb globe temperature (WBGT) was used to monitor heat parameters, categorized thermal comfort using the Universal Thermal Climate Index (UTCI), and acquire residential factors through the characterization of sampled areas. **Results:** All of the flats we examined had ambient and radiant temperatures that were higher than the recommended ranges, leading to "moderate" to "strong" UTCI thermal stress. The age of the building, the density of the building, and the floor level all had a statistically significant impact on UTCI heat exposure ($p<0.05$). **Conclusion:** Therefore, it is essential to employ cooling systems in order to improve indoor air circulation, reduce temperatures, and minimize the dangers associated with high temperatures, especially during periods of intense heat.
Malaysian Journal of Medicine and Health Sciences (2024) 20(6): 250-256. doi:10.47836/mjmhs20.6.33

Keywords: Low-cost housing, Residential factor, Thermal comfort, Urban area, Universal thermal climate index (UTCI)

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INTRODUCTION

The Malaysian government consistently implements successful affordable housing programs to address the housing needs of both urban and rural households. The National Housing Department (Jabatan Perumahan Negara, JPN), operating under the Ministry of Urban Wellbeing, Housing, and Local Government (Kementerian Perumahan dan Kerajaan Tempatan, KPKT), has developed the People's Housing Program (Program Perumahan Rakyat, PPR) specifically to provide affordable housing options for low-income groups (1). Malaysia has experienced heat wave episodes recently, resulting in 39 cases of heat-related illnesses between April and June 2023 (2). Therefore, balancing affordability and comfort is crucial. Comfortable indoor temperatures are vital to protect occupants from heat-related risks, especially during heat waves.

Land use expansion, pollution growth, and the development of major industrial activities in metropolitan areas have caused Kuala Lumpur to form a micro-climate and experience continuous heat waves throughout the year (3). Towns and cities often experience the strongest impact of heatwaves due to their concentrated populations and the unintentional production of an urban heat island (UHI) effect by the climate, which significantly warms urban areas compared to surrounding rural areas (4). This is concerning, given the high population density in Kuala Lumpur, and the increasing trend in annual temperatures (5).

The design and construction of residential buildings significantly influence the thermal comfort that occupants experience. With the growing trend towards vertical expansion in cities due to limited land availability, multi-story residential buildings have become increasingly common. Kuala Lumpur has since built PPR with multi-story designs to optimize land use (6). However, thermal comfort experienced in such high-rise structures may differ significantly from that in traditional single-story residences, owing to factors such as green spaces, building density, materials used, and building height (7¬-9).

Several heat indices, such as the Universal Thermal Climate Index (UTCI), humidex, and Wet-bulb globe temperature (WBGT) index have been developed to assess thermal comfort or heat stress classification. UTCI accurately assesses the effects of climate change on human health, considering various ambient stimuli such as temperature, sun radiation, wind, and humidity (10,11). The indoor thermal comfort assessed by previous studies mainly focused on the levels of individual heat parameters, such as air temperature and air velocity (7), relative humidity (12), and air temperature and relative humidity (13,14). This limited the understanding of overall interrelation among heat parameters (ambient temperature, radiant temperature, air velocity, and relative humidity) in determining the thermal stress classification and its potential impact on human health. Thus, this study aims to assess thermal comfort based on UTCI within residential buildings in Kuala Lumpur and explore the contributing factors affecting heat exposure levels. By providing valuable insights for urban planners and policymakers, we aim to optimize the future design and operation of residential buildings, thereby fostering comfortable living environments and preventing heat-related risks for residents in urban settings.

MATERIALS AND METHODS

Study sampling

A cross-sectional study involving a total of 55 units from three low-cost flats located in Kuala Lumpur was conducted. There are three types of PPR buildings which are multi-level flats (more than five floors), walk-up flat (five floors), and terrace house. Only multi-level PPR buildings were selected in this study. A multistage sampling was used, beginning with the selection of three PPR using cluster random sampling from the list of high-rise PPR located in Kuala Lumpur. Subsequently, simple random sampling was applied to select units from the identified PPR buildings. Permission was obtained from the units' owners before conducting heat exposure monitoring. The data were collected between May and September 2022, during the Southwest monsoon period in Malaysia. Southwest monsoon periods are typically associated with drier weather, receiving less rainfall, and experiencing hotter temperatures compared to the Northeast monsoon (15). Figures 1 shows the typical floor plan and unit layout for PPRs in Kuala Lumpur.

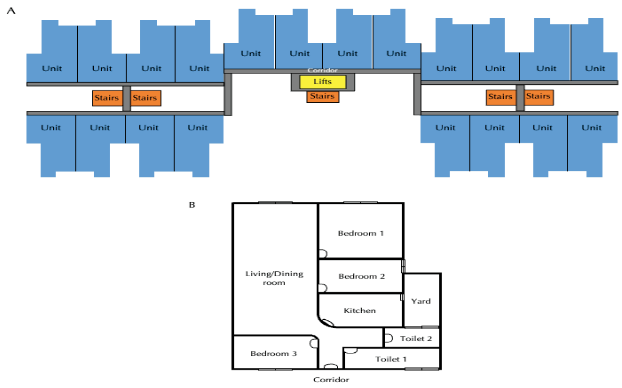

Figure 1: Typical floor plan and unit layout for PPRs in Kuala Lumpur. (A) The typical floor plan of PPR in Kuala Lumpur for level 1 to 14 (excluding the ground floor) contains 20 units per floor. Level 15 to 17 contain of 12 units per floor. (B) The typical PPR unit layout in Kuala Lumpur consists of one living/dining room, three bedrooms, two toilets, one kitchen, and one yard.

Research instruments

Two methods were conducted: indoor heat exposure monitoring using WBGT (Model: QUESTemp) and sampling area characterization using a checklist, virtual interpretation from Google Earth Images, and a laser meter (Model: Bosch).

The WBGT was set up at the centre of the living room, with windows/doors opened. Fans and air conditioning were turned off during the monitoring to obtain accurate readings based on natural ventilation. Monitoring was conducted for one-hour durations between 12 p.m. and 3 p.m., as recommended by ISO 7243:2017 (16). The measurement consisted of four parameters: ambient temperature, radiant temperature, air velocity, and relative humidity. We calculated the average value of each parameter and used the following formula from UTCI calculations to determine thermal comfort.

$$UTCI = 3.21 + 0.872 \times t + 0.2459 \times M_{rt} – 2.5078 \times v – 0.0176 \times RH$$

Where t is air temperature, M_{rt} is mean radiant temperature, v is wind speed, and RH is relative humidity. We then used the calculated value to determine the thermal stress category based on the UTCI equivalent temperature scale. Figure 2 shows the UTCI thermal stress category (17).

UTCI (°C)	Stress Category
UTCI > 46	Extreme heat stress
38 < UTCI < 46	Very strong heat stress
32 < UTCI < 38	Strong heat stress
26 < UTCI < 32	Moderate heat stress
9 < UTCI <26	No thermal stress

Figure 2: UTCI thermal stress category

We employed a checklist to characterize the sampling area, gathering information on residential characteristics such as building materials (wall, ceiling, roofing, and floor), building age, floor level, and the number of occupants in a unit. On the other hand, ceiling height and unit size were measured using a laser meter, while building density and green space ratio were calculated using virtual interpretation from Google Earth Images. The total building area includes all constructed buildings, while the total green space area encompasses any designated land covered with vegetation and natural elements, including water features, gardens, parks, and grasses, within the plot area of 16,000 m^2 (400 m width x 400 m length). The results were expressed as percentages (%). The formulas for calculating building density and green space ratio are as follows:

$$\text{Building density (\%)} = \frac{\text{Total Building Area}}{\text{Plot Area}} \times 100\%$$

$$\text{Green space ratio (\%)} = \frac{\text{Total Green Space Area}}{\text{Plot Area}} \times 100\%$$

Statistical analysis

Statistical analysis was conducted using Prism version 9.5.1 to perform descriptive analysis, one-way ANOVA and Pearson correlation test. A p-value less than 0.05 (p<0.05) was considered significant.

RESULTS

Residential characteristics

Table I represents the results of the residential characteristics of the sampling areas. All three PPR have the same building materials for the wall (concrete blocks), roofing (prefabricated steel), floor (concrete), and ceiling (concrete). PPR B is the oldest building (19.3 years), followed by PPR A (19.3 years) and PPR C (14.7 years). The house or unit in PPR A has the widest size (66.2 m^2) and ceiling height (2.6m). The green space ratio shows that PPR A has the highest green space compared to PPR B and C. However, PPR C has the lowest building density (13.9%) compared to other PPRs. The average number of occupants staying in the same unit ranges from four to five people, based on the three PPR studied. Most of the units assessed in PPR C are located on higher floors (7.0 ± 4.0), compared to PPR A (6.0 ± 5.0) and PPR B (2.0 ± 2.0).

Table I: Residential characteristics of the sampling areas (N=55)

Variables	PPR A (n=14)	PPR B (n=15)	PPR C (n=26)
Building age (year)	17.3	19.3	14.7
House or unit size (m^2)	66.2	46.7	60.4
Ceiling height (m)	2.6	2.5	2.6
Building density (%)	24.1	24.8	20.1
Green space ratio (%)	23.8	14.4	13.9
Wall material	Concrete blocks	Concrete blocks	Concrete blocks
Roofing material	Prefabricated steel	Prefabricated steel	Prefabricated steel
Ceiling material	Concrete	Concrete	Concrete
Floor material	Concrete	Concrete	Concrete
		Mean (SD)	
Number of occupants per unit	4.0 (2.0)	4.0 (2.0)	5.0 (2.0)
Floor level involved in sampling	6.0 (5.0)	2.00 (2.0)	7.0 (4.0)

Green space ratio (%) = percentage of green spaces in 16000m^2 land area
Building density (%) = percentage of building density in 16000m^2 land area

Comparison of heat parameters and thermal stress classification

Table II shows the comparison of heat parameters and thermal stress classification among the PPR buildings. Based on the analysis, a significant difference was identified in all parameters (ambient temperature, radiant temperature, relative humidity, and air velocity) between PPR buildings (p<0.05). PPR B exhibits the highest UTCI heat exposure level (32.02 ± 0.93), classified as strong thermal stress. We classified PPR A and C as having moderate thermal stress because their UTCI heat exposure levels were below 32°C. Figure 3 illustrates the comparison of heat parameters and thermal stress classification.

Table II: Comparison of heat exposure levels and thermal stress classification (N=55)

Variables	Mean (SD)			p-value
	PPR A (n=14)	PPR B (n=15)	PPR C (n=26)	
Ambient temperature (°C)	30.24 (0.41)	30.13 (0.88)	29.55 (0.45)	<0.001**
Radiant temperature (°C)	30.26 (0.37)	30.06 (0.85)	29.60 (0.60)	<0.001**
Relative humidity (%)	63.04 (12.79)	66.71 (4.47)	70.55 (3.68)	0.02*
Air velocity (m/s)	0.19 (0.04)	0.20 (0.00)	0.20 (0.00)	0.047*
UTCI heat exposure level (°C)	31.93 (0.81)	32.02 (0.93)	31.38 (0.45)	0.011*
UTCI thermal stress classification	Moderate	Strong	Moderate	-

Statistical test: One-way ANOVA
* Significant at the 0.05 level (2-tailed)
** Significant at the 0.001 level (2-tailed)

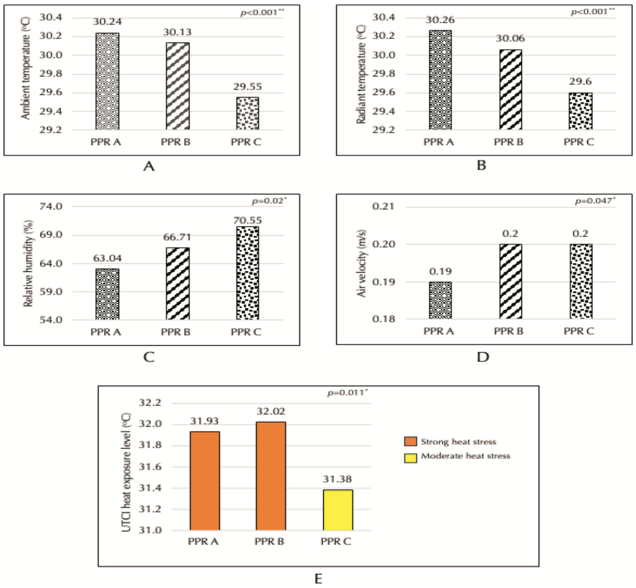

Figure 3: Comparison of heat parameters and thermal stress classification. (A) The comparison of ambient temperature (oC) between PPRs. (B) The comparison of radiant temperature (oC) between PPRs. (C) The comparison of relative humidity (%) between PPRs. (D) The comparison of air velocity (m/s) between PPRs. (E) The comparison of UTCI heat exposure level (oC) between PPRs.

Comparison between heat parameters and recommended range

Table III shows the comparison between heat parameters and the recommended range based on MS1525:2014 and MS2680:2017. Ambient and radiant temperatures for all PPR buildings exceeded the recommended range. However, all PPR buildings fell within the recommended range for air velocity and relative humidity, except for PPR C, where the relative humidity recorded exceeded 70%.

Table III: Comparison between heat exposure levels and recommended range (N=55)

Variables	PPR A (n=14)	PPR B (n=15)	PPR C (n=26)	Recommended range
Ambient temperature (ºC)	30.24 (0.41)	30.13 (0.88)	29.55 (0.45)	[a]24-26 ºC
Radiant temperature (ºC)	30.26 (0.37)	30.06 (0.85)	29.60 (0.38)	[b]18-27 ºC
Relative humidity (%)	63.04 (12.79)	66.71 (4.47)	70.86 (6.29)	[a]50-70%
Air velocity (m/s)	0.19 (0.04)	0.20 (0.00)	0.20 (0.00)	[a]0.15-0.50 m/s

Source of recommended range: [a]MS1525:2014, [b]MS2680:2017

Association between residential characteristics with heat parameters and UTCI heat exposure level

Based on the correlation test, three factors (building age, building density, and floor level) showed a significant association with UTCI heat exposure level ($p<0.05$). A significant positive correlation was found between building age ($R^2 = 0.39$, $p<0.05$) and UTCI heat exposure level, as well as building density ($R^2 = 0.40$, $p<0.05$) and UTCI heat exposure level. Conversely, floor level shows a significant negative correlation with UTCI heat exposure level ($R^2 = -0.42$, $p<0.05$). Factors significantly associated with ambient and radiant temperatures are building age, building density, green space ratio, and floor level ($p<0.05$). Relative humidity was significantly associated with building density and green space ratio ($p<0.05$), whereas air velocity was significantly associated with green space ratio and floor level. Table IV displays the association between residential characteristics and heat parameters, as well as the UTCI heat exposure level.

Table IV: Association between residential characteristics with heat parameters and UTCI heat exposure level (N=55)

Variables	Ambient temperature	Radiant temperature	Relative humidity	Air velocity	UTCI heat exposure level
Building age	0.43*	0.38*	-0.26	-0.07	0.39*
Unit size	-0.09	-0.02	-0.05	-0.21	-0.16
Ceiling height	-0.14	-0.07	0.06	-0.05	-0.15
Building density	0.47**	0.44*	-0.32*	-0.15	0.40*
Green space ratio	0.33*	0.37*	-0.33*	-0.33*	0.20
Floor level	-0.28*	-0.27*	0.08	-0.33*	-0.42*
No. of occupants	0.07	0.12	0.05	-0.03	0.04

Statistical analysis: Pearson correlation test
*. Significant at the 0.05 level (2-tailed)
** Significant at the 0.001 level (2-tailed)

DISCUSSION

Interrelation between heat parameters and UTCI heat exposure level

The heat exposure level depends on the interrelation between four parameters: ambient temperature, radiant temperature, relative humidity, and air velocity (18). Daylighting, or the admission of direct sunlight through windows, is the primary source of ambient heat that affects a residential building's indoor temperature. Based on the results, all PPR buildings exceeded the recommended ambient temperature range according to MS1525:2014 (19).

Residential buildings can generate radiant heat either externally from sunlight or internally from electrical appliances like microwaves, ovens, and heaters. Since the sampling area monitoring did not include any internal sources, this study concentrates on radiant heat from an external source. Sunlight exposure to external building surfaces, such as walls and roofs, can radiate heat into the internal area, increasing indoor temperature (20). Concrete walls are typical building materials in low-cost flats. Since concrete has high thermal conductivity, heat radiating into the internal area will contribute to an increase in internal temperature (21).

Relative humidity also influences indoor thermal comfort. Warmer air can hold more water vapor or moisture and reach 100% relative humidity when saturated (12). However, excessive humidity in the surrounding environment can suppress heat dissipation from the human body by evaporating the body's sweat, slowing the thermoregulation process, and reducing heat tolerance (22,23). High humidity poses a more significant effect on heat tolerance than ambient temperature in a hot and humid environment (23). Only the relative humidity in PPR C exceeded the recommended range in this study.

Air velocity, or wind speed, also plays a vital role in the heat exposure level. Air velocity can help improve air circulation in indoor spaces by lowering indoor air temperature (7) and facilitating evaporation to cool down the body (22). However, higher air velocity can increase the heat load on occupants in hot and humid regions, leading to excessive evaporation and dehydration (22). All the assessed PPR buildings in this study recorded an average air velocity within the recommended range. Thus, air velocity in this study might not be the main parameter influencing the UTCI heat exposure level.

Overall, higher ambient temperature, radiant temperature, relative humidity, and air velocity in hot and humid environments can lead to a higher heat exposure level or thermal stress. According to the results, PPR B had the highest UTCI heat exposure levels because two parameters exceeded the recommended range, and it had among the highest air velocities. Even though urban areas recorded lower ambient and radiant temperatures on average, higher relative humidity in urban areas dramatically alters heat exposure levels. Since the average air velocities for both areas were almost similar, relative humidity (>70%) primarily influences the heat exposure level in this study.

Association between residential characteristics and UTCI heat exposure level

Environmental factors, such as building density and green spaces, influence the level of heat exposure, indirectly contributing to the community's heat stress (14,24). Living in highly dense areas with fewer green spaces leads to poor air circulation and increased trapped heat in the environment, resulting in higher heat exposure (13,24). However, in this study, we only found building density to be significantly associated with the UTCI heat exposure level. Building density increased ambient and radiant temperature, contributing a significant positive correlation between building density and UTCI heat exposure level. Higher building density often results in increased ambient temperatures due to urban heat island effect, where densely built-up areas retain and generate more heat compared to less dense areas (25). Similarly, densely packed buildings and infrastructure tend to absorb and re-radiant more heat, thereby increasing the overall thermal load in the area (25). As the indoor temperature increases, the air capacity to hold moisture increases, lowering the relative humidity levels (26).

This study found that green spaces do not facilitate a reduction in UTCI heat exposure levels based on the correlation results. This could be explained by the tall buildings positioned around the green spaces, diminishing the effectiveness of green spaces in moderating the temperature of residential areas. Furthermore, the cooling effect not only depends on the amount of green areas; vegetation types can also influence the temperature variations (25). We included any vegetated land, open-space areas (such as parks, garden, and grassed areas), and water features in the green space ratio calculation, regardless of the available vegetation types in the sampling areas. Thus, there is lack of understanding of the effect of vegetation types on reducing surrounding temperature through various mechanisms such as its shading effect (canopy coverage) (27) and carbon capture capacity (28).

Lower floors are likely to record higher temperatures due to poor air velocity and ventilation (7). This is similar to our findings, where we found that air velocity had a negative correlation with the UTCI heat exposure level. This might be due to the fact that lower levels are associated with low ventilation and wind speed, resulting in higher indoor temperatures (8). Even though the top floor also reported high temperatures due to the higher amount of solar radiation received (13), better air circulation might help lower the overall indoor temperature. In our study, we observed that higher floor levels receive stronger winds or better airflow into the unit due to fewer obstructions along their path. Lower levels tend to receive reduced airflow due to the presence of other nearby buildings or facilities, such as commercial buildings (shops and restaurants), motorcycles and car parks, recreational areas (parks, playgrounds, and sports facilities), as well as prayer and community halls. Another study investigated the indoor air temperature of a multi-story residential building in Kuala Lumpur, finding living rooms ranging between 27.4°C and 28.6°C, with the lower floor having a higher overall indoor air temperature than the upper floor (8).

This study found a positive correlation between building age and UTCI heat exposure level. According to previous studies (9,29), living in an old house is associated with poor insulation, outdated construction materials, and worn-out infrastructure, leading to an increase in indoor temperature. As time progresses, architectural trends evolve, leading to advancements in building design aimed at optimizing functionality, sustainability, and occupant comfort. We observed distinct architectural designs in all three PPRs assessed, corresponding to the different construction years. Despite their similar building materials, prolonged used of these buildings over the years may have led to a decrease in insulation effectiveness. In addition, building size was also suggested to contribute to the building's internal temperature (14,24). Our findings revealed a contradictory outcome. For instance, our correlation test did not find a direct influence of unit size on UTCI heat exposure level, despite the oldest low-cost flat (PPR B) having a different unit size compared to the other newest PPR buildings assessed in this study.

Malaysians commonly construct low-cost flats with concrete for the building frame and precast concrete for the external walls (30). This study found similar characteristics of building materials for low-cost flats in terms of walls, ceilings, floors, and roofing. A previous study comparing thermal conductivity between building materials' properties found that concrete has the highest thermal conductivity and the highest heat absorption capacity (31), which could increase the internal temperature. All assessed low-cost flats show no differences, making it impossible to determine the association between building materials and the UTCI heat exposure level.

While our study has highlighted the interrelation of heat parameters in indoor buildings located in hot and humid regions, it has also derived the thermal comfort of low-cost residential buildings (PPR) based on UTCI to simulate the heat health risks related to indoor heat exposure. However, it is worth noting the limitations of our study. This study only assessed heat exposure levels at a single point (living room only) due to instrument availability and time constraints to collect data within the stipulated monsoon period. Therefore, future studies could expand monitoring to include other areas like bedrooms and kitchens, providing a more comprehensive assessment of indoor heat stress. This broader approach would better capture potential health risks and refine targeted interventions. Besides, the monitored units came from different blocks in each PPR, which have different arrangements, limiting the understanding of the shading and building orientation effects on indoor temperature. In addition, the quantification of green spaces is not limited solely to the green space ratio. Future studies might also consider other quantitative perspectives, such as tree canopy coverage, green coverage, and green plot ratio, to determine the effectiveness off green spaces in improving the thermal comfort of residential buildings.

CONCLUSION

In conclusion, all three low-cost flats assessed in this study exceeded the recommended range for ambient temperature and radiant temperature, contributing to moderate and strong UTCI thermal stress, which might pose a heat health risk among occupants. We recommend using cooling systems like fans and air conditioning to reduce heat exposure levels, as natural ventilation is insufficient in this context. Also, considering passive design strategies such as shading devices, insulation improvements and natural ventilation enhancements could offer valuable insights into improving thermal comfort in these low-cost residential buildings. Several contributing factors, such as building age, density, and floor level, significantly affected UTCI heat exposure levels. With these findings, we recommend urban planners and policymakers optimize the design and operation of residential buildings in future housing plans, especially focusing on the highlighted contributing factors.

ACKNOWLEDGEMENT

This work was funded by the Ministry of Higher Education (Malaysia), under the Fundamental Research Grant Scheme (FRGS/1/2020/SKK06/UPM/02/1).

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