Modeling PCM-Based Passive Cooling Strategies for Heat Adaptation in Low-Income Housing in Indonesia

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Abstract: *This study investigates the effectiveness of Phase Change Materials (PCM) as a passive cooling strategy for low-income housing in Indonesia's tropical climate. Using EnergyPlus simulations, various PCM placements on inner and outer wall surfaces across different orientations were evaluated to assess their impact on indoor thermal performance. Results indicate that while PCM integration only modestly reduces peak indoor temperatures, it contributes to improved thermal stability and comfort, particularly when applied to east- and west-facing walls. Annual assessments based on ASHRAE 55 adaptive comfort criteria show an increase in the fraction of hours within comfort limits from 57.6% in the baseline to up to 63.0% in PCM-integrated cases. The findings highlight the importance of PCM placement, orientation, and solar exposure in optimizing performance. This study provides insights into cost-effective design strategies for enhancing thermal resilience in low-income dwellings, supporting more sustainable housing development in hot and humid urban environments.*

Keywords: Phase change materials; natural ventilation; low-income housing; urban heat island; building simulation

1. INTRODUCTION

Global climate change has led to rising temperatures and more frequent, intense heatwaves, posing significant risks to low-income urban housing in tropical developing countries such as Indonesia [1]. These settlements often lack climate-responsive design and are typically constructed with high thermal conductivity materials like concrete, zinc, and asbestos. Such materials absorb excessive heat during the day, leading to elevated indoor temperatures. As a result, thermal discomfort becomes prevalent, negatively impacting the health, well-being, and productivity of the occupants [2,3].

Moreover, rapid urbanization has exacerbated this issue, prompting the government to construct thousands of social housing units [4]. However, these units are often built without adequate thermal insulation, leading to indoor temperatures that can exceed 30°C [5,6]. In response, residents tend to rely on active cooling technologies such as electric fans and air conditioners (ACs). Unfortunately, these solutions introduce new challenges, including increased energy consumption, greater financial burdens on low-income households, and higher carbon emissions, which further intensify the urban heat island (UHI) impact [7]. Therefore, there is an urgent need for more effective and sustainable passive cooling strategies to reduce dependence on energy-intensive technologies while improving thermal comfort for low-income urban communities [8,9].

One promising solution to mitigate indoor overheating is the integration of Phase Change Materials (PCM) into building components. PCM have the ability to absorb and release latent heat during phase transitions, thereby stabilizing indoor temperatures by storing heat during the day and releasing it at night [10]. Recent studies indicate that PCM integration can reduce indoor temperature fluctuations and cooling loads by up to 30%, depending on material characteristics and environmental conditions [11]. However, existing research has largely concentrated on subtropical and temperate regions, with limited investigation into PCM performance under humid tropical climates, particularly in the context of low-income housing in Indonesia.

To address this research gap, the present study focuses on the application of Phase Change Materials (PCM) as a passive cooling strategy for low-income housing. Using thermal simulations on typical urban housing models in Indonesia, the study evaluates the effectiveness of PCM-enhanced building envelopes in improving indoor thermal comfort during extreme heat events, while maintaining cost-efficiency in construction and retrofitting.

2. LITERATURE REVIEW

2.1 PCM Applications in Buildings

Passive cooling strategies have gained increasing attention as sustainable solutions to mitigate heat stress in buildings, particularly in regions where mechanical cooling is economically or environmentally unsustainable [12,13]. Approaches such as natural ventilation, shading devices, reflective roofing, and thermal mass utilization have been extensively studied for their potential to reduce indoor temperatures without increasing energy demand [14,15]. In tropical climates, natural ventilation is especially vital, as it leverages wind-driven and buoyancy-driven airflow to dissipate internal heat. However, its effectiveness can be limited by outdoor temperature, humidity levels, and urban geometry, making it insufficient as a standalone solution in many densely populated urban areas [13]. Phase

Change Materials (PCM) offer a promising complement to traditional passive strategies. By utilizing latent heat storage, PCM can delay indoor temperature peaks and maintain comfort levels for extended periods. Applications of PCM in building envelopes—such as wallboards, roof panels, and plaster layers—have demonstrated potential to enhance thermal inertia and reduce cooling energy demands [14]. Studies in Europe, China, and the Middle East have reported significant improvements in thermal comfort and energy savings, especially when PCMs are optimized for the building's climatic context [11,16]. Nevertheless, PCM performance is highly sensitive to phase transition temperatures and the thermal conductivity of the surrounding materials, necessitating careful integration into building designs [17].
Despite the growing body of literature, research on PCM implementation in tropical climates remains limited. A few studies conducted in Southeast Asia and sub-Saharan Africa suggest that PCM performance can be compromised in consistently hot and humid conditions where night-time cooling is insufficient to regenerate the material's thermal capacity [18]. Moreover, most studies have focused on high-performance buildings or laboratory settings, with minimal attention to informal or low-income housing contexts. These buildings often lack insulation, airtightness, and design optimization, presenting unique challenges that affect PCM behavior and overall system performance [19].

2.2 Research Gap

Critical research gap of this study lies in the lack of studies exploring synergistic effects between PCM and natural ventilation in tropical low-income housing. While individual benefits of each strategy are well-documented, their integration could yield additive or even multiplicative impacts on indoor thermal comfort and resilience during heatwaves. Some simulation-based studies indicate that when ventilation is timed appropriately, PCM can effectively recharge overnight, enhancing their cooling potential during the day [20]. However, there is a need for location-specific assessments that reflect realistic building typologies, material availability, and occupant behavior in low-income settlements. This study contributes to filling these knowledge gaps by evaluating the performance of a combined PCM-natural ventilation strategy in typical low-income urban housing in Indonesia. It employs building energy simulation (BES) to test various PCM configurations, placement strategies, and ventilation scenarios, providing insights into cost-effective design solutions for enhancing heat resilience in resource-constrained settings. Thus, it aims to support evidence-based policy and design interventions to promote healthier and more thermally comfortable environments for vulnerable urban populations.

3. METHODOLOGY

3.1 Household Model

This study focuses on a house located in Surakarta City, Indonesia. The dwelling is owned by a low-income resident who operates a home-based food enterprise (HBE), making the house function both as a residence and a small-scale production space. Situated on a plot of approximately 30 m² (see Fig.1), the main structure consists of plastered autoclaved aerated concrete (AAC) walls and a gable roof constructed from uninsulated galvalume, with no ceiling layer. This configuration allows significant heat transfer from the roof into the interior.
Fig. 2 shows the interior of the household. Both the internal and external wall surfaces are unpainted and lack additional finishing layers, further exacerbating indoor heat gain. Spatially, the house is divided into private and semi-public zones: the bedroom and bathroom are enclosed with full-height partitions, while the living room, kitchen, and storefront area are arranged in an open-plan layout without separations. A common thermal adaptation practice by the occupant involves keeping the windows open throughout the day to promote natural ventilation and mitigate indoor heat accumulation. The physical characteristics of the building, combined with its multifunctional use and occupant behaviors underscore the thermal vulnerability of such dwellings. This makes it a relevant case study for evaluating the potential of PCM-based strategies to improve indoor environmental quality in low-income urban housing.

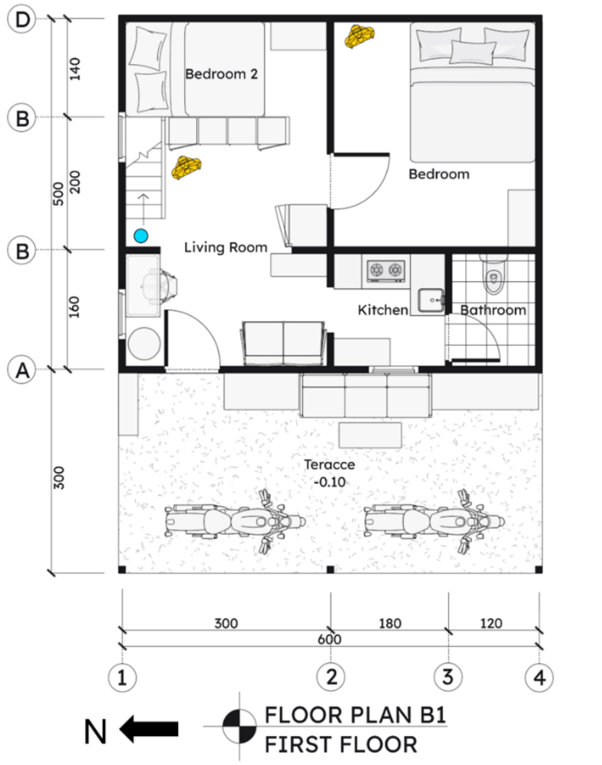

Fig. 1. Floor plan of the representative household model based on an actual low-income dwelling in Surakarta City, Indonesia.

3.2 Material Properties and Scenario Settings

Table 1 lists the building materials and thermal properties of the observed house. The modeled dwelling is simplified to be a single-zone, low-rise urban house with a total floor area of 30 m² and a ceiling height of 3 meters. Its envelope construction incorporates standard materials commonly used in Indonesian residential buildings, including 18 mm cement plaster as the outermost layer and 114 mm brick as the structural core. The roof is constructed using uninsulated concrete roof tiles, reflecting typical low-cost residential construction practices in tropical climates. Windows are located on the west and south façades, using simple 3 mm clear glazing with high visible transmittance, facilitating daylight access (See Figure 3).

Fig. 2. Interior view of the household, showing the integrated living room and kitchen area.

Table 1. The detailed of building envelope materials used for building simulation.

Components	Materials	Thermal properties
Wall	18mm thickness cement plaster 114mm AAC Block	Cement plaster: Conductivity= 0.5 W/m·K, Density=1300 kg/m³, Specific Heat=1000 J/kg·K AAC block: Conductivity= 0.16 W/m·K, Density=600 kg/m³, Specific Heat=1000 J/kg·K
Roof	Galvalume roof tiles	Conductivity= 160 W/m·K, Density=3300 kg/m³, Specific Heat=500 J/kg·K
Windows	3mm glazing	Conductivity= 0.1 W/m·K, Solar Transmittance=0.837, Visible Transmittance=0.898, Infrared Emissivity= 0.84
Door	35mm hardwood panel	U-value= 1.6 W/m^{2}K
PCM wall construction	Paraffin wax-based PCM	Conductivity= 0.2 W/m·K, Density=1000 kg/m³, Specific Heat=800 J/kg·K, phase change range: 24-32^{o}C, total enthalpy change from 10000-220000 J/kg

A key feature of the building envelope is the integration of Phase Change Material (PCM) in either the internal or external wall construction. The PCM is applied as a 20 mm thick layer with specific thermal properties such as thermal conductivity of 0.2 W/m·K and a latent heat capacity peaking between 24°C and 32°C. This material enhances the thermal mass of the wall and stabilizes indoor temperatures by absorbing and releasing latent heat during phase transitions. The PCM-enriched wall construction is explicitly defined as "PCM Wall Construction" in the IDF model and is used selectively to evaluate passive cooling performance under tropical heat stress. This modeling approach provides insight into how PCMs can effectively contribute to thermal comfort in cost-constrained housing.

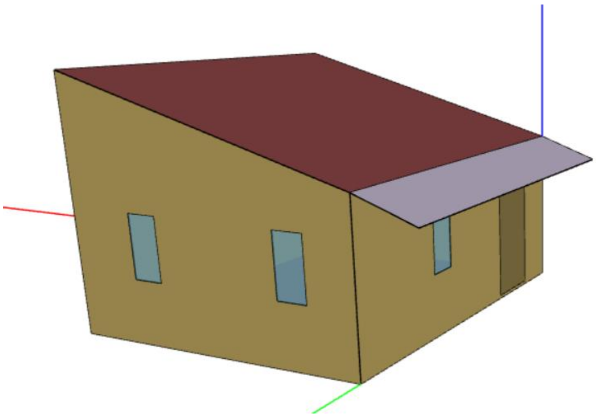

Figure 3. House model used in EnergyPlus as a single-zone.

Furthermore, Table 2 summarizes the geometric configuration of the simulated house model, including the surface areas and orientations of key building components. The building envelope consists of four external walls with varying surface areas: 16 m² (North), 14 m² (West), 20 m² (East), and 18 m² (South), capturing the asymmetric facade exposure typical of urban housing layouts. Openings include two windows, one on the north facade (2 m²) and one on the west facade (1 m²) along with a west-facing door measuring 3 m². The roof and floor areas are not directionally oriented and are considered as horizontal surfaces.

Table 2. Geometry information about the house model.

Components	Orientation	Size (m^2)
Wall	North	16
	West	14
	East	20
	South	18
Floor	-	
Windows	North	2
	West	1
Roof	-	
Door	West	3

Moreover, Table 3 depicts the detailed simulation scenarios used to evaluate the thermal performance of Phase Change Material (PCM) integration into different wall orientations and layer positions of a single-zone building. The baseline scenario includes no PCM, serving as a reference case. Scenarios 1 to 8 examine the application of PCM on a single façade (North, West, East, or South) either on the interior or exterior layer of the wall. For instance, in Scenario 1, PCM is applied to the inner surface of the north wall, while in Scenario 2, it is applied to the outer surface. This systematic variation allows the study to isolate and compare the effects of PCM placement and orientation on indoor thermal comfort under tropical climate conditions.

Regarding the simulation framework, natural ventilation is modeled using the object with an operable opening area of 0.5 m², representing a typical window configuration in low-income tropical dwellings. The ventilation follows a daytime-only schedule, which enables airflow between 06:00 and 18:00 to reflect common occupant practices and safety considerations in urban residential settings. This setup assumes optimal ventilation performance with an effectiveness of 1.0 and a discharge coefficient of 0.5, aligning with established values for single-sided natural ventilation. Background air infiltration is accounted for through a separate schedule (Infiltration) that remains active at all times, capturing the continuous leakage typically present in naturally ventilated buildings. These combined settings provide a realistic representation of passive airflow conditions for evaluating the effectiveness of PCM-integrated envelope configurations.

Table 3. PCM scenarios adopted in this study.

Scenario	PCM inside	PCM outside	Wall orientation
Baseline (BL)			
N_in	√		North
N_out		√	North
W_in	√		West
W_out		√	West
E_in	√		East
E_out		√	East
S_in	√		South
S_out		√	South

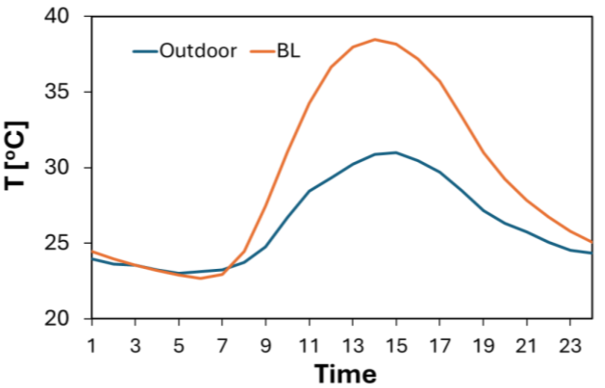

Figure 4. Daily averaged of the baseline and outdoor temperature.

4. RESULTS

4.1 Daily indoor and outdoor temperature for the baseline

To begin with, understanding the thermal performance of buildings requires a comparison between indoor and outdoor temperature variations throughout the day. Figure 4 illustrates the daily average temperature profiles for both the baseline (BL) and outdoor conditions over a 24-hour period. The outdoor temperature starts and ends the day at approximately 25°C, showing a moderate increase peaking around 30°C in the early afternoon. In contrast, the baseline temperature exhibits a more pronounced rise, reaching a maximum of nearly 39°C around 15:00, significantly higher than the outdoor environment. This indicates substantial heat accumulation or poor thermal regulation within the baseline condition.

4.2 Indoor air temperature distribution between baseline and PCM scenarios

Figure 5 illustrates the probability density distribution of simulated air temperatures adopting all scenarios: the baseline condition without phase change material (BL) and the inner wall surfaces facing north, west, east, and south where phase change material (PCM) has been applied (N_in, W_in, E_in, S_in), along with the outdoor environment for reference. The outdoor temperature curve shows a sharp peak around 24°C, reflecting direct environmental exposure and rapid diurnal fluctuations. In contrast, the BL condition exhibits a wider distribution with a noticeable shift toward higher temperatures, indicating significant indoor heat accumulation due to limited thermal buffering. The PCM-integrated inner wall surfaces display simulated temperature distributions that are broadly similar to the baseline but with slightly reduced peak intensities. This suggests that the PCM may have absorbed and delayed a portion of the thermal load, providing some moderation of indoor temperature. However, the relatively small differences between the PCM and BL profiles imply that the phase change material offered only modest thermal buffering under the current simulation settings. This underscores the importance of optimizing PCM characteristics, installation strategies, and phase transition ranges to enhance their performance in building energy simulations.

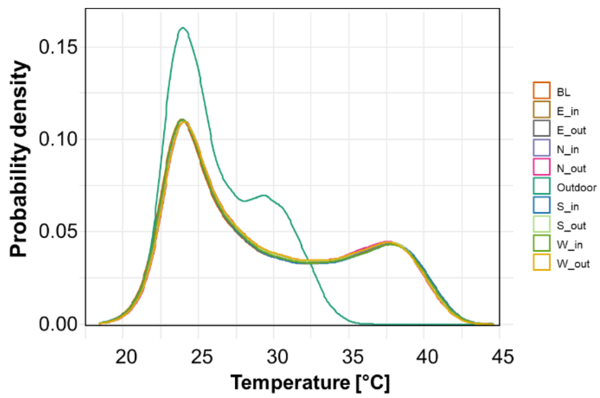

Figure 5. Probability density distributions of simulated air temperatures across different scenarios.

Additionally, when comparing PCM installed on inner versus outer wall surfaces, clear differences emerge in their thermal behavior. PCM on inner surfaces tends to interact more directly with indoor air, allowing it to modulate indoor thermal conditions more effectively through delayed heat release and absorption. However, its impact is somewhat limited by the insulation and thermal lag of the building envelope. On the other hand, PCM on outer surfaces is more exposed to direct solar radiation, enabling it to absorb peak external heat loads before they reach the interior. This placement, while more effective at intercepting solar gains, can also lead to premature or full melting during periods of intense radiation, as observed in the west orientation. The comparative analysis suggests that while both configurations offer distinct advantages, their effectiveness depends heavily on orientation, solar timing, and thermal coupling with indoor spaces. Strategic placement (possibly combining both inner and outer installations) may be necessary to optimize PCM performance in passive thermal control systems.

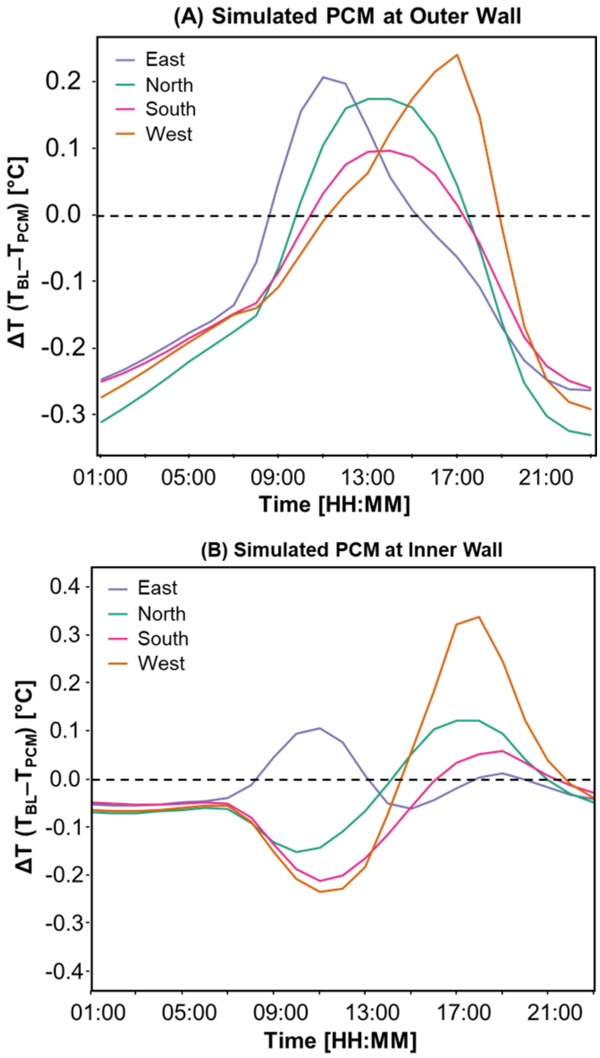

Figure 6. Daily averaged temperature difference between the baseline and PCM scenarios.

Moreover, given that the previous analysis revealed only modest temperature differences between the baseline (BL) and PCM-integrated cases, a more targeted evaluation was conducted by plotting the daily averaged temperature differences between BL and each PCM scenario (calculated as BL minus PCM). A positive value indicates a reduction in temperature due to PCM, while a negative value suggests that PCM increased the temperature relative to the baseline. As illustrated in Figure 6, orientation plays a significant role in determining the thermal impact of PCM. PCM applied to north-facing walls (N) yielded the most consistent cooling effect, particularly during mid-day hours, likely due to stable diffuse radiation enabling more predictable phase transitions. East-facing walls (E) exhibited temperature reductions primarily in the morning, corresponding with early-day solar exposure, while the south-facing (S) configuration produced modest but steady reductions throughout the day. In contrast, PCM on west-facing walls (W) showed weaker performance, with temperature differences near zero or even slightly negative in the late afternoon, likely due to overheating and full melting during peak solar gain, which diminishes its thermal storage capacity.

4.3 Annual Adaptive Thermal Comfort Analysis Based on ASHRAE 55

Figure 7 depicts the annual fraction of hours within adaptive indoor thermal comfort 80% acceptability limits, as defined by ASHRAE Standard 55, across different wall configurations in the simulated building scenarios. The baseline case (BL), which represents conventional construction without phase change material (PCM), yields the lowest comfort compliance at 57.6%. In contrast, all PCM-integrated cases demonstrate improved performance, with comfort percentages ranging from 62.1% to 63.0%, depending on the orientation and whether PCM is applied on the inner or outer wall surfaces. Notably, the highest comfort fractions are observed in the W_in and E_in configurations (both at 63.0%), suggesting that PCM placed on the inner surfaces of west- and east-facing walls most effectively moderates indoor thermal conditions. While the differences among orientations are relatively small, the consistent improvement across all PCM cases underscores the potential of passive thermal storage materials to enhance adaptive comfort performance over the course of a year. These findings highlight the role of PCM placement in optimizing thermal resilience in naturally ventilated buildings under dynamic climatic conditions.

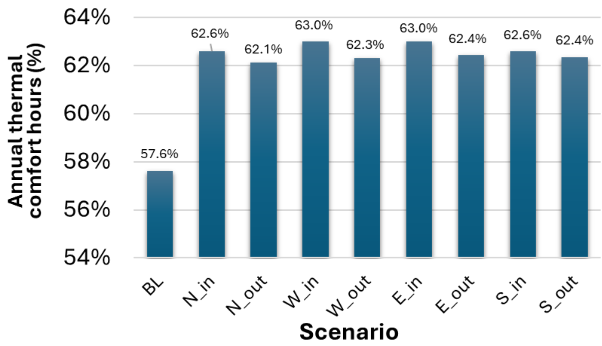

Figure 7. Annual percentage of hours within the adaptive thermal comfort limits as defined by ASHRAE Standard 55.

5. CONCLUSIONS

This study evaluated the effectiveness of phase change material (PCM) integration as a passive cooling strategy for low-income housing in tropical Indonesia using building energy simulations. While the integration of PCM into the building envelope led to observable reductions in indoor temperature fluctuations, the overall thermal buffering effect was relatively modest under current modeling conditions. Probability density and time-series analyses revealed that PCM installation slightly reduced peak indoor temperatures but did not significantly alter the daily thermal profile compared to the baseline case without PCM. These results highlight the thermal limitations of PCM in high-heat-load environments when not optimally configured, especially in buildings with minimal insulation and persistent daytime overheating.

Despite the modest temperature reduction, further analyses focusing on temperature differences and adaptive comfort compliance showed more promising outcomes. When annual thermal comfort was assessed using ASHRAE Standard 55 adaptive comfort criteria, all PCM-integrated scenarios exhibited improved comfort fractions compared to the baseline, with the most favorable results seen when PCM was placed on the inner surfaces of east- and west-facing walls. Orientation-specific trends further demonstrated that PCM effectiveness is strongly influenced by the timing and intensity of solar exposure. PCM on east walls was more effective during morning hours, while PCM on west-facing walls showed vulnerability to overheating due to prolonged afternoon solar gains. Inner-wall PCM offered more stable indoor thermal moderation, while outer-wall PCM, despite its potential to intercept solar loads, suffered from premature melting under extreme heat.

Based on these findings, the use of PCM as a retrofit or design intervention in low-income housing holds merit but requires targeted implementation strategies. PCM should be carefully matched to the building orientation, surface exposure, and local climatic conditions, with priority given to inner surface applications on east and west façades. Future work should explore hybrid configurations that combine PCM with shading, insulation, and optimized ventilation schedules to enhance performance. Additionally, experimental validation under real-world tropical conditions and economic feasibility assessments are recommended to support wider adoption. These insights can guide policy and design efforts toward improving thermal resilience in vulnerable housing while maintaining affordability and energy efficiency.

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