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HEAT ACCUMULATION REDUCTION IN CONDOMINIUM BUILDINGS USING MULTI-TYPOLOGY ROOFTOP LANDSCAPES

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ABSTRACT: This report presents the findings of the heat reduction performance of rooftop garden designs tailored to suit the activities of residents in four condominium buildings (Buildings A to D). The study applied four rooftop garden design types (Types 01 to 04), comprising open walkways, lawn areas, vegetative coverage, and swimming pools, respectively. Each design was installed on a concrete rooftop surface with a thickness of 0.15 meters. The rooftop area covered by Type 01 design elements was set at 80%, 60%, 40%, and 20% for Buildings A, B, C, and D, respectively. Temperature data collected from rooms and corridors beneath the rooftop gardens revealed that Building D had the lowest average indoor temperature, which was up to 2°C lower than that of Building A and up to 0.74°C below the average ambient temperature. In addition, heat flux measurements indicated a maximum reduction of 46% compared to baseline conditions prior to installation. This study underscores the influence of rooftop garden design principles, which collectively shape rooftop thermal behavior, and highlights the importance of ecological design strategies in enhancing indoor comfort and mitigating urban heat accumulation.

Keywords: Green roof, Heat Accumulation, Rooftop, Thermal Performance

1. INTRODUCTION

Rapid urbanization has intensified across major cities worldwide over the past decades, driven by economic growth, infrastructure expansion, demographic shifts, and increased land-use demand [1–5]. Rising land values in metropolitan areas have accelerated the transition from low-rise to high-density vertical development, especially in Asian cities where spatial constraints are critical. As urban land becomes increasingly scarce, natural and permeable surfaces are often replaced with impervious structures, resulting in reduced ecological functions and greater environmental stress [6,7]. This pattern of development has played a significant role in amplifying the Urban Heat Island (UHI) effect, whereby metropolitan temperatures remain consistently higher than those of surrounding suburban or rural regions [8]. Empirical research has shown that UHI intensifies both daytime and nighttime temperatures, placing vulnerable populations such as children, older adults, and individuals with respiratory problems at elevated health risks during extreme heat events [9–12]. Climate change further exacerbates the challenges of UHI. Increasing global temperatures, prolonged heatwaves, and shifts in precipitation patterns have collectively heightened the urgency for adaptive urban design strategies [11,12]. In response, green infrastructure solutions have gained substantial attention as an effective method to mitigate thermal impacts and improve environmental resilience. Among these, rooftop gardens and green roofs represent a key opportunity to introduce greenery into dense urban areas without requiring additional land [13–18]. Rooftop gardens provide multiple environmental benefits, including reductions in surface and air temperatures, improved thermal comfort, enhanced stormwater retention, and increased biodiversity. Studies report that rooftop vegetation can reduce ambient temperatures by 2–5°C [15,16] and lessen building cooling loads by 20–30% [17–20]. In addition to thermal advantages, extensive and intensive green roof systems contribute to carbon sequestration, with estimated storage potential of up to 375 g CO_2/m^2 annually [21].

Beyond temperature reduction, rooftop gardens play an important role in urban water management. Recent studies highlight their capacity to retain rainfall, delay runoff, and reduce flood peaks, thereby supporting broader climate-adaptation and flood-mitigation strategies [22–25]. The integration of rainwater harvesting systems with green roofs has been shown to further enhance hydrological performance, offering synergistic benefits for water reuse and household-level resource conservation [23,24]. From a social perspective, rooftop green spaces can also enhance mental well-being, promote outdoor activity, and provide accessible nature-based environments for residents living in high-rise buildings [14]. These multifaceted advantages underline the growing importance of rooftop landscape systems as part of sustainable and resilient urban design. Despite the documented benefits of rooftop gardens, several research gaps remain. First, the majority of existing studies concentrate on either experimental test beds or controlled laboratory environments, which do not fully represent the thermal behavior of actual residential buildings operating under real-world conditions. Second, while prior literature demonstrates the general effectiveness of green roofs, few studies compare multiple rooftop configurations simultaneously within comparable building typologies, especially in tropical climates where solar radiation intensity and humidity levels differ markedly from temperate regions. Third, limited research examines how rooftop design features such as vegetation density, soil depth, water elements, and functional spatial arrangements collectively influence indoor temperatures and heat flux at the scale of occupied condominium buildings. Recent GEOMATE articles have highlighted the importance of passive ventilation systems and thermal design innovations for improving building energy efficiency [19,20], yet there remains a lack of empirical field data linking rooftop landscape design variations to measurable thermal performance outcomes in tropical urban housing.

This study aims to address these gaps by evaluating the thermal performance of rooftop areas with differing design compositions on four condominium buildings located in a tropical climate. The research investigates how design types including open hardscape areas, lawn systems, vegetative zones, and water-based features affect heat accumulation, indoor temperatures, and heat flux transfer through rooftop slabs. By analyzing real-time field data collected simultaneously from multiple residential structures, this study provides insights into how rooftop garden configurations can be optimized to reduce thermal loads and improve indoor comfort for high-density urban dwellings. The remainder of this paper is organized as follows: Section 2 presents the research significance and conceptual framework. Section 3 describes the rooftop garden development and design typologies. Section 4 outlines the experimental setup, instrumentation, and measurement procedures. Section 5 reports and discusses the results related to position-specific temperatures, room and corridor thermal behavior, and rooftop heat flux reduction. Finally, Section 6 concludes with key findings, contributions, and recommendations for future applications and research.

2. RESEARCH SIGNIFICANCE

The rapid expansion of urban areas and the intensification of high-density residential development have increased thermal stress on building envelopes, particularly in tropical climates where solar radiation and humidity levels are high. Prior studies have highlighted the potential of rooftop gardens to lower surface and air temperatures, reduce cooling energy demand, improve stormwater management, and enhance microclimatic conditions. However, limited research has examined how different rooftop garden configurations perform when implemented on actual condominium buildings under real environmental conditions. This study addresses this gap by providing field-based evidence on how the composition and proportion of rooftop garden elements influence thermal performance. The significance of this research lies in its comprehensive evaluation of rooftop gardens as architectural systems capable of reducing indoor heat accumulation. By comparing four rooftop design typologies across four condominium buildings, the study demonstrates how variations in vegetation density, soil depth, open spaces, and water features affect indoor temperatures, corridor conditions, and heat flux transfer. These comparative findings contribute directly to design guidelines that aim to enhance passive cooling performance through optimized rooftop layouts.

This work further contributes to the advancement of climate-responsive design strategies for tropical urban environments. The results provide valuable insights for architects, engineers, planners, and building owners who seek evidence-based approaches for improving rooftop functional design, structural considerations, and long-term sustainability. The outcomes also highlight the potential scalability of specific rooftop configurations for high-density residential applications, promoting both environmental benefits and enhanced user experience. Overall, the findings offer a foundation for developing practical design strategies and policy recommendations that support resilient, energy-efficient, and thermally comfortable high-rise living environments. The empirical data also pave the way for future innovations in green roof systems, integrated water management solutions, and passive cooling technologies in rapidly urbanizing regions.

3. DEVELOPMENT OF ROOFTOP GARDEN

The development of the rooftop garden systems in this study was guided by the objective of creating functional outdoor spaces that align with residents' daily activities while simultaneously improving the thermal performance of condominium buildings. Four distinct rooftop garden typologies were designed and implemented on the rooftops of four residential buildings. These configurations, illustrated in Fig. 1, were developed to assess how variations in landscape composition influence heat reduction efficiency under actual tropical environmental conditions. All design types were installed on a 0.15-meter-thick concrete rooftop slab, which served as the structural foundation for the applied systems. The first design type consists of open hardscape walkways situated directly on the structural slab at an elevation of 0.00 meters. This configuration represents the minimal-green baseline commonly found on high-density urban rooftops. The second design type incorporates a lawn assembly consisting of a 0.05-meter grass layer placed above a 0.25-meter soil substrate, providing improved shading performance and enabling evaporative cooling. The third design type integrates multi-layered vegetation, comprising approximately 0.30-meter-high shrubs, selected tree species reaching about 2.50 meters, and elevated planting beds with a depth of 0.60 meters. This configuration increases canopy density, reduces direct solar exposure on the rooftop surface, and enhances microclimate regulation through transpiration processes. The fourth design type features a swimming pool with a depth of 1.20 meters, contributing to thermal stabilization through the heat capacity of water and evaporative cooling at the water–air interface.

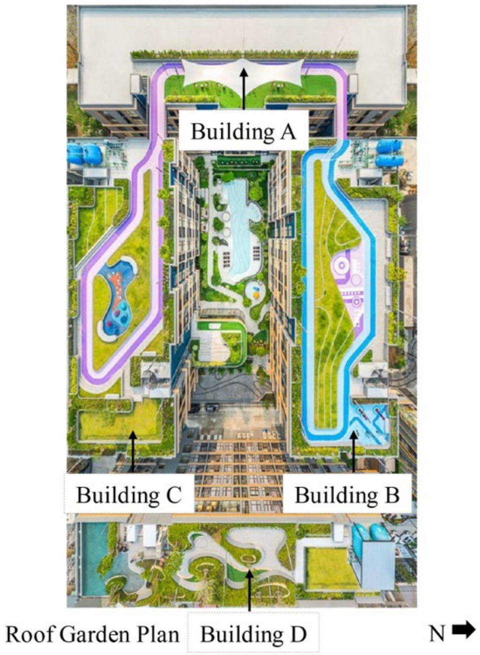

Fig.1 Design of Rooftop Gardens on Four Condominium Buildings to Evaluate Heat Reduction Efficiency

Although each rooftop includes essential service structures such as staircases, elevator shafts, and water storage tanks of approximately 2.50 meters in height, these elements were excluded from the calculation of usable rooftop area due to their limited thermal contribution and nonparticipation in the design configurations. The distribution of the four design types across the buildings is summarized in Table 1, which details the percentage allocation assigned to each rooftop garden condition. Building A includes 80 percent Type 01 coverage, representing the least vegetated configuration, while Building D includes only 20 percent Type 01 coverage and significantly higher proportions of Types 02, 03, and 04, making it the most ecologically intensive rooftop among the four. A design tolerance of ±10 percent was permitted to accommodate construction variability and ensure realistic implementation.

This gradual variation in rooftop composition across the four buildings enables a systematic assessment of how increasing vegetation density, substrate depth, and water surface area influence rooftop thermal behavior. By comparing heat accumulation and heat-flux performance across these design gradations, the study provides insight into the incremental benefits of different ecological design elements, thereby informing practical strategies for optimizing rooftop thermal performance in high-density urban environments.

Table 1. The rooftop areas of the four buildings were modified based on the percentage allocation of the design conditions

Design conditions	Each building for rooftop areas = 100%			
	A	B	C	D
Type 01	80%	60%	40%	20%
Type 02	15%	20%	40%	20%
Type 03	5%	20%	20%	40%
Type 04	–	–	–	20%

Note: The margin of error in the design proportions is ±10%.

4. EXPERIMENTAL SET-UP

The experimental investigation was conducted to evaluate the thermal performance of four rooftop garden configurations installed on four condominium buildings located in Salaya, Phutthamonthon, Nakhon Pathom, Thailand. The testing took place in April 2025, a period representative of peak summer conditions in a tropical climate. Each building had an average rooftop area of approximately 1,200 square meters, upon which the four design typologies were applied according to the distribution presented earlier. Several indoor spaces beneath the rooftop level on the eighth floor were selected as temperature and heat-flux monitoring points, allowing for direct comparison with outdoor ambient conditions.

Each condominium building contained between 23 and 27 residential units, with slight variations in room size due to differences between central and corner units. All buildings were designed with a central corridor measuring 1.5 meters in width, a floor-to-ceiling height of 2.60 meters, and a 0.40-meter air gap above the ceiling to accommodate electrical and mechanical installations. Staircase and elevator zones followed consistent dimensional standards across the buildings, with the exception of Building D, where part of the space was allocated to mechanical systems associated with the rooftop swimming pool. Temperature measurements were conducted using K-type thermocouples with an operational range of 0 to 1250°C and a measurement resolution of ±0.5°C. The sensors were installed at the center of selected rooms and corridor locations beneath the rooftop slab. These thermocouples were connected to a multi-channel data logger (Hioki Model 8422-52, accuracy ±0.8 percent), which recorded synchronous temperature data across all buildings. To quantify the heat transfer passing through the rooftop slab into the rooms below, heat flux meters (Omega HFS-3, range 1 to 1400 W/m², error ±0.5 percent) were installed on the ceiling surfaces directly beneath the rooftop gardens. All doors and windows of monitored rooms were kept closed during the measurement period to ensure that heat transfer could be attributed solely to rooftop thermal behavior.

Data collection was conducted simultaneously for all four buildings from 08:00 to 18:00 at 30-minute intervals. The sensor layout and measurement positions are illustrated in Fig. 2, which shows the spatial arrangement of indoor temperature sensors, corridor monitoring points, and heat flux instrumentation. The monitoring scheme allowed for synchronized temperature and heat-flux comparisons among the four buildings, ensuring consistent exposure to ambient solar radiation and environmental conditions throughout the testing period. The variables recorded during the experiment included room temperature (Tr), corridor temperature (Tc), outdoor ambient temperature (Tamb), and heat flux (HF). These measurements formed the basis for analyzing the thermal impacts of each rooftop design configuration and for determining the relative heat accumulation differences across the four buildings.

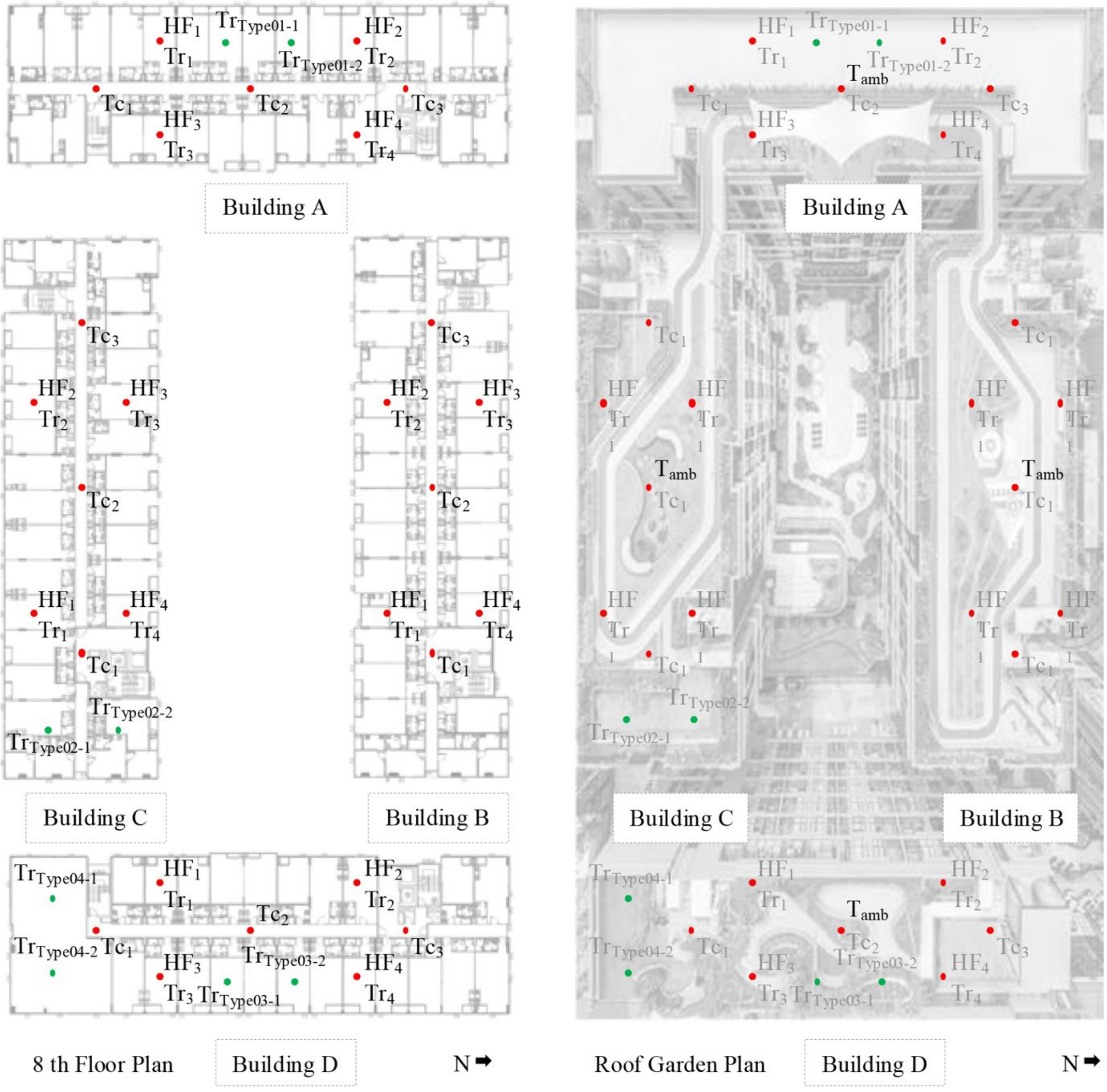

Fig. 2 Measured positions of four buildings

5. RESULTS AND DISCUSSION

5.1 Location Specific Temperatures

The temperature variations recorded at specific rooftop locations corresponding to the four design types were analyzed to determine the extent to which each configuration affected the thermal environment beneath the rooftop slab. The measurements were collected from 08:00 to 18:00 and were compared directly with the outdoor ambient temperature. The hourly temperature trends for each design type are illustrated in Fig. 3.

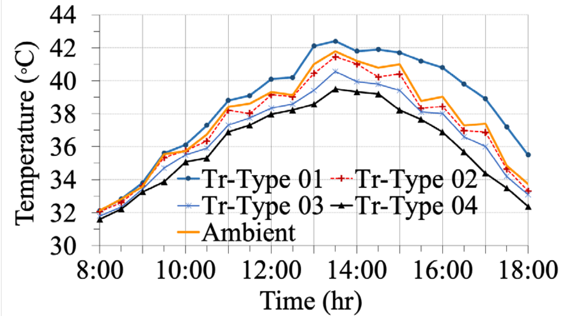

Fig.3 Hourly variations of temperature of location-specific (type 01, 02, 03, and 04)

During the early morning period between 08:00 and 09:30, the average temperature at the Type 01 location was nearly identical to the ambient temperature, indicating minimal thermal influence during low solar intensity. As the day progressed and solar radiation increased, the temperature at this location consistently exceeded the ambient temperature. Between 10:00 and 18:00, the Type 01 position exhibited temperature differences ranging from 0.36°C to 2.44°C above ambient, with the largest deviation occurring at approximately 13:30. This pattern reflects the high heat absorption and limited thermal resistance of the open hardscape system.

In contrast, the areas corresponding to Types 02, 03, and 04 maintained lower temperatures than the outdoor ambient temperature throughout the day. The morning temperature differences among the four design types resulted in a gap of 1.36°C, while in the afternoon this difference increased to 2.96°C, as shown in Table 2. These variations demonstrate the increasing capacity of each design type to mitigate rooftop heat loads, particularly during periods of peak solar exposure. A clear hierarchical thermal performance was observed across the four design conditions. At any given time, Type 01 consistently recorded the highest temperatures, followed by Type 02, Type 03, and Type 04. The mean temperature differences between these sequential configurations were 1.29°C (Type 01 versus Type 02), 0.55°C (Type 02 versus Type 03), and 0.65°C (Type 03 versus Type 04). Notably, Type 04 achieved an average temperature that was 1.52°C lower than the ambient temperature, as presented in Table 3. This result indicates the substantial cooling benefit provided by water-based rooftop systems due to evaporative and thermal mass effects.

Overall, the analysis confirms that rooftop configurations incorporating vegetation and water features offer superior thermal moderation compared to open hardscape roofs. Increasing vegetation density, deeper soil layers, and the presence of water elements significantly enhance thermal performance by reducing heat absorption, increasing evaporative cooling, and moderating rooftop surface temperatures. These findings demonstrate the effectiveness of ecological rooftop design strategies in lowering localized temperatures and reducing heat transfer into indoor spaces.

Table 2. The average temperatures at specific positions for Type 01, 02, 03, and 04

Type /Ambient	Time	Average Temperature
type 01	08.00–12.00	36.19
	12.00–16.00	41.36
type 02	08.00–12.00	35.68
	12.00–16.00	39.83
type 03	08.00–12.00	35.23
	12.00–16.00	39.12
type 04	08.00–12.00	34.83
	12.00–16.00	38.40
Ambient	08.00–12.00	35.87
	12.00–16.00	40.22

Table 3. The differences in average temperatures at specific positions for Type 01, 02, 03, and 04

Type /Ambient	Average Temperature	Type comparerison	Temperature difference
Type 01	38.53	01 vs 02	1.29
Type 02	37.25	02 vs 03	0.55
Type 03	36.70	03 vs 04	0.65
Type 04	36.05	04 vs Ambient	-1.52
Ambient	37.56	–	–

5.2 Corridor Temperatures

he thermal conditions within the corridors located directly beneath the rooftop of each building were examined to assess how the different rooftop garden configurations influenced shared interior spaces. The hourly variations in corridor temperatures for Buildings

A, B, C, and D, together with the outdoor ambient temperature, are illustrated in Fig. 4. All measurements were recorded from 08:00 to 18:00 under consistent weather conditions.

Throughout the monitoring period, the corridor temperatures exhibited fluctuations ranging from approximately 0.5°C to 1.8°C. A distinct thermal hierarchy emerged, consistent with the rooftop design intensity of each building. Building A, which possessed the highest proportion of open hardscape rooftop area, consistently recorded the highest corridor temperatures. Building B followed, while Buildings C and D registered progressively lower corridor temperatures. This pattern aligns with the incremental increase in green and water-based design components applied to the rooftops of these buildings. The comparative analysis presented in Table 4 confirms these observations. The average corridor temperatures of Buildings A and B differed by 0.51°C, while Buildings B and C differed by 0.58°C. The smallest difference, 0.34°C, occurred between Buildings C and D, reflecting the more substantial ecological enhancements applied in the latter two configurations. Importantly, the corridor temperatures in Buildings C and D were lower than the outdoor ambient temperature by 0.56°C and 0.89°C, respectively. This finding indicates that increased vegetation density and deeper substrate layers on the rooftop can significantly reduce heat transfer into communal interior spaces.

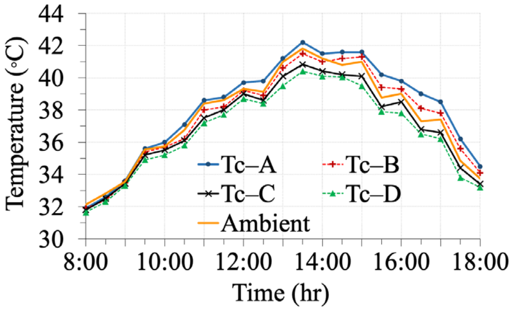

Fig.4 Hourly variations of temperature of corridor in buildings A, B, C, and D

Table 4. Comparison of average corridor temperature differences across each building

Building /Ambient	Average Temperature	Type comparerison	Temperature difference
Tc-A	38.10	A vs B	0.51
Tc-B	37.59	B vs C	0.58
Tc-C	37.01	C vs D	0.34
Tc-D	36.67	Ambient vs D	0.89
Ambient	37.56	Ambient vs C	0.56

The observed temperature reductions can be attributed to several mechanisms, including shading from vegetation, increased evapotranspiration, and reduced direct solar gain on the rooftop surface. These combined effects result in lower conductive heat transfer through the rooftop slab and contribute to maintaining cooler corridor environments. In high-density residential buildings, where corridors serve as primary circulation and ventilation pathways, improved thermal performance in these areas enhances overall indoor comfort and reduces reliance on mechanical cooling systems. In summary, the results demonstrate that rooftop gardens with higher ecological design intensity provide measurable cooling benefits not only to individual rooms but also to shared indoor environments. This emphasizes the broader thermal impact of rooftop landscape interventions and supports their application as passive cooling strategies in tropical residential developments.

5.3 Room Temperatures

The indoor temperatures of the residential units located directly beneath the rooftop slab were analyzed to evaluate the influence of the rooftop garden configurations on heat transfer into occupied spaces. The hourly temperature variations for Buildings A, B, C, and D are presented in Fig. 5, covering the monitoring period from 08:00 to 18:00. These measurements provide direct insight into how the rooftop design typologies affected interior thermal conditions during daytime hours with high solar radiation. The indoor temperatures recorded across the four buildings fluctuated by approximately 0.5°C to 2.0°C throughout the day. A clear stratification of thermal performance was observed, aligned with the degree of ecological enhancement in each rooftop design. Building A, which had the highest proportion of open hardscape rooftop area, consistently recorded the highest indoor temperatures. Building B exhibited moderately lower temperatures, while Buildings C and D recorded the lowest. This progression demonstrates the effectiveness of increased vegetation density, deeper substrate layers, and water elements in reducing rooftop heat accumulation and conductive heat transfer into interior rooms.

The comparative temperature differences summarized in Table 5 reinforce these findings. The average indoor temperatures between Buildings A and B differed by 0.80°C, while Buildings B and C differed by 0.72°C. The smallest difference, 0.49°C, was observed between Buildings C and D, reflecting the diminishing marginal impact of ecological enhancement as rooftop designs became increasingly intensive. Notably, the indoor temperatures of Buildings C and D were consistently lower than the outdoor ambient temperature by 0.25°C and 0.74°C, respectively. This is a significant outcome because it indicates that well-designed rooftop garden systems can maintain indoor environmental temperatures below ambient levels without the use of mechanical cooling. The cooling effects observed in Buildings C and D can be attributed to shading from vegetation, reduced solar absorption due to vegetated surfaces, increased evapotranspiration, and thermal buffering provided by soil and water features. These mechanisms collectively decrease the thermal load transmitted through the rooftop slab. The superior performance of Building D, which incorporates both vegetation and a water element, further demonstrates the synergistic benefits of integrating diverse ecological components into rooftop design.

Overall, the room temperature analysis confirms that more advanced rooftop garden systems significantly improve thermal comfort within residential units in tropical climates. By reducing heat gain at the building envelope, these systems lessen dependence on mechanical air conditioning and support energy-efficient residential building operation. The results highlight the importance of rooftop garden configurations as passive cooling strategies for high-density urban developments.

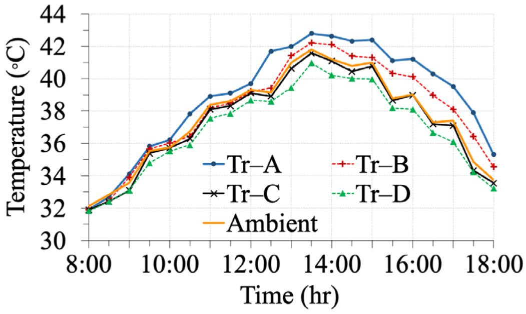

Fig.5 Hourly variations of temperature of room in buildings A, B, C, and D

Table 5. Comparison of average indoor temperature differences across each building

Building /Ambient	Average Temperature	Type comparerison	Temperature difference
Tr-A	38.83	A vs B	0.80
Tr-B	38.03	B vs C	0.72
Tr-C	37.31	C vs D	0.49
Tr-D	36.83	Ambient vs D	0.74
Ambient	37.56	Ambient vs C	0.25

5.4 Percentage heat flux reduction

The heat flux measurements provided a direct assessment of the thermal energy transferred through the rooftop slab of each building. This parameter is critical because it indicates the extent to which rooftop surface conditions influence indoor heat gain. The hourly variations in heat flux for the four buildings are shown in Fig. 6, alongside the corresponding solar radiation profile. The heat flux of all buildings followed the same general pattern as solar radiation, with values increasing sharply during late morning, peaking near midday, and declining toward late afternoon.

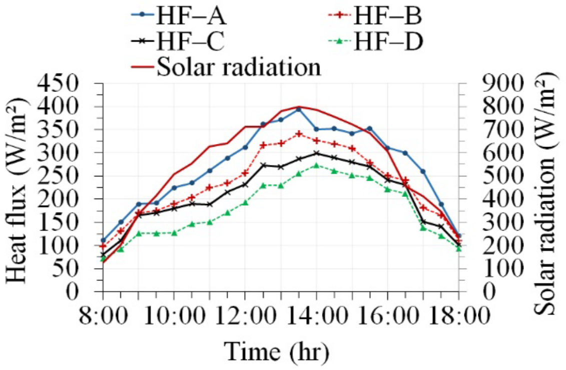

Fig.6 Hourly variations in heat flux and solar radiation of buildings A, B, C, and D

Building A, which features a predominantly open hardscape rooftop configuration, consistently exhibited the highest heat flux values throughout the day. On average, its heat flux exceeded that of Building B by approximately 32 W/m². Similarly, Building C recorded higher heat flux values than Building D by a comparable margin. This indicates that increased vegetation density, deeper soil layers, and the presence of water features can substantially reduce conductive heat transfer into the interior spaces below the rooftop slab.

The percentage of heat flux reduction was calculated using the relationship:

$$Reduction\ (\%) = \left(\frac{q_{\text{before}} - q_{\text{after}}}{q_{\text{before}}}\right) \times 100 \qquad (1)$$

where:

q_{before} = heat flux before improvement (W/m²)
q_{after} = heat flux after improvement (W/m²)

A comparison between Buildings A and B is presented in Fig. 7. Building B recorded heat flux values that were 10 to 78 W/m² lower than Building A. During the morning period from 08:00 to 12:00, the percentage heat flux reduction ranged from 9 percent to 19 percent. In the afternoon, from 12:00 to 18:00, the reduction ranged from 7 percent to 21 percent. The slightly lower reduction rate in the afternoon may be attributed to accumulated thermal mass within rooftop materials, which delayed the release of stored heat. A similar trend was observed between Buildings C and D, illustrated in Fig. 8. Building D consistently exhibited lower heat flux values, with differences ranging from 8 to 53 W/m² compared to Building C. Heat flux reduction between the two buildings ranged from 11 percent to 29 percent in the morning and from 8 percent to 16 percent in the afternoon. The enhanced performance of Building D is associated with its thicker substrate layer and higher vegetation density, which improve evapotranspiration and provide greater thermal insulation.

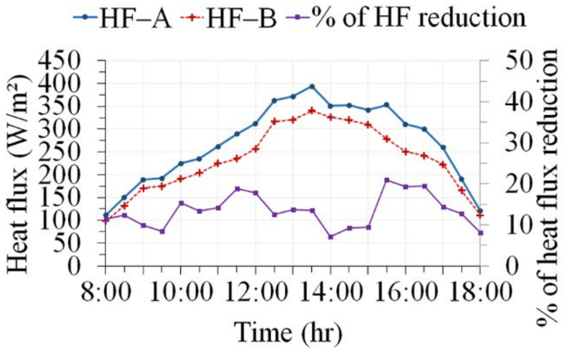

Fig.7 Hourly variations in heat flux and percentage heat flux reduction of the buildings A and B

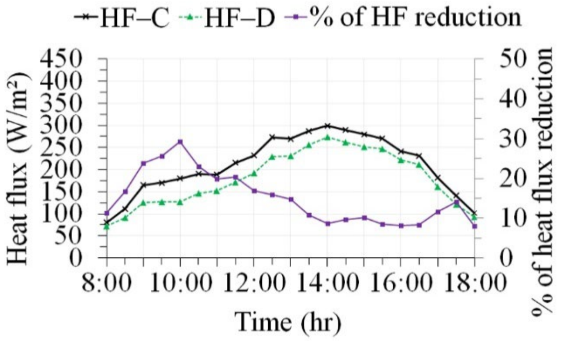

Fig.8 Hourly variations in heat flux and percentage heat flux reduction of the buildings C and D

Additional comparison between Buildings B and C, presented in Fig. 9, revealed a more modest difference in heat flux. Building C achieved an average heat flux reduction of 9.99 percent relative to Building B. Although the improvement is smaller than other comparisons, it demonstrates that moderate increases in rooftop vegetation and substrate depth can still yield meaningful thermal performance benefits. The most notable thermal improvement was observed between Buildings A and D, as shown in Fig. 10. Building D exhibited the highest overall reduction in heat flux, with an average decrease of 34.34 percent across the monitoring period and peak reductions reaching up to 46 percent. This significant thermal mitigation effect is attributed to the combined influence of vegetation layers, soil depth, and the water feature integrated into the rooftop garden system of Building D. The presence of multiple ecological and thermal-mass components substantially reduced direct solar absorption and enhanced evaporative and conductive heat dissipation.

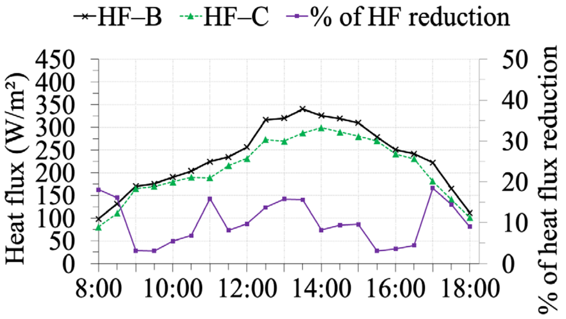

Fig.9 Hourly variations in heat flux and percentage heat flux reduction of the buildings B and C

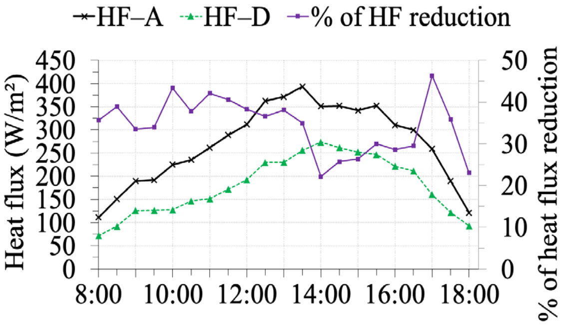

Fig.10 Hourly variations in heat flux and percentage heat flux reduction of the buildings A and D

6. CONCLUSIONS

This study evaluated the thermal performance of four condominium buildings with varying rooftop garden configurations designed to accommodate different resident activities. The experimental results confirm that rooftop gardens, when designed with appropriate landscape and functional elements, provide significant cooling benefits in high-density residential environments located in tropical climates. The comparative temperature analysis demonstrated a clear hierarchy of thermal performance across the buildings. Room temperatures beneath the rooftop of Building D were consistently lower than those of Buildings C, B, and A, respectively. Notably, field measurements showed that indoor temperatures in Buildings D and C remained close to or below ambient outdoor temperature throughout the monitoring period. This is a particularly important finding, as it confirms the capability of intensive green roof systems and integrated amenity features to maintain comfortable indoor conditions without reliance on mechanical cooling during daytime hours.

Heat flux analysis further validated these thermal benefits. During the testing period from 08:00 AM to 06:00 PM, reductions in heat flux ranged from 7% to 21% between Buildings A and B, and from 8% to 29% between Buildings C and D. These findings demonstrate that the extent of heat flux reduction is influenced not only by solar intensity but also by the rooftop design configurations, including open hardscape areas (Type 01), lawn systems (Type 02), vegetative planting zones (Type 03), and swimming pool elements (Type 04). The results highlight that both the depth and type of planting media, vegetation density, and water-surface elements can enhance rooftop thermal performance and reduce heat transfer into occupied spaces below.

Overall, Building D, with the most comprehensive rooftop design incorporating increased vegetation coverage and water elements, achieved the greatest reduction in heat accumulation. This confirms that advanced green roof systems serve as effective passive strategies to reduce indoor temperatures, mitigate heat stress, and improve thermal comfort in high-rise structures.

Beyond environmental performance, the findings emphasize the importance of aligning rooftop garden design with the social and recreational needs of residents, thereby maximizing space utilization and enhancing urban livability. Designers should consider rooftop functions that support resident activities while ensuring that structural load capacity, support systems, and financial investment remain feasible for building owners. Balancing thermal performance with architectural function and economic practicality is essential for scalable rooftop garden implementation in urban settings.

In conclusion, this study demonstrates that rooftop gardens can significantly reduce roof-related heat gain and support sustainable building performance in tropical climates. Future research should explore long-term monitoring across seasonal variations, quantify energy-saving potential, and evaluate integration with renewable energy, stormwater management, and carbon-reduction strategies. These insights can contribute to advancing policy frameworks and design standards for urban green infrastructure, promoting resilient and climate-adaptive cities.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] Tan, M., Li, X., Lu, C., Luo, W., Kong, X., and Ma, S., Urban Population Densities and Their Policy Implications in China. Habitat International, Vol. 32, 2008, pp. 471-484. https://doi.org/10.1016/j.habitatint.2008.01.003

[2] Xu, G., Zhou, Z., Jiao, L., and Zhao, R., Compact Urban Form and Expansion Pattern Slow Down the Decline in Urban Densities: A Global Perspective. Land Use Policy, Vol. 94, 2020, 104563. https://doi.org/10.1016/j.landusepol.2020.104563

[3] Gu, D., Andreev, K., and Dupre M.E., Major Trends in Population Growth Around the World. China CDC Weekly, Vol. 3, Issue 28, 2021, pp. 604-613. https://doi.org/10.46234/ccdcw2021.160

[4] Zhang, D., Liu, J., Liu, K., and Zhang, Y., The Non-Linear Impact of Urban Rail Transit on Commercial Property Prices: Based on a Spatial Heterogeneity Perspective. Applied Geography, Vol. 171, 2024, 103385. https://doi.org/10.1016/j.apgeog.2024.103385

[5] Xu, T., Zhang, M., and Aditjandra, P., The Impact of Urban Rail Transit on Commercial Property Value: New Evidence from Wuhan, China. Transportation Research Part A: Policy and Practice, Vol. 91, 2016, pp. 223-235. https://doi.org/10.1016/j.tra.2016.06.026

[6] Deng, X., Huang, J., Rozelle, S., and Uchida, E., Economic Growth and the Expansion of Urban Land in China. Urban Studies, Vol. 47, Issue 4, 2009, pp. 813-843. https://doi.org/10.1177/0042098009349770

[7] Ouyang, X., Wei, X., Wei, G., and Wang, K., The Expansion Efficiency of Urban Land in China's Urban Agglomerations and Its Impact on Ecosystem Services. Habitat International, Vol. 141, 2023, 102944. https://doi.org/10.1016/j.habitatint.2023.102944

[8] Santamouris, M., Recent Progress on Urban Overheating and Heat Island Research. Integrated Assessment of the Energy, Environmental, Vulnerability and Health Impact. Synergies with the Global Climate Change. Energy and Buildings, Vol. 207, 2020, 109482. https://doi.org/10.1016/J.ENBUILD.2019.109482

[9] Yang, L., Qian, F., Song, D .X., Zheng, K . J., Research on Urban Heat-Island Effect. Procedia Engineering, Vol. 169, 2016, pp. 11-18 https://doi.org/10.1016/j.proeng.2016.10.002

[10] Heaviside, C., Macintyre, H., and Vardoulakis S., The Urban Heat Island: Implications for

Health in a Changing Environment. Current Environmental Health Reports, Vol. 4, 2017, pp. 296–305. https://doi.org/10.1007/s40572-017-0150-3

[11] Halder, B., Bandyopadhyay, J., and Banik, P., Evaluation of the Climate Change Impact on Urban Heat Island Based on Land Surface Temperature and Geospatial Indicators. International Journal of Environmental, Vol. 15, 2021, 819–835. https://doi.org/10.1007/s41742-021-00356-8

[12] Karimi, A., Mohammad, P., García-Martínez, A., Moreno-Rangel, D., Gachkar, D., and Gachkar, S., New Developments and Future Challenges in Reducing and Controlling Heat Island Effect in Urban Areas. Environ Dev Sustain, Vol. 25, 2023, pp. 10485–10531. https://doi.org/10.1007/s10668-022-02530-0

[13] Berndtsson, J. C., Green Roof Performance Towards Management of Runoff Water Quantity and Quality: A Review. Ecological Engineering, Vol. 36, Issue, 4, 2010, pp. 351-360. https://doi.org/10.1016/j.ecoleng.2009.12.014

[14] Soga, M., Evans, M. J., Tsuchiya, K., and Fukano, Y., A Room with a Green View: The Importance of Nearby Nature for Mental Health During the COVID-19 Pandemic. Ecological Applications, Vol. 31, Issue 2, 2021, e2248. https://doi.org/10.1002/eap.2248

[15] Peng, L. L. H., and Jim, C. Y., Green-Roof Effects on Neighborhood Microclimate and Human Thermal Sensation. Energies, Vol. 6, Issue 2, 2013, pp. 598-618. https://doi.org/10.3390/en6020598

[16] Krebs, L. F., and Johansson, E., Influence of Microclimate on the Effect of Green Roofs in Southern Brazil – A Study Coupling Outdoor and Indoor Thermal Simulations. Energy and Buildings, Vol. 241, 2021, 110963. https://doi.org/10.1016/j.enbuild.2021.110963

[17] Castleton, H.F., Stovin, V., Beck, S.B.M., and Davison, J.B., Green Roofs; Building Energy Savings and the Potential for Retrofit. Energy and Buildings, Vol. 42, Issue 10, 2010, pp. 1582-1591. https://doi.org/10.1016/j.enbuild.2010.05.004

[18] William, R., Goodwell, A., Richardson, M., Le, P.V.V., Kumar, P., and Stillwell, A.S., An Environmental Cost-Benefit Analysis of Alternative Green Roofing Strategies. Ecological Engineering, Vol. 95, 2016, pp. 1-9. https://doi.org/10.1016/j.ecoleng.2016.06.091

[19]Ananacha, T., Thermal Performance of the Clear Block Wall for Ventilation. International Journal of GEOMATE, Vol. 23, Issue 96, 2022, 25–31. https://doi.org/10.21660/2022.96.3061

[20] Khedari, G., Chantawong, P., and Ananacha, T., Enhancing Indoor Air Quality and Thermal Comfort with a Ventilated Built-in Closet Design. International Journal of Heat and Technology, Vol. 42, No. 6, 2024, pp. 1963-1968. https://doi.org/10.18280/ijht.420613

[21]Getter, K. L., Rowe D.B., Robertson, G.P., Cregg, B. M., and Andresen, J. A., Carbon Sequestration Potential of Extensive Green Roofs. Environmental Science & Technology, Vol. 43, Issue 19, 2009, pp. 7564-7570. https://doi.org/10.1021/es901539x

[22]Cristiano, E., Farris, S., Deidda, R., and Viola, F., How Much Green Roofs and Rainwater Harvesting Systems Can Contribute to Urban Flood Mitigation?. Urban Water Journal, Vol. 20, Issue 2, 2023, pp. 140-157. https://doi.org/10.1080/1573062X.2022.2155849

[23] Xie, H., Randall, M. & dos Santos, S.M. Optimization of Roof Coverage and Tank Size for Integrated Green Roof Rainwater Harvesting Systems-a Case Study. Water Resour Manage 37, 4663–4678 (2023). https://doi.org/10.1007/s11269-023-03568-z

[24] Prayogo, T. B., and Susilo, G. E., Rainwater Harvesting and Electricity Saveing on Household Scale. International Journal of GEOMATE, Vol. 17, Issue 62, 2019, pp. 92-100. https://doi.org/10.21660/2019.62.91544

[25] Jokowinarno, D., and Kusumastuti, D. I., Rainwater Harvesting for Flood Peak Reduction in Way Awi Catchment, Indonesia. International Journal of GEOMATE, Vol. 18, Issue 70, 2020, pp. 246–251. https://doi.org/10.21660/2020.70.49845