

Evaluating The Effect of Various Urban Green Infrastructure Types on Thermal Comfort.

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ABSTRACT

The expansion of cities has led to an increase in man-made surfaces, exacerbating the urban heat island effect. One effective strategy for mitigating urban heat and regulating climate change is the implementation of urban green spaces. This study aimed to compare the cooling potential of various types of urban green infrastructure. The current conditions and different types of green infrastructure were designed and simulated using the ENVI-met model across four scenarios. The results indicated that green walls and green roofs significantly influence the micrometeorological conditions within urban canyons by increasing relative humidity and decreasing air temperature (T_a). Trees, in addition to these effects, also reduce mean radiative temperature (T_{mrt}) and physiological equivalent temperature (PET). When comparing the cooling potential of different green infrastructure types, the study found that, in terms of thermal comfort, only trees have a substantial impact on reducing PET, with reductions ranging from 6°C to 8.9°C, significantly more than green walls and green roofs, which showed no significant effect. However, in terms of micrometeorological conditions, all three types of urban green infrastructure demonstrated positive effects. Trees exhibited the highest cooling potential, with a reduction of 0.2°C to 1.5°C in air temperature, while green roofs had the lowest impact. The findings of this study provide valuable insights for landscape and urban designers in selecting and designing appropriate urban green infrastructure to enhance micrometeorological conditions and improve thermal comfort.

Keywords: Green infrastructure, Urban heat island, Thermal comfort, Outdoor cooling

Mathematics Subject Classification Number: 62P13

1. INTRODUCTION

More than half of the world's population lives in urban areas, and the urban population is growing, with 30 megacities in the world with a population of more than 10 million (Saaroni et al., 2018). The expansion of cities led to increase in man-made surfaces and thus to the increase the effect of urban heat island (Chun & Guldmann, 2018). The increase in temperature of urban centers compared to suburban and rural areas is defined as the urban heat island (Oke, 1982). Climate change also raises the average temperature in cities and exposes citizens to heat stress, which has negative effects such as increased mortality, reduced worker efficiency, increased urban pollution and increased energy consumption (Zölch et al., 2016).

More than half of the world's population now resides in urban areas, and this number is steadily increasing, with 30 megacities across the globe hosting populations exceeding 10 million (Saaroni et al., 2018). The expansion of cities has led to an increase in man-made surfaces, which in turn has amplified the urban heat island (UHI) effect (Chun & Guldmann, 2018). The UHI effect refers to the rise in temperature in urban centers compared to suburban and rural areas (Oke, 1982). Additionally, climate change is raising average temperatures in cities, exposing residents to heat stress with serious consequences such as increased mortality, heightened urban pollution, and greater energy consumption (Zölch et al., 2016).

One effective strategy to combat urban heat and regulate the impacts of climate change is through urban green spaces. Urban green infrastructure plays a crucial role in enhancing the microclimate in cities by promoting evapotranspiration, providing shade, and reducing the intensity of heat waves (Bartasaghi Koc et al., 2018). According to Herz and Schlink (2019), heat stress is more severe in densely populated areas with less vegetation and materials that absorb sunlight.

Various studies have highlighted the significance of urban green infrastructure (UGI) in enhancing thermal comfort in urban areas. Research has shown that different types of UGI, such as green stormwater infrastructure (GSI) combinations (Xu et al., 2024), trees, living facades, and high albedo pavements (Taher et al., 2024), play a crucial role in mitigating urban heat islands (UHIs) and improving outdoor thermal environments. For instance, the effectiveness of UGI in improving heat comfort can vary based on factors like precipitation levels and relative humidity (Byeong et al., 2024). Additionally, the impact of UGI on thermal comfort differs based on the specific form of greening, with studies indicating that planting trees has the best effect on outdoor thermal environments compared to green facades and green roofs (Chang et al., 2024).

Urban green infrastructures that contribute to lowering air temperature (T_a) in cities include parks, street trees, green walls, and green roofs (Lu et al., 2017). On the other hand, Plants enhance microclimatic conditions and mitigate the UHI effect through shading and evapotranspiration (Abdi et al., 2020; Hami et al., 2019), the creation of cool air islands (Lin & Lin, 2016), reflecting solar radiation and reducing mean radiant temperature (T_{mrt}) (Salata et al., 2017). Understanding these nuances is essential for designing sustainable and effective UGI strategies to enhance thermal comfort in urban settings.

Previous research has frequently looked at the impact of certain forms of urban green infrastructure separately. Unal et al. (2018) discovered that planting street trees in hot and humid areas increases thermal comfort, with planting density and tree canopy size impacting cooling potential. Morakinyo et al. (2017) demonstrated that tree height is an essential factor in the cooling potential of street trees, with taller trees in deep urban canyons and shorter trees in shallow canyons providing the best cooling effects. Yang et al. (2018) showed that the distance of trees from buildings and other vegetation also affects the microclimate of streets. According to Ahmadi Vehari et al. (2019), the arrangement of street trees improves pedestrian thermal comfort by reducing the physiologically equivalent temperature (PET) by up to 0.5 °C. Similarly, Park et al. (2019) discovered that as tree size increases and planting distance decreases, the T_{mrt} on sidewalks and street surfaces declines.

Vertical Greening Systems have played a crucial role in enhancing thermal comfort in both indoor and outdoor environments. Baghaei Daemei et al. (2018) measured the cooling effect of vertical greenery systems, finding that T_a decreases by 0.39 °C to 0.75 °C within 0-0.5 meters of these systems. According to Koch et al. (2019), the morphological properties of plants in green walls can help reduce air pollution and the UHI effect. Also, Ottel  and Perini (2017) reported that during 8 hours of summer heat, direct green fa ades reduced temperatures by 1.7 °C while living walls with planter boxes reduced temperatures by 8.4 °C. Zhang et al. (2019) identified leaf transpiration and photosynthesis as critical factors in the cooling effect of green fa ades. Yin et al. (2017) highlighted other factors influencing the cooling potential of vertical green systems, including vegetation coverage, plant thickness, point density, and green fa ade volume.

Green roofs are one type of green infrastructure that has been shown to reduce heat. According to Dong et al. (2020), research demonstrates that green roofs directly mitigate the UHI effect in dense metropolitan areas, lowering average land surface temperatures by 0.91 °C. Berardi (2016) emphasizes that the combination of green roofs and water-to-air heat exchangers successfully lowers indoor and outdoor temperatures. In another study, Jin et al. (2018) found that green roofs lowered T_a by up to 0.5 °C. Rahimi and Nobar (2023) also show how green infrastructure can revitalize urban agricultural land by enhancing thermal comfort and improving people's well-being. Alcazar et al. (2016) discovered that leaf area density has a substantial effect on the cooling potential of green roofs, with larger densities capable of reducing T_a by approximately 1 °C.

Some studies demonstrate the cooling impacts of different urban green infrastructures. Gromke et al. (2015), the pedestrian level, and street trees provided a maximum reduction in T_a of 1.6 °C, outperforming green fa ades, which only reduced T_a by 0.3 °C, while the cooling effect of green roofs was negligible. Z lch et al. (2016) obtained similar results, reporting that trees decreased the PET index by 13% compared to the current situation, offering better thermal comfort than green fa ades, which only reduced the PET index by 5–10%. Herath et al. (2018) also concluded that curbside trees were more effective in improving thermal comfort and reducing the UHI effect by reducing T_a by 1.87 °C compared to green walls and green roofs. Comparing the cooling effects of different green infrastructures is crucial, as it is not always feasible to implement all types of these infrastructures in various urban environments. For example, in deep urban canyons, limited space may prevent tree planting, or the conditions for green wall plant growth may be inadequate. Since different green infrastructures may have varying impacts in other urban settings, such as deep canyons versus open spaces, it is critical to evaluate their cooling capability in these scenarios. This research looks at the plant's impact on densely inhabited urban buildings in Tehran. Three scenarios are designed to contain three types of green infrastructure: trees, walls, and roofs. In this study, we began by identifying the study location and then conducted field studies. On the simulation day, we used meteorological data to simulate the chosen section of the study area in ENVI-met for model validation. We then designed and simulated scenarios incorporating urban green infrastructure, including street trees, green walls, and green roofs. To evaluate the micrometeorological conditions, we compared the thermal outputs of the ENVI-met model, specifically the simulated air temperature (T_a), across different scenarios. Furthermore, the PET index was calculated using RayMan software to measure

thermal comfort across various circumstances." Given the need for a more detailed examination of the cooling benefits of various urban green infrastructures, taking into account their area and effectiveness under different climatic conditions. The best infrastructures for enhancing thermal comfort and reducing the UHI impact are identified by comparing their cooling effects in this study. and ultimately provided answers to these queries:

- How Does Urban Green Infrastructure Influence Thermal Comfort in Urban Canyons?
- What role do street trees, green walls, and green roofs play in mitigating urban heat island effects?

2. MATERIAL AND METHODS

2.1. STUDY AREA

The study site is in Tehran, Iran's capital city, at a latitude of 39.52° N and a longitude of 54.26° E. We chose a specific section of Modares Street, near Haft Tir Square, as the focus of this research (see Fig. 1). With peak summer temperatures between 28°C and 30°C from July to September, Tehran has a cold, semi-arid climate. The city receives an average annual precipitation of approximately 200 mm (Daemei et al., 2018). Positioned at an elevation of 1,189 meters above sea level, Tehran features minimal vegetation within the study area, bordered by tall buildings. The street is subject to heavy vehicular traffic and significant pedestrian movement, primarily due to the concentration of shopping centers in the vicinity. For this study, the simulation day was set for July 16th, 2020. Meteorological data, including air temperature, relative humidity, wind speed, and direction, were obtained from the Geophysics Meteorological Station near the study site (Table 1).

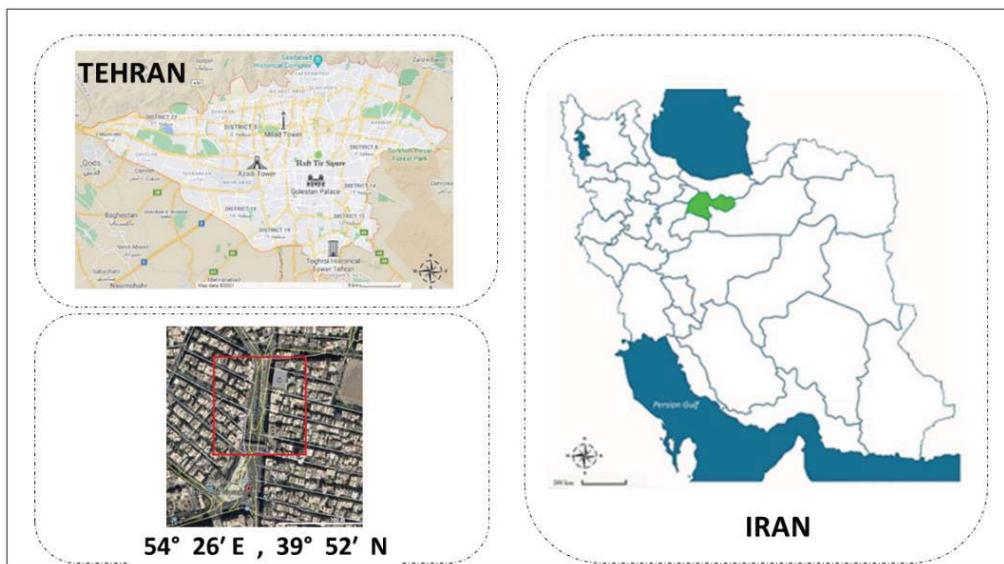


Figure 1. Location of Tehran and study area google map.

Table 1: meteorological data and model features.

Variable	Value
Longitude, Latitude	54°26'E, 39°52'N
Grids resolution (horizontal, vertical)	4 m, 4m
Simulation date	16.07.2020
Start time (hh:mm)	06:00
Total simulation time	14 h
Minimum and Maximum T _a	25.4 °C, 31.3 °C
Minimum and maximum relative humidity	25 %, 42 %
Wind speed at 10 m	2.0 m/s
Wind direction	200°

2.2 SIMULATION MODEL

The ENVI-met model was utilized to simulate various scenarios. This model can simulate interactions between the atmosphere, plants, and surfaces with a spatial accuracy greater than 0.5 m and a temporal resolution of 10 seconds. It is particularly effective in complex environments with diverse surfaces, materials, buildings of different shapes and heights, various types of vegetation, and varying arrangements of elements (Morakinyo et al., 2017). RayMan software (Matzarakis et al., 2010) was employed to calculate the PET index. The RayMan model is suitable for simulating temporal and spatial radiation fluxes and their density (Morakinyo et al., 2017). While RayMan operates based on three-dimensional radiation simulation, the ENVI-met model is grounded in the principles of computational fluid dynamics and thermodynamics (Acero & Herranz-Pascual, 2015). RayMan is highly capable of estimating changes in radiation fluxes across different environments, making it suitable for simulating micrometeorological conditions in complex urban settings (Sodoudi et al., 2018). In the simulation, ENVI-met treats plants as dynamic entities, taking into account plant properties such as porosity, evapotranspiration, photosynthesis, and energy absorption (Morakinyo et al., 2018; Zhang et al., 2018). Several studies have employed this model to evaluate thermal comfort and micrometeorological conditions across various scenarios (Morakinyo et al., 2017; Morakinyo & Lam, 2016; Sodoudi et al., 2018; Zhao & Fong, 2017).

Meteorological data were initially input into the ENVI-met model. After simulation, the ENVI-met output was used as input to the RayMan model to derive the PET index. According to Höppe (1999), PET is defined as "the air temperature at which, in a typical indoor setting, the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed." Factors such as shortwave and longwave radiation, which influence the thermal balance of the human body, are also included in the calculation of PET (Morakinyo et al., 2018; Morakinyo & Lam, 2016). The PET index is based on considering the physiological conditions of the

human body and uses the principles of the Munich Energy-balance Model for Individuals (Höppe, 1999) to model the thermal condition of the human body.

2.3 . MODEL VALIDATION

To validate the ENVI-met model, air temperature (T_a) and relative humidity were measured at two validation points, V01 and V02, through field measurements conducted between 9:00 and 16:00 on the simulation day. These points were selected based on the feasibility of placing measurement instruments and the suitability of the locations. The validation points were not situated under the direct shade of trees to avoid unrealistic results, and artificial shading was used to prevent direct sunlight from affecting the measuring instruments. Measurements were taken at a height of 1.2 meters, representative of the pedestrian level. The validation points were positioned as close to the center of the model as possible. Additionally, there was no vegetation around the validation points that could have influenced the relative humidity readings, nor were there any tall objects casting shadows on the instruments. The locations of the validation points were chosen near the edge of a building and a side street to minimize the impact of building shadows on the results.

The measured values were then compared with the simulated values at the same points using the coefficient of determination (R^2) and the Root Mean Square Error (RMSE). At validation point V01, a Digital Temperature and Humidity Meter (Clock/Humidity) – HTC 1 was used, with an accuracy of $\pm 1^\circ\text{C}$ for T_a and $\pm 5\%$ for relative humidity. At V02, a data logger model Mic 98581 was used, with an accuracy of $\pm 0.6^\circ\text{C}$ for T_a . At validation point V01, the R^2 value was 0.95, and the RMSE value was 0.65 for T_a , while the R^2 value for relative humidity was 0.91, and the RMSE was 2.12. At validation point V02, the R^2 value was 0.96, and the RMSE was 0.57. In previous studies, R^2 values ranged from 0.52 to 0.96, and RMSE values ranged from 0.26 to 4.83 (López-Cabeza et al., 2018). Therefore, the simulation results in this study were deemed valid and closely aligned with the measured values.

2.4 . SCENARIO DESIGN

This study examined four scenarios and compared them during the eight hours (9:00- 17:00). The first scenario reflected existing conditions, with less green space around the street. In all cases, the vegetation in the median stayed consistent.

The second scenario entailed green walls, with the walls along the street recognized as appropriate for such installation. The third scenario centred on the construction of green roofs, with the total area of the green roofs matching that of the green walls in the previous scenario. The last scenario consisted of trees that, taking into the height and width dimensions of the tree, attempted to make the total area equal to the green wall and green roof scenario, with a total of 30 trees. That's 30 trees, regardless of how many trees were in the middle of the street in all scenarios, all scenarios utilized deciduous species.

Four receptor sites were strategically positioned on both sides of the roadway to evaluate thermal comfort and micrometeorological parameters at the pedestrian level in various situations. Receptors R01 and R03 were on the east side, whereas R02 and R04 were on the west (Fig. 2). These areas were chosen based on their lot of traffic, notably on sidewalks near shopping malls. The building

adjacent to R01 is 15 meters tall, while the structures near the other three sites are 10 meters tall. These receptor locations are not located beneath tree canopies and are not considerably affected by shading. While there is some greenery at the R04 receptor, the other three points are not surrounded by flora. The overall methodology and approach adopted in this study are comprehensively depicted in Fig. 3, providing a visual representation of the study's design and execution.

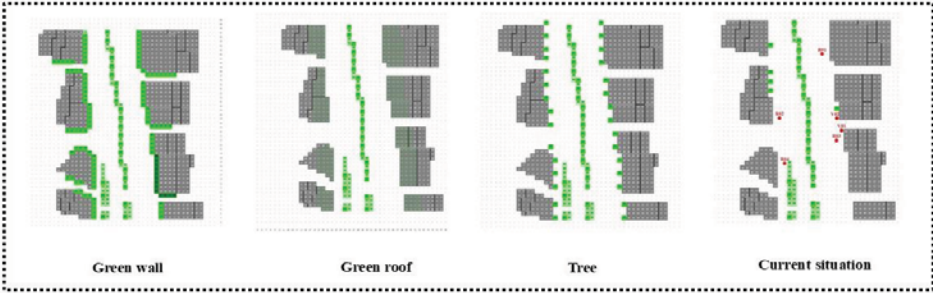


Figure 2. Scenarios and receptor's location

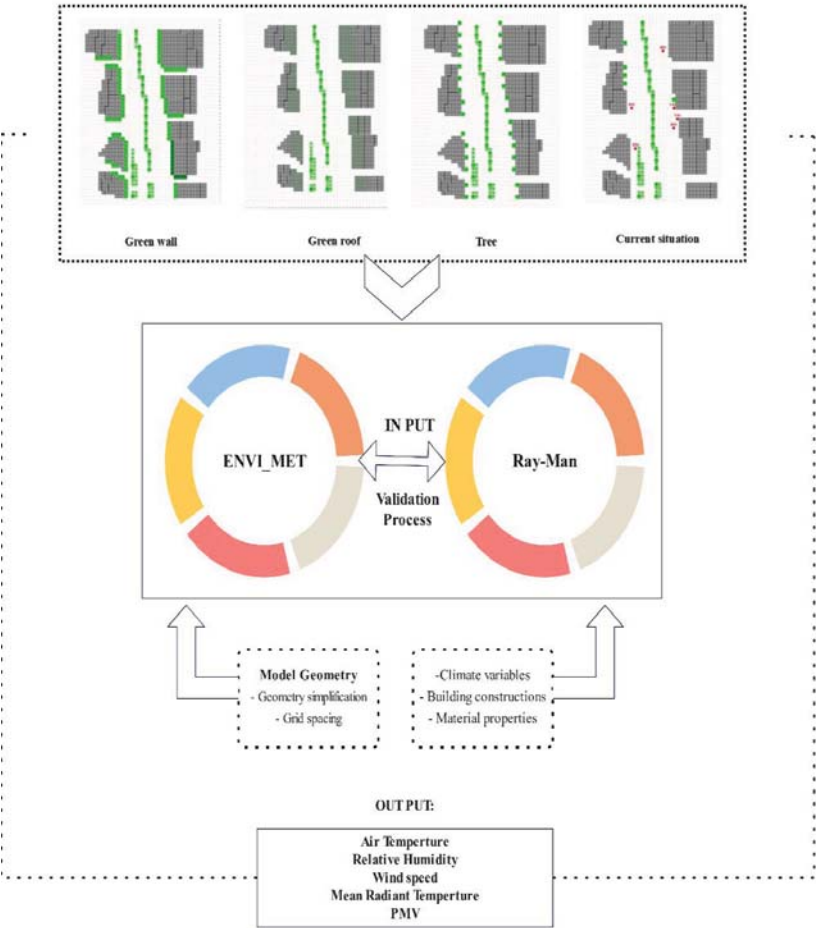


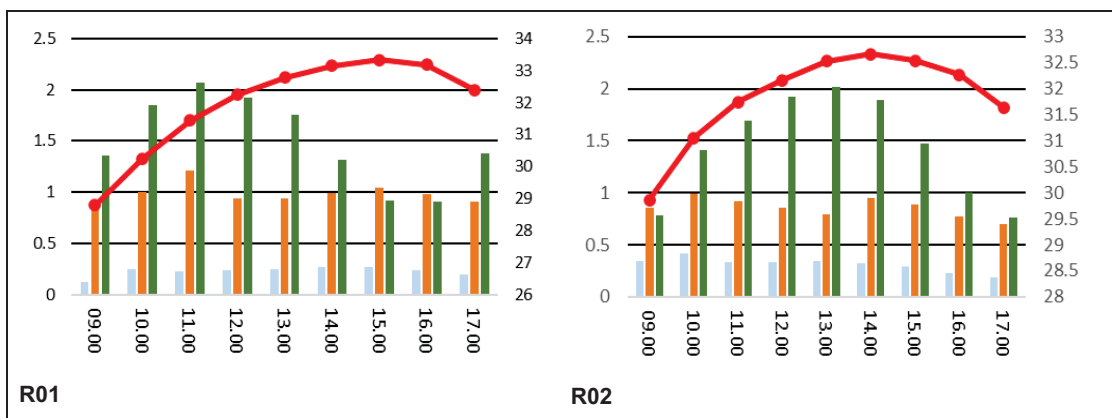
Figure 3. General approach of the study

3. RESULTS

The simulation outcomes were analyzed at four distinct receptor points positioned at a height of 1.2 meters. To assess the micrometeorological impacts of green infrastructure and its influence on the urban heat island effect, air temperature (T_a), mean radiant temperature (T_{mrt}), and physiological equivalent temperature (PET) were compared during the timeframe of 9:00 to 17:00. The extent of reduction in each of these indices, relative to the current baseline conditions, was systematically evaluated.

3.1 OUTDOOR COOLING

The results of the air temperature analysis conducted over eight hours from 9:00 to 17:00 demonstrate that the current condition, represented by receptor R01, exhibited the highest temperature, reaching 32 °C. In contrast, the scenario involving trees, as observed in receptor R04, recorded the lowest temperature at 29.8 °C. The simulation findings suggest that the lack of green space within the urban canyon is the cause of the higher temperatures observed in the current scenario. Across all four receptor points analyzed, it was evident that the tree-based scenarios outperformed others in mitigating air temperature, whereas the green roof scenarios demonstrated comparatively limited effectiveness in reducing T_a . Notably, at 13:00, receptor R02 experienced a reduction of 2°C in air temperature relative to the current state, marking the most significant hourly decrease (see Fig. 4). The mean air temperature across the four receptors further reinforces the superior cooling performance of the tree scenario, which achieved an average reduction of 1.5 °C. Thus, the deployment of street trees, when compared to green walls and green roofs, proves to be more effective in reducing T_a within urban canyons. This improved performance of trees can likely be attributed to their ability to obstruct the absorption of solar radiation by hard surfaces, thereby reducing surface temperatures through shading, decreasing short-wave radiation exposure, and enhancing the cooling effects of evapotranspiration.



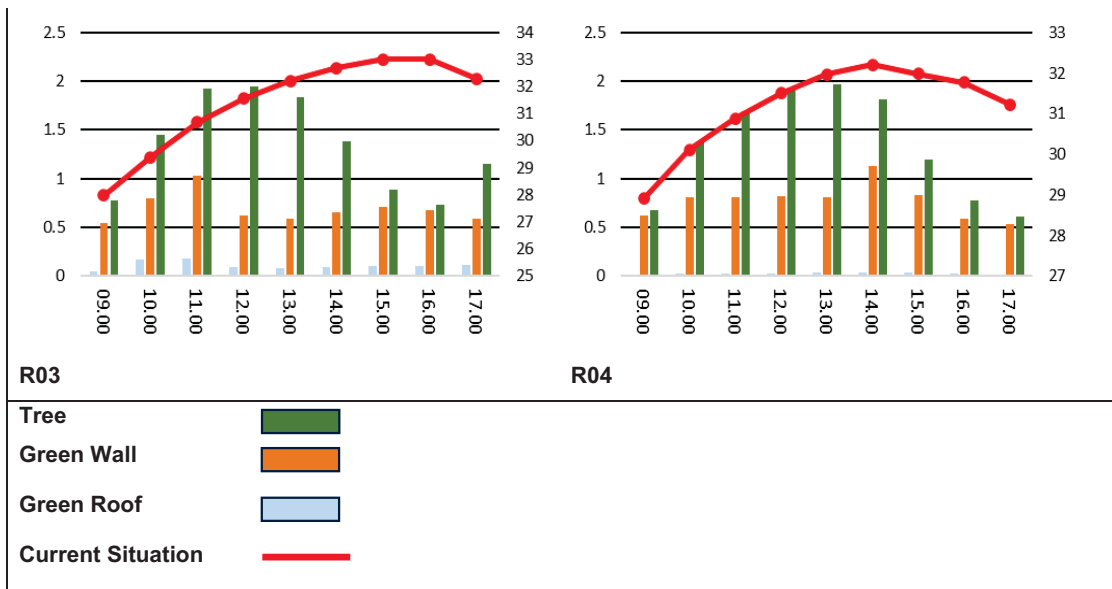


Figure 4. Ta change in different scenarios in receptors (R01, R02, R03, and R04).

A comparison of Ta through the canyon revealed that trees' surroundings have cooling impacts on areas further away, including the canyon's centre. In contrast, the green wall scenario reduced the air temperature exclusively near the wall and did not affect the canyon's core (Fig. 5). Furthermore, the green roof had a low effect, decreasing the Ta by an average of 0-0.3 °C. The canopy of trees reduces Ta in various areas of the canyon by preventing solar radiation from reaching vertical and horizontal surfaces, whereas green roofs and walls do not have this impact, which is why trees have a better cooling effect than other green infrastructures. Green roofs and green walls reduce air temperature through evapotranspiration while reducing solar radiation absorption on the surfaces of built green infrastructures. The results showed that, while the green roof at roof heights has more of a cooling impact than the pedestrian level and the green wall at heights has a different cooling effect, a comparison of the cooling potential of types of green infrastructure at building roof heights also shows that trees have a higher cooling effect on the canyon and the entire environment than the green wall and green roof.

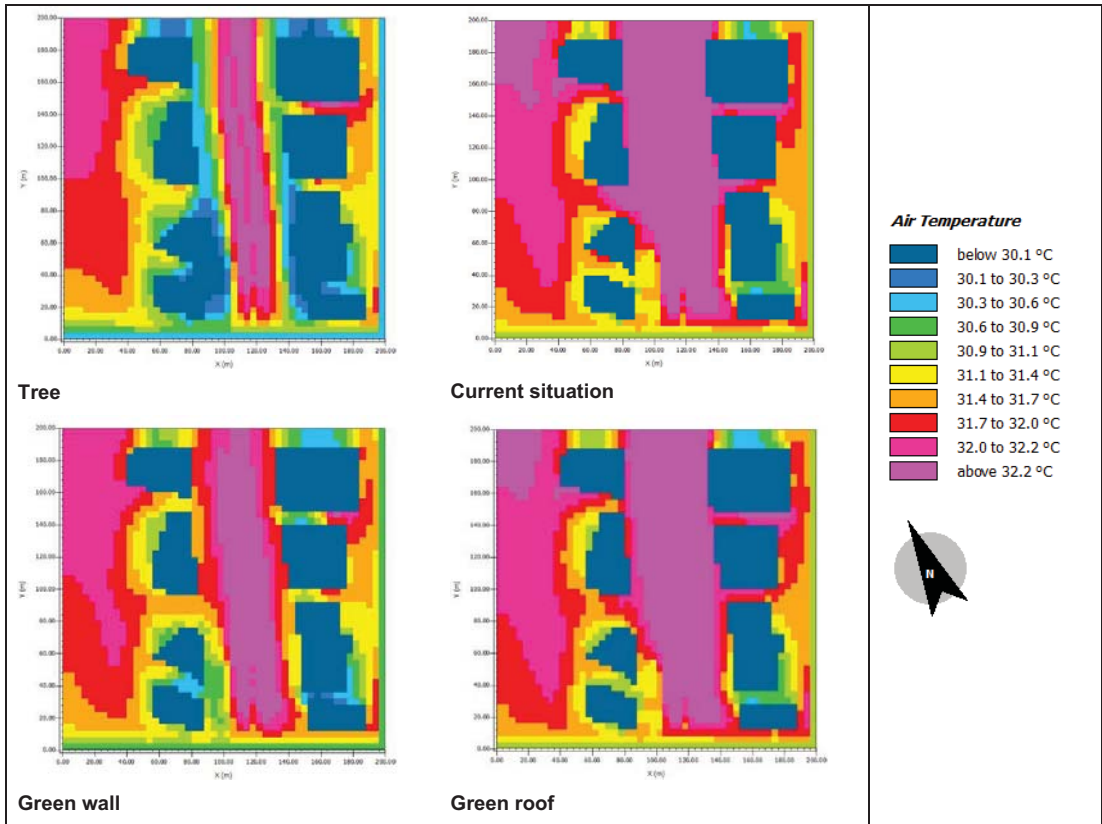


Figure 5. Comparison of simulated Ta in different scenarios at a height of 1.2m at 13:00.

3.2 HUMAN THERMAL COMFORT

Thermal comfort was assessed in each condition using PET and Tmrt for eight hours (9:00-17:00) at a height of 1.2 m. The results revealed that the means of PET in the receptors was 42.5-45.6 °C, indicating severe heat stress in the pedestrian area. This thermal discomfort is caused by a lack of vegetation in the canyon and the absorption of solar radiation by the canyon's hard surfaces during the hottest hours of the day. The mean PET in the tree scenario ranged between 34.5 and 36.7 °C, indicating an increase in thermal comfort at the sensors. The tree scenario had the best decrease in PET relative to the current circumstance at the R04 receptor at 14:00, with a 15.7 °C drop. Trees had a better effect on Ta and relative humidity than green walls, and they provided more shade, resulting in improved thermal comfort for people. The green wall, with an average PET of 39.4-42.7 °C, had minimal influence on thermal comfort due to its modest shading effects. Because of the long distance from the walkways and the absence of shade, the green roof had little influence on relative humidity, Ta, and Tmrt, resulting in no meaningful effect on PET (Fig 6).

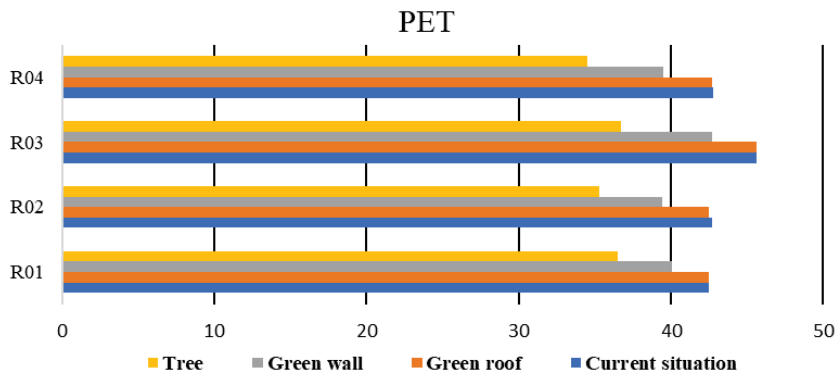


Figure 6. Mean PET (°C) values averaged over 9:00-17:00 at height of 1.2m

Temperature mean radiation has the best effect on outdoor thermal comfort; this index was evaluated in various settings from 9:00-17:00 at a height of 1.2 m. The simulation results of the Tmrt revealed that the scenario of trees with a mean of 44.6-48.7 °C had the lowest rate, and the green roof scenario had an unuseful influence on decreasing this index. The green roof scenario has a somewhat higher Tmrt than the current situation since the numerous trees in the canyon decreased in the green roof and other scenarios. The trees decreased the Tmrt by limiting shortwave radiation and providing shade, whereas the green wall and roof had negligible or no impact. The Tmrt is affected by these circumstances, which is the reason. Based on the TMR data, trees are the most effective of green infrastructure to enhance thermal comfort in urban canyons(fig.7).

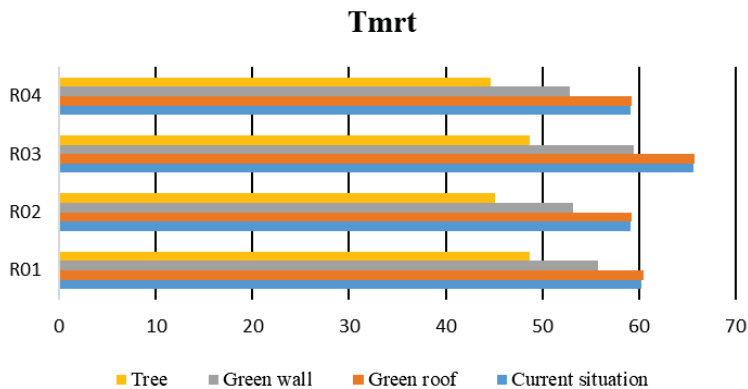


Figure 7. Mean Tmrt (°C) values averaged over 9:00-17:00 at height of 1.2m.

4. DISCUSSION

4.1 IMPACT OF URBAN CANYONS' GREEN INFRASTRUCTURE ON THERMAL COMFORT

The integration of green infrastructure in urban canyons significantly enhances thermal comfort, particularly during hot summer days. Research indicates that optimizing landscape patterns and

vegetation types can lead to substantial improvements in thermal conditions, although the effectiveness varies based on environmental factors. Urban green infrastructure, including trees, green walls, and green roofs, significantly influences thermal comfort in urban canyons by mitigating the urban heat island (UHI) effect and enhancing micrometeorological conditions. Studies such as Nobar et al.,(2025), Ahmadi Venhari et al. (2019), Aminipouri et al. (2019), and Klemm et al. (2015) have confirmed that green infrastructure reduces the ambient temperature (T_a) and surface temperatures within canyons through shading and the evapotranspiration process. This reduction in solar radiation absorption results in improved thermal comfort for residents. Liu et al. (2023) found that optimizing road greening can improve daytime thermal comfort in street canyons, with a maximum difference in the Universal Thermal Climate Index (UTCI) of 0.76 °C during the day, while nighttime improvements were minimal. Park et al. (2023) highlighted that green infrastructure's cooling effects are contingent on humidity levels, suggesting that in humid regions, additional strategies may be necessary to enhance thermal comfort. While the thermal comfort provided by different types of green infrastructure varies, the overall impact is positive. Trees, for example, significantly lower T_a and physiological equivalent temperature (PET) by shading vertical and horizontal surfaces, as well as enhancing evapotranspiration. Trees are most effective at reducing mean radiant temperature and air temperature, with the cooling effect positively correlated to plant area index (Rahimi and Nobar, 2023; Rahimi et al.,2025). Street trees, green spaces, and green walls show great cooling potential at the pedestrian level, while green roofs have negligible effects (Quadros & Mizgier, 2023). Mature trees provide thermal comfort by offering sufficient shading and reducing mean radiant temperature and physiologically equivalent temperature (Zheng et al., 2023). The effectiveness of UGI varies with climate, urban form, and vegetation patterns. Closed urban forms tend to have higher air temperatures, while open forms experience higher wind speeds. Vegetation density and leaf area influence thermal comfort improvement, with trees and shrubs being more effective than ground-cover plants (He & Reith, 2023; Rahimi and Nobar,2024). Weather conditions can significantly impact UGI's effectiveness in regulating microclimate (Yang et al.,2024). The presence of street trees not only improves thermal comfort within the canyon but also influences microclimates in more distant areas, demonstrating a broader cooling effect on the urban environment. Additionally, green walls contribute to thermal comfort through evapotranspiration, although their impact on shading is less pronounced. Green roofs provide localized cooling benefits at rooftop levels, though their effects on pedestrian-level thermal comfort are often minimal. Various factors, such as building height, vegetation type, and urban layout, can affect the microclimatic benefits of green roofs, leading to variations in cooling performance across studies.

4.2 THE FUNCTION OF STREET TREES, GREEN WALLS, AND GREEN ROOFS IN MITIGATING URBAN HEAT ISLAND EFFECTS.

Urban green infrastructure, including street trees, green walls, and green roofs, plays a crucial role in mitigating the Urban Heat Island (UHI) effect, which is characterized by elevated temperatures in urban areas compared to their rural surroundings. The integration of these green elements can significantly enhance urban thermal comfort and contribute to climate adaptation strategies.

Street trees, green walls, and green roofs each play a distinct role in mitigating the urban heat island (UHI) effect by reducing ambient air temperatures and surface temperatures through different mechanisms. Trees have been identified as the most effective urban green infrastructure in reducing T_a , T_{mrt} , and PET within urban canyons, primarily due to their ability to provide extensive shading and promote evapotranspiration (Aminipouri et al., 2019; Morakinyo et al., 2017). Street trees provide shade and release moisture through transpiration, effectively lowering surface and air temperatures in urban settings (Fernández & Navarro, 2024). The results also highlight the role of trees in influencing wind speed and direction, which contributes to improved ventilation in urban streets, further enhancing their cooling potential. Street trees thus emerge as a critical tool for addressing UHI in densely populated urban environments. Studies indicate that areas with dense tree cover experience significantly cooler temperatures, particularly during the summer months (Fernández & Navarro, 2024). Green roofs and walls have been shown to reduce UHI effects by insulating buildings and lowering surrounding temperatures. In Nigeria, for instance, these structures contributed to notable energy savings and improved air quality (Singh & Chandra Tiwari, 2024; Unegbu et al., 2014). Green walls, while less effective than trees in terms of shading, contribute to cooling primarily through evapotranspiration and the reduction of solar radiation on vertical surfaces (Lee & Jim, 2017; Tan et al., 2014). Although their impact on temperature reduction is typically more localized, green walls still play a supportive role in moderating urban temperatures and improving thermal comfort. However, the effectiveness of green roofs can vary based on their design and the local climate. Realistic assessments suggest that while they can provide cooling benefits, their impact may be limited without widespread implementation (Joshi & Teller, 2024). Green roofs, similarly, affect UHI by reducing surface temperatures through shading and evapotranspiration, although their overall cooling impact is often limited. Factors such as direct sunlight, wind speed, and the specific characteristics of the green roof (e.g., vegetation type and coverage) can influence its effectiveness. Studies have found mixed results regarding the cooling potential of green roofs, with some reporting negligible impacts (Gromke et al., 2015), while others suggest a significant effect in certain conditions (Herath et al., 2018b). Nevertheless, when combined with other forms of green infrastructure, green roofs can contribute to reducing UHI in diverse urban environments.

5. CONCLUSION

The accelerated growth of urban populations and the concomitant expansion of cities have exacerbated climate change and intensified the urban heat island (UHI) effect. This study evaluated the cooling performance of three types of urban green infrastructure—street trees, green walls, and green roofs—through ENVI-met simulations validated by in-situ measurements and interpreted using thermal indices derived from the RayMan model. Given that urban street canyons are critical urban spaces particularly vulnerable to UHI, targeted interventions to improve thermal comfort are urgently required. Among the examined strategies, street trees exhibited the most significant reduction in physiological equivalent temperature (PET), outperforming green walls and green roofs. While all three green infrastructure types improved micrometeorological conditions, their performance varied substantially. Trees were the most effective, significantly reducing air temperature (T_a), mean radiant

temperature (T_{mrt}), and PET. In contrast, green roofs had negligible impact on PET, while green walls provided moderate improvements. Notably, the tree scenario led to a PET reduction of up to [15.7°C] compared to baseline conditions, reflecting a substantial improvement in thermal comfort during peak afternoon hours. Simulations were carried out using the ENVI-met model to model existing and modified GI scenarios, and these were validated with field measurements of air temperature (T_a) and relative humidity. The RayMan model was then employed to calculate PET, allowing for a comprehensive assessment of the micrometeorological and thermal comfort outcomes across all configurations. These findings offer significant implications for urban climate resilience by providing a robust, evidence-based framework for prioritizing GI investments in thermally stressed urban canyons. Urban vegetation improved thermal comfort primarily by reducing direct solar radiation and enhancing evapotranspiration, thus mitigating the UHI effect. Street trees, in particular, were shown to exert broader and deeper cooling influences, including on pedestrian-level zones and rooftop microclimates. Even at rooftop heights, tree canopies outperformed green roofs and walls, emphasizing their vertical and horizontal thermal regulation capacities. Green roofs showed only marginal cooling effects at the pedestrian level (0–0.3°C). While green walls produced localized improvements near their placement, they were less effective than trees across canyon-wide metrics. This research also provides methodological contributions through the integrated use of ENVI-met and RayMan models alongside empirical data. Importantly, the study advances applied modeling techniques that can guide decision-making in urban heat mitigation. Future studies are encouraged to explore hybrid solutions—such as combining trees with green walls or roofs—and assess their long-term performance under various urban morphologies and projected climate change scenarios. However, the findings are subject to limitations. This study focused exclusively on summer daytime conditions, analyzed specific canyon morphologies, and used simplified vegetation types within ENVI-met. These factors may limit the generalizability of results to different climates and urban forms. Overall, this study offers practical guidance for urban planners, architects, and policymakers in selecting and implementing green infrastructure. Street trees should be prioritized where spatial configurations allow due to their superior cooling effects. Where tree planting is not feasible, green walls and green roofs may serve as complementary alternatives, though their effectiveness is highly dependent on urban geometry and building characteristics. Future research should also assess the synergistic performance of combined green infrastructure elements across diverse canyon typologies, accounting for variables such as canyon depth, orientation, sky view factor (SVF), and surface albedo characteristics.

REFERENCES

- Acero, J. A., & Herranz-pascual, K. (2015). A comparison of thermal comfort conditions in four urban spaces by means of measurements and modelling techniques. *Building and Environment*, 93, 245–257. <http://doi.org/10.1016/j.buildenv.2015.06.028>
- Ahmadi Venhari, A., Tenpierik, M., & Taleghani, M. (2019). The role of sky view factor and urban street greenery in human thermal comfort and heat stress in a desert climate. *Journal of Arid Environments*, 166, 68–76. <http://doi.org/10.1016/j.jaridenv.2019.04.009>

- Akbar RAHIMI, Cristian I. IOJĂ, Sedighe KHORAMROU & Zahra NOBAR MODELLING NATURE-BASED SOLUTIONS IN DENSELY BUILT-UP AREAS, *Carpathian Journal of Earth and Environmental Sciences*, August 2025 Vol. 20, No. 2, p. 347 – 361; <https://doi.org/10.26471/cjees/2025/020/338>
- Akbar Rahimi, Sajjad Osan and Zahra Nobar (2025). The Impact of Different Tree Species on Enhancing Thermal Comfort , *International Journal of Ecology & Development*.40,1
- Alcazar, S. S., Olivieri, F., & Neila, J. (2016). Green roofs : Experimental and analytical study of its potential for urban microclimate regulation in Mediterranean – continental climates. *Urban Climate*, 17, 304–317. <http://doi.org/10.1016/j.uclim.2016.02.004>
- Aminipouri, M., Jensen, A., Krayenho, E. S., & Zickfeld, K. (2019). Modelling the impact of increased street tree cover on mean radiant temperature across Vancouver's local climate zones. *Urban Forestry & Urban Greening*, 39, 9–17. <http://doi.org/10.1016/j.ufug.2019.01.016>
- Andreou, E. (2013). Thermal comfort in outdoor spaces and urban canyon microclimate. *Renewable Energy*, 55, 182–188. <http://doi.org/10.1016/j.renene.2012.12.040>
- Andreou, E. (2014). The effect of urban layout , street geometry and orientation on shading conditions in urban canyons in the Mediterranean. *Renewable Energy*, 63, 587–596. <http://doi.org/10.1016/j.renene.2013.09.051>
- Bartesaghi Koc, C., Osmond, P., & Peters, A. (2018). Evaluating the cooling effects of green infrastructure: A systematic review of methods, indicators and data sources. *Solar Energy*, 166, 486–508. <http://doi.org/10.1016/j.solener.2018.03.008>
- Berardi, U. (2016). The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. *Energy & Buildings*, 121, 217–229. <http://doi.org/10.1016/j.enbuild.2016.03.021>
- Byeong, Jin, Park., Dong, Kun, Lee., Seok, Hwan, Yun., Eun, Sub, Kim., Jae, Hong, Lee., Sang, Hyuck, Kim. (2024). Assessing the Impact of Green Infrastructure on Thermal Comfort in Relation to Humidity: A Case Study in Korea. doi: 10.1016/j.ufug.2024.128305
- Chang, Lin., Zhuotong, Wu., Hui, Li., Jun, Huang., Quanle, Huang. (2024). Comprehensive Analysis on the Thermal Comfort of Various Greening Forms: A Study in Hot-humid Areas. *Environmental research communications*, doi: 10.1088/2515-7620/ad277e
- Chun, B., & Guldmann, J.-M. (2018). Impact of greening on the urban heat island: Seasonal variations and mitigation strategies. *Computers, Environment and Urban Systems*, 71, 165–176.
- Daemei, A. B., Azmoodeh, M., Zamani, Z., & Khotbehsara, E. M. (2018). Experimental and simulation studies on the thermal behavior of vertical greenery system for temperature mitigation in urban spaces. *Journal of Building Engineering*, 20, 277–284.
- de Quadros, B. M., & Mizgier, M. G. O. (2023). Urban green infrastructures to improve pedestrian thermal comfort: A systematic review. *Urban Forestry & Urban Greening*, 128091.
- Dong, J., Lin, M., Zuo, J., Lin, T., Liu, J., Sun, C., & Luo, J. (2020). Quantitative study on the cooling effect of green roofs in a high-density urban Area—A case study of Xiamen, China. *Journal of Cleaner Production*, 255, 120152.
- Fernández, C. T., & Navarro, I. M. (2024). Analysis of the Impact of Urban Green Spaces on Mitigating the Urban Heat Island Effect. *Innovation in Science and Technology*, 3(3), 11-20.
- Gromke, C., Blocken, B., Janssen, W., Merema, B., Hooff, T. Van, & Timmermans, H. (2015). CFD analysis of transpirational cooling by vegetation : Case study for specific meteorological conditions during a heat wave in Arnhem, Netherlands. *Building and Environment*, 83, 11–26. <http://doi.org/10.1016/j.buildenv.2014.04.022>

- Harshita Singh, Subhash Chandra Tiwari (2024). Inventory of forest growing tree species around Thermal Power Plant, Sipat, Bilaspur, Chhattisgarh, Central India International Journal of Ecology & Development.39,2
- He, Q., & Reith, A. (2023). A study on the impact of green infrastructure on microclimate and thermal comfort. *Pollack Periodica*, 18(1), 42-48.
- Herath, H. M. P. I. K., Halwatura, R. U., & Jayasinghe, G. Y. (2018a). Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy. *Urban Forestry and Urban Greening*, 29, 212–222. <http://doi.org/10.1016/j.ufug.2017.11.013>
- Herath, H. M. P. I. K., Halwatura, R. U., & Jayasinghe, G. Y. (2018b). Modeling a tropical urban context with green walls and green roofs as an urban heat island adaptation strategy. *Procedia Engineering*, 212, 691–698. <http://doi.org/10.1016/j.proeng.2018.01.089>
- Hertel, D., & Schlink, U. (2019). Environmental Modelling & Software Decomposition of urban temperatures for targeted climate change adaptation. *Environmental Modelling and Software*, 113, 20–28. <http://doi.org/10.1016/j.envsoft.2018.11.015>
- Höppe, P. (1999). The physiological equivalent temperature—a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology*, 43(2), 71–75.
- Jin, C., Bai, X., Luo, T., & Zou, M. (2018). Effects of green roofs ' variations on the regional thermal environment using measurements and simulations in Chongqing, China. *Urban Forestry & Urban Greening*, 29, 223–237. <http://doi.org/10.1016/j.ufug.2017.12.002>
- Joshi, M. Y., & Teller, J. (2024). Assessing urban heat island mitigation potential of realistic roof greening across local climate zones: A highly-resolved weather research and forecasting model study. *Science of The Total Environment*, 173728.
- Klemm, W., Heusinkveld, B. G., Lenzholzer, S., & Hove, B. Van. (2015). Street greenery and its physical and psychological impact on thermal comfort. *Landscape and Urban Planning*, 138, 87–98. <http://doi.org/10.1016/j.landurbplan.2015.02.009>
- Koch, K., Samson, R., & Denys, S. (2019). Aerodynamic characterisation of green wall vegetation based on plant morphology: An experimental and computational fluid dynamics approach. *Biosystems Engineering*, 178, 34–51.
- Lee, L. S. H., & Jim, C. Y. (2017). Subtropical summer thermal effects of wirerope climber green walls with different air-gap depths. *Building and Environment*, 126, 1–12.
- Lin, B. S., & Lin, C. T. (2016). Preliminary study of the influence of the spatial arrangement of urban parks on local temperature reduction. *Urban Forestry and Urban Greening*, 20, 348–357. <http://doi.org/10.1016/j.ufug.2016.10.003>
- Liu, J., Zheng, B., Tang, H., & Fan, J. (2024). The Impact of Green Spaces on Thermal Comfort in Urban Street Canyons during Hot Summer Days and Nights.
- Lobaccaro, G., & Acero, J. A. (2015). Comparative analysis of green actions to improve outdoor thermal comfort inside typical urban street canyons. *Urban Climate*, 14, 251–267. <http://doi.org/10.1016/j.uclim.2015.10.002>
- López-Cabeza, V. P., Galán-Marín, C., Rivera-Gómez, C., & Roa-Fernández, J. (2018). Courtyard microclimate ENVI-met outputs deviation from the experimental data. *Building and Environment*, 144, 129–141. <http://doi.org/10.1016/j.buildenv.2018.08.013>
- Lu, J., Li, Q., Zeng, L., Chen, J., Liu, G., Li, Y., ... Huang, K. (2017). A micro-climatic study on cooling effect of an urban park in a hot and humid climate. *Sustainable Cities and Society*, 32, 513–522. <http://doi.org/10.1016/j.scs.2017.04.017>

- Matzarakis, A., Rutz, F., & Mayer, H. (2010). Modelling radiation fluxes in simple and complex environments : basics of the RayMan model. *International Journal of Biometeorology*, 54(2), 131–139. <http://doi.org/10.1007/s00484-009-0261-0>
- Milosevic, D. D., Bajsanski, I. V., & Savic, S. M. (2017). Influence of changing trees locations on thermal comfort on street parking lot and footways. *Urban Forestry & Urban Greening*, 23, 113–124. <http://doi.org/10.1016/j.ufug.2017.03.011>
- Morakinyo, T. E., & Lam, Y. F. (2016). Simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon's micro-climate and thermal comfort. *Building and Environment*, 103, 262–275. <http://doi.org/10.1016/j.buildenv.2016.04.025>
- Morakinyo, T. E., Kong, L., Lau, K. K. L., Yuan, C., & Ng, E. (2017). A study on the impact of shadow-cast and tree species on in-canyon and neighborhood's thermal comfort. *Building and Environment*, 115, 1–17. <http://doi.org/10.1016/j.buildenv.2017.01.005>
- Morakinyo, T. E., Lau, K. K. L., Ren, C., & Ng, E. (2018). Performance of Hong Kong's common trees species for outdoor temperature regulation, thermal comfort and energy saving. *Building and Environment*, 137, 157–170. <http://doi.org/10.1016/j.buildenv.2018.04.012>
- nobar, Z. , Rahimi, A. and breuste, J. (2025). Edible parks are an innovative strategy for enhancing environmental comfort and promoting sustainable urban development. *Journal of Geography and Planning*, 28(90), 465–440. doi: 10.22034/gp.2025.64192.3318
- Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, 108(455), 1–24.
- Otelé, M., & Perini, K. (2017). Comparative experimental approach to investigate the thermal behaviour of vertical greened façades of buildings. *Ecological Engineering*, 108, 152–161.
- Park, B. J., Lee, D. K., Yun, S. H., Kim, E. S., Lee, J. H., & Kim, S. H. (2024). Assessing the impact of green infrastructure on thermal comfort in relation to humidity: A case study in Korea. *Urban Forestry & Urban Greening*, 95, 128305.
- Park, C. Y., Lee, D. K., Krayenho, E. S., Heo, H. K., & Hyun, J. H. (2019). Variations in pedestrian mean radiant temperature based on the spacing and size of street trees. *Sustainable Cities and Society*, 48, 1–9. <http://doi.org/10.1016/j.scs.2019.101521>
- Rahimi, A. and Nobar, Z. (2024). Investigating the role of cover plants (grass) in improving the physiological equivalent temperature and relative humidity (study area: Tabriz University Stadium). *Journal of Agricultural Science and Sustainable Production*, 34(1), 187–204. doi: 10.22034/saps.2023.53515.2930
- Rahimi, A., & Nobar, Z. (2023). The impact of planting scenarios on agricultural productivity and thermal comfort in urban agriculture land (case study: Tabriz, Iran). *Frontiers in Ecology and Evolution*, 11, 1048092.
- Ruiz, M. A., Sosa, M. B., Correa, E. N., & Cantón, M. A. (2017). Design tool to improve daytime thermal comfort and nighttime cooling of urban canyons. *Landscape and Urban Planning*, 167, 249–256. <http://doi.org/10.1016/j.landurbplan.2017.07.002>
- Saaroni, H., Amorim, J. H., Hiemstra, J. A., & Pearlmutter, D. (2018). Urban Green Infrastructure as a tool for urban heat mitigation: Survey of research methodologies and findings across different climatic regions. *Urban Climate*, 24, 94–110.
- Salata, F., Golasi, I., Petitti, D., de Lieto Vollaro, E., Coppi, M., & de Lieto Vollaro, A. (2017). Relating microclimate, human thermal comfort and health during heat waves: An analysis of heat island mitigation strategies through a case study in an urban outdoor environment. *Sustainable Cities and Society*, 30, 79–96. <http://doi.org/10.1016/j.scs.2017.01.006>

- Schindler, B. Y., Blaustein, L., Vasl, A., Kadas, G. J., & Seifan, M. (2019). Cooling effect of Sedum sediforme and annual plants on green roofs in a Mediterranean climate. *Urban Forestry & Urban Greening*, 38, 392–396.
- Shashua-bar, L., Tsiros, I. X., & Hoffman, M. (2012). Passive cooling design options to ameliorate thermal comfort in urban streets of a Mediterranean climate (Athens) under hot summer conditions. *Building and Environment*, 57, 110–119. <http://doi.org/10.1016/j.buildenv.2012.04.019>
- Shashua-bar, L., Tsiros, I. X., & Hoffman, M. E. (2010). A modeling study for evaluating passive cooling scenarios in urban streets with trees . Case study : Athens , Greece. *Building and Environment*, 45(12), 2798–2807. <http://doi.org/10.1016/j.buildenv.2010.06.008>
- Sodoudi, S., Zhang, H., Chi, X., Müller, F., & Li, H. (2018). The influence of spatial configuration of green areas on microclimate and thermal comfort. *Urban Forestry and Urban Greening*, 34, 85–96. <http://doi.org/10.1016/j.ufug.2018.06.002>
- Srivani, M., & Hokao, K. (2013). Evaluating the cooling effects of greening for improving the outdoor thermal environment at an institutional campus in the summer. *Building and Environment*, 66, 158–172. <http://doi.org/10.1016/j.buildenv.2013.04.012>
- Taher, H., Elsharkawy, H., & Rashed, H. F. (2024). Urban green systems for improving pedestrian thermal comfort and walkability in future climate scenarios in London. *Buildings*, 14(3), 651.
- Tan, C. L., Wong, N. H., & Jusuf, S. K. (2014). Effects of vertical greenery on mean radiant temperature in the tropical urban environment. *Landscape and Urban Planning*, 127, 52–64.
- Unal, M., Uslu, C., Cilek, A., & Altunkasa, M. F. (2018). Microclimate Analysis for Street Tree Planting in Hot and Humid Cities. *Journal of Digital Landscape Architecture*, 3, 34–42. <http://doi.org/10.14627/537642004>
- Unegbu, H. C. O., Yawas, D. S., Dan-asabe, B., & Alabi, A. A. (2024). Evaluating the Effectiveness of Green Roofs and Walls in Nigeria's Urban Centers.
- Victorero, F., Vera, S., Bustamante, W., Tori, F., Bonilla, C., Gironás, J., & Rojas, V. (2015). Experimental study of the thermal performance of living walls under semiarid climatic conditions. *Energy Procedia*, 78, 3416–3421.
- Xu, H., Liao, J., & Hong, Y. (2024). The Effect of Green Stormwater Infrastructures on Urban-Tier Human Thermal Comfort—A Case Study in High-Density Urban Blocks. *Forests*, 15(5), 862.
- Yang, J., Liang, Y., Zhong, Z., Dharmasastha, K., Xie, Y., & Niu, J. L. (2024). Thermal comfort investigation of membrane-assisted radiant cooling in outdoor settings. *Sustainable Cities and Society*, 113, 105634
- Yang, Y., Zhou, D., Gao, W., Zhang, Z., Chen, W., & Peng, W. (2018). Simulation on the impacts of the street tree pattern on built summer thermal comfort in cold region of China. *Sustainable Cities and Society*, 37, 563–580. <http://doi.org/10.1016/j.scs.2017.09.033>
- Yin, H., Kong, F., Middel, A., Dronova, I., Xu, H., & James, P. (2017). Cooling effect of direct green façades during hot summer days: an observational study in Nanjing, China using TIR and 3DPC data. *Building and Environment*, 116, 195–206.
- Zhang, Lei, Deng, Z., Liang, L., Zhang, Y., Meng, Q., Wang, J., & Santamouris, M. (2019). Thermal behavior of a vertical green facade and its impact on the indoor and outdoor thermal environment. *Energy and Buildings*, 204, 109502.
- Zhang, Li, Zhan, Q., & Lan, Y. (2018). Effects of the tree distribution and species on outdoor environment conditions in a hot summer and cold winter zone: A case study in Wuhan

residential quarters. *Building and Environment*, 130, 27–39.
<http://doi.org/10.1016/j.buildenv.2017.12.014>

- Zhao, T. F., & Fong, K. F. (2017). Characterization of different heat mitigation strategies in landscape to fight against heat island and improve thermal comfort in hot-humid climate (Part II): Evaluation and characterization. *Sustainable Cities and Society*, 35, 841–850. <http://doi.org/10.1016/j.scs.2017.05.006>
- Zheng, S., He, C., Guldmann, J. M., Xu, H., & Liu, X. (2023). Heat Mitigation Benefits of Urban Trees: A Review of Mechanisms, Modeling, Validation and Simulation. *Forests*, 14(12), 2280.
- Zölch, T., Maderspacher, J., Wamsler, C., & Pauleit, S. (2016). Using green infrastructure for urban climate-proofing: An evaluation of heat mitigation measures at the micro-scale. *Urban Forestry & Urban Greening*, 20, 305–316.