E-ISSN:
2721-13988

PROCEEDINGS OF THE INTERNATIONAL CONFERENCE OF GRADUATE SCHOOL ON SUSTAINABILITY (ICGSS)

10th International Conference on Sustainability (ICoS10)
University of Merdeka Malang, November 15, 2025
https://jurnal.unmer.ac.id/index.php/icgss

# Cooling Effectiveness of Urban Green Infrastructure: A Review of Urban Heat Island Mitigation Strategy

**Miftahul Huda[1*], Respati Wikantiyoso[1], Nurul Aini[1], Pindo Tutuko[1]**
[1]Magister of Architecture, University of Merdeka Malang
*Corresponding author: miftahulhuda0281@gmail.com

**Abstract.**

The Urban Heat Island (UHI) phenomenon represents a significant environmental challenge in modern cities, intensifying air temperatures and degrading thermal comfort. Green Infrastructure (GI) has emerged as the primary intervention in mitigating this issue due to its capacity to provide shading, evapotranspiration cooling, and improved microclimatic balance. This study aims to synthesize existing research on GI-based UHI mitigation strategies by examining methodological approaches, cooling performance, influencing factors, and climatic context through a narrative review. A total of 31 peer-reviewed articles published between 2015 and 2025 were systematically identified using Publish or Perish. The results show that simulation-based approaches dominate the field, with ENVI-met forming the primary analytical tools, while empirical measurements remain crucial for calibration and validation. Across typologies, trees produce the strongest and most consistent cooling, followed by green walls and green roofs, whereas groundcovers provide the weakest cooling response for single interventions. However, it is important to note that multi-layered or combined GI configurations substantially outperform single-strategy approaches. Cooling outcomes are strongly shaped by vegetation characteristics, spatial configuration, hydrological and meteorological conditions, and the methodological frameworks used to measure cooling. Climatic context further mediates GI performance by influencing how strongly vegetation can express its shading and evapotranspirative functions across different environmental conditions. Overall, the review confirms that GI is an effective strategy for reducing urban heat and highlights the need for context-sensitive urban vegetation planning.

**Keywords:** Green Infrastructure, Mitigation Strategy, Urban Heat Island, Urban Vegetation.

## 1. Introduction

Rapid urbanization has heightened concerns about the UHI phenomenon, a persistent microclimatic consequence of land-use changes. The extensive replacement of vegetated and permeable surfaces with dense built forms and impervious materials disrupts the surface energy balance by increasing heat storage, reducing evapotranspiration, and decreasing albedo, which collectively result in elevated air and surface temperatures in urban areas compared to their rural surroundings (Imran et al., 2021; Jabbar et al., 2023; Nuruzzaman, 2015) (Figure 1). The elevated temperatures associated with UHI reduce outdoor thermal comfort, discouraging public space use and diminishing urban livability. This discomfort drives increased reliance on mechanical cooling, which elevates building energy demand and carbon emissions (Li et al., 2019). Prolonged heat exposure also heightens health risks, particularly cardiovascular, respiratory, and psychological disorders among vulnerable populations (Wardana et al., 2025; Wong et al., 2018). Beyond human well-being, persistent urban overheating degrades ecological quality by stressing vegetation, altering land surface moisture balance, and reducing biodiversity, thereby weakening the natural cooling function of urban ecosystems (Nguyen et al., 2019). Given these cascading effects, UHI mitigation is not merely an environmental concern but a cornerstone of resilient urban development (Fu et al., 2024). As global climate change accelerates the frequency and intensity of heat extremes (IPCC, 2023; Santamouris, 2020), developing effective mitigation strategies is increasingly vital to alleviate thermal stress and sustain urban livability.

*Figure 1.* Characteristics of (a) rural, pervious landscapes and (b) urban, impervious environments, illustrating how urban properties contribute to elevated temperatures relative to rural areas.
*Source: (Imran et al., 2021)*

Urban GI has been widely recognized as an effective nature-based solution (NbS) for mitigating UHI effects. GI integrates ecological processes into urban systems to enhance thermal regulation, microclimatic stability, and overall urban resilience (Kabisch et al., 2017; Raymond et al., 2017). Vegetation contributes to thermal regulation through shading, evapotranspiration, radiation absorption, heat conduction, and airflow alteration within built surfaces (Budzik et al., 2025) (Figure 2). Various GI typologies, including urban trees, green roofs, green walls, and groundcovers, have demonstrated measurable cooling effects and improved outdoor thermal comfort (Zölch et al., 2016). However, existing reviews also highlight inconsistencies in GI performance across climatic zones, suggesting that the complex interplay between vegetation attributes and local climate remains insufficiently examined (Antoszewski et al., 2020; Koc et al., 2018). Consequently, while GI is among the most sustainable strategies for alleviating urban heat, its thermal performance is inherently context-dependent. It warrants deeper investigation to identify the parameters that most effectively enhance UHI mitigation outcomes.

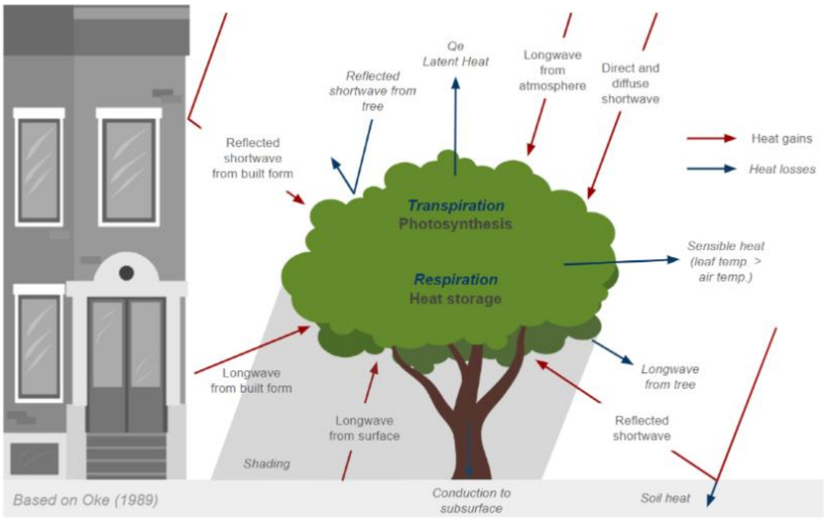

*Figure 2.* Schematic representation of vegetation-driven cooling processes in urban environments.
*Source: (Budzik et al., 2025)*

Despite the growing body of research on GI-based UHI mitigation, comparative insights remain fragmented due to substantial differences in methodological approaches. Over the past decade, studies have examined UHI mitigation using empirical field measurements and simulation-based analyses, each offering distinct but often non-comparable perspectives on microclimatic behavior (Apritasari et al., 2022; Bahadori et al., 2025; Balany et al., 2020). Such discrepancies undermine comparability between studies, as variations in measurement techniques, modeling assumptions, and analytical resolutions often lead to divergent conclusions. Therefore, a comparative synthesis is necessary to evaluate how empirical and simulation-based methods complement and contrast in assessing GI performance.

In response, the present review synthesizes peer-reviewed studies published between 2015 and 2025 by organizing the discussion into four key analytical components. First, the review examines the methodological approaches employed in GI-based UHI mitigation studies. Second, it evaluates the cooling performance of various GI typologies. Third, the review identifies the key factors shaping cooling outcomes. Finally, it analyzes how climatic context influences GI cooling performance.

## 2. Method

This study adopts a narrative review approach to examine the role of GI in mitigating the UHI phenomenon. Narrative reviews are designed to explore broad topics through conceptual synthesis, thematic comparison, and interpretive analysis, rather than through statistical aggregation or protocol-heavy procedures typical of systematic reviews (Chaney, 2021). This flexibility is particularly valuable for UHI research, where the literature spans multiple measurement techniques, GI typologies, and climatic contexts. Such heterogeneity makes it difficult, and often counterproductive, to impose rigid inclusion criteria or attempt to homogenize evidence in a purely systematic manner. Accordingly, the narrative review approach is the most suitable framework for achieving the aims of this study, as it allows the review to retain necessary breadth while producing a conceptually grounded synthesis.

A comprehensive literature search was conducted using Publish or Perish 8 with Google Scholar as the primary database. To ensure adequate coverage, the search included a combination of core and extended keywords such as “urban heat island,” “green infrastructure,” “mitigation strategy,” “urban vegetation,” “green roof,” and “green wall.” The 2015–2025 search window was selected to ensure coverage of the most recent developments in GI-based UHI mitigation. This approach ensured that the review drew on contemporary developments while remaining relevant to current urban design and planning discourse.

Although PRISMA guidelines are not mandatory for narrative reviews (Chaney, 2021), this study applied a structured selection flow to organize and document the review process more systematically. The literature selection process followed four stages: Identification, Screening, Eligibility, and Inclusion, which together organized and refined the final set of studies included in the review. An initial pool of 150 records was identified. After removing 39 irrelevant or out-of-scope studies during screening and excluding 80 non-research documents during eligibility assessment, a final set of 31 empirical and simulation-based articles was obtained (Figure 3). This systematic selection ensured that the review is grounded in the most relevant and methodologically robust evidence available.

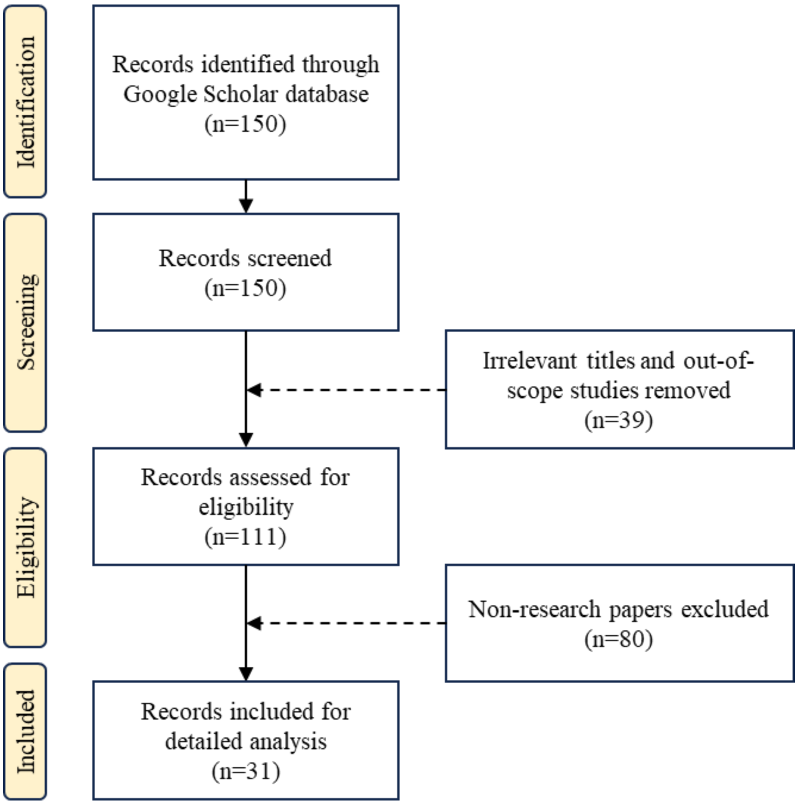

*Figure 3.* PRISMA Flow Diagram of the Study Identification and Selection Process
*Source: (Author, 2025)*

Each article was examined for key analytical elements. The resulting matrix established a clear basis for categorizing the studies along several analytical axes, allowing patterns to emerge across methods, GI typologies, influencing factors, and climatic settings. The extracted information was then synthesized qualitatively, offering an integrated understanding of how different forms of GI operate as nature-based cooling strategies across diverse environmental and methodological settings, directly supporting the review's aims.

## 3. Result and Discussion

### 3.1 Methodological Approaches in GI-Based UHI Mitigation Studies

The methodological landscape of GI-based UHI mitigation research is overwhelmingly dominated by numerical and computational modelling. Among the 31 reviewed studies, 27 employ simulation-based approaches, while only four rely exclusively on empirical observations (Table 1). This trend highlights the central role of computational tools in assessing intervention impacts that cannot be directly measured in situ (Hosseinzadeh et al., 2022), with most studies integrating field-derived parameters to calibrate their models (Piao, 2022; Tariq, 2023). Simulation, therefore, functions as a foundational analytical tool in contemporary UHI research. Among the available modelling tools, ENVI-met is the most widely used platform for micro-scale thermal analysis and pedestrian-level comfort assessment (Ali et al., 2021; Esfehankalateh et al., 2021; Piao, 2022). Its capability to simulate interactions between vegetation, built form, and atmospheric processes enables researchers to test a wide range of GI configurations (Oğuztürk et al., 2025; Park et al., 2022). Other studies adopt more specialised modelling frameworks: Computational Fluid Dynamics (CFD) is frequently used to investigate wind flow modification, pollutant dispersion, and turbulence-vegetation interactions (Hosseinzadeh et al., 2022; Irie, 2022), while mesoscale atmospheric models such as WRF support investigations that situate local microclimatic changes within broader synoptic conditions (Mohammed et al., 2023). Even in entirely observational studies, statistical modelling is typically employed to interpret relationships between vegetation characteristics and temperature variability (Park et al., 2018; Wang et al., 2015). These patterns collectively affirm that computational modelling is now the methodological standard for generating scalable, reproducible, and statistically robust insights (Lin & Zhang, 2024; Yang & La Roche, 2025). These trends collectively indicate a decisive methodological shift toward simulation-based analysis, reflecting the field's growing reliance on computational tools to evaluate complex microclimatic processes.

*Table 1.* Distribution of Methodological Approaches in the Reviewed GI-based UHI mitigation Studies

| **Method Category** | **Detail** | **Number of Studies** | | **Proportion in the Reviewed Literature** |
|---|---|---|---|---|
| Software Simulation | ENVI-met | 17 | 27 studies | 87% |
| | CFD | 2 | | |
| | Others (Numerical/Statistical Modeling, ADMS-TH, 3D-USM, i-Tree Cool Air, DesignBuilder, GIS-based thermal modeling) | 8 | | |
| Field Measurement | In-situ sensors, thermal cameras, mobile/fixed microclimate surveys. | | 4 studies | 13% |

*Source: (Reviewed studies, 2025)*

Despite the predominance of modelling, empirical data remain essential for strengthening model reliability and constraining uncertainty. The four purely empirical studies employ fixed sensors, mobile transects, and controlled thermal experiments to document actual microclimatic behaviour (Fallahi & Ayvazian, 2016; Moreno-García & Baena, 2019; Park et al., 2018; Tan et al., 2021). Such datasets are invaluable for simulation validation, and most modelling-focused studies report strong agreement between observed and simulated temperatures, often achieving coefficients of determination exceeding 0.85 (Ananyeva, 2021; Battista et al., 2020). This reinforces the importance of empirical calibration in enhancing model fidelity and ensuring that computational outputs remain grounded in real environmental conditions (Mutani & Todeschi, 2020; Razzaghmanesh et al., 2016; Wang et al., 2015). These findings underscore that empirical measurement is not merely complementary but fundamentally indispensable for ensuring the accuracy, credibility, and real-world applicability of simulation-based UHI and GI assessments.

Nevertheless, several methodological limitations continue to limit the accuracy and transferability of GI-based UHI assessments. Many simulations rely on simplified boundary conditions, uniform material parameters, or short diurnal windows that fail to capture long-term or extreme-heat dynamics (Mohammed et al., 2023; Yang & La Roche, 2025). Vegetation is often under-parameterised, with key attributes such as LAI, LAD, canopy porosity, and stomatal behaviour frequently omitted (Esfehankalateh et al., 2021), while radiation processes are simplified through bottom-heating schemes or homogeneous albedo assumptions, especially problematic in high-reflectivity arid settings (Tiwari et al., 2021). Collectively, these issues highlight the need for improved parameterisation, stronger validation datasets, and higher-fidelity physical modelling to produce reliable and transferable design recommendations.

### 3.2 Cooling Performance of GI Typologies

Although numerical reductions in temperature are frequently reported, the literature lacks a unified framework for quantifying cooling. Measurement protocols differ substantially across studies, with some assessing pedestrian-level air temperature, others focusing on canopy-level or rooftop air layers, and many relying on surface or satellite-derived land-surface temperatures. Additional approaches quantify cooling using thermal comfort indicators such as PET or UTCI, or non-thermal metrics, including cooling load reduction and energy performance. These methodological inconsistencies mean that reported values cannot be directly compared without considering the measurement technique, spatial scale, and thermal parameter examined. Within this diverse landscape, urban trees remain the most frequently assessed GI typology, followed by green roofs, ground-level vegetation, and green walls (Figure 4).

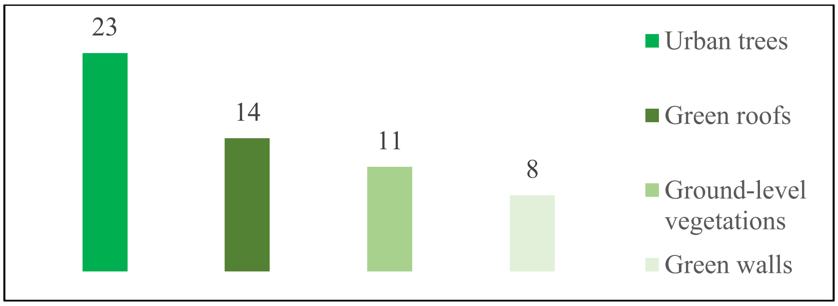

*Figure 4: Types of GI in the reviewed articles*
*Source: (Reviewed studies, 2025)*

Across the 31 reviewed studies, trees and tree-based systems consistently emerge as the strongest and most reliable cooling intervention. Street trees, park forests, and clustered canopies provide substantial ambient cooling through combined shading, evapotranspiration, and aerodynamic effects (Ali et al., 2021; Herath et al., 2018; Mohammed et al., 2023; Wang et al., 2015; Zölch et al., 2016). Evidence from urban parks further demonstrates that forested areas function as both daytime shading structures and nocturnal cold-air reservoirs (Irie, 2022; Moreno-García & Baena, 2019; Semenzato & Bortolini, 2023). Field studies from tropical and semi-arid contexts additionally confirm that trees outperform grass and shrubs, and that tree–water interactions can intensify cooling through the synergy between shading and evaporative processes (Park et al., 2017; Tariq, 2023). Even modelling exercises involving tree densification consistently reveal that incremental additions of canopy cover enhance cooling more than any equivalent increase in roof- or wall-based greening (Ananyeva, 2021; Battista et al., 2020; Hosseinzadeh et al., 2022). Collectively, these findings identify trees as the most consistently compelling and scalable GI strategy for urban cooling.

Green roofs exhibit a dual behavioral pattern: at the rooftop micro-scale, extensive and intensive systems substantially cool roof surfaces and alter local rooftop microclimates (Park et al., 2018; Razzaghmanesh et al., 2016), but their influence at the pedestrian level is markedly weaker unless coverage is dense, deeply vegetated, or combined with other measures such as reflective pavements (Esfehankalateh et al., 2021; Park et al., 2022). At neighborhood and city scales, green roofs generate only modest cooling unless deployed at very high coverage or integrated with broader vegetated networks (Mohammed et al., 2023; Sánchez-Cordero et al., 2025). Green walls provide moderate yet spatially meaningful cooling in street canyons, where façade shading directly affects pedestrian microclimates(Battista et al., 2020; Galagoda et al., 2018; Herath et al., 2018; Lin & Zhang, 2024). CFD-based evaluations also show that green walls often outperform green roofs at modifying pedestrian-level temperatures because they intercept radiation closer to where people experience heat (Hosseinzadeh et al., 2022). Furthermore, Habibi & Kahe (2024) show that while green roofs and green walls contribute meaningfully to microclimate improvement and energy efficiency, their cooling influence remains strongly dependent on vegetation density and is limited in reach at pedestrian height. Ground-level vegetation such as grass generally yields the weakest standalone cooling performance across studies, with several models indicating minimal or even adverse nighttime warming effects in water-limited climates (Tariq, 2023; Tiwari et al., 2021; Wang et al., 2015). These findings indicate that while green roofs, green walls, and groundcovers each contribute conditionally to urban cooling, their effectiveness is highly scale-dependent, with vertical and rooftop systems offering only localized benefits.

Across all studies, the hierarchy for single GI typologies is clear: trees provide the most significant cooling, followed by green walls, then green roofs, while groundcovers deliver the smallest cooling response (Park et al., 2017; Semenzato & Bortolini, 2023; Zölch et al., 2016). However, when typologies are combined, their cooling performance increases substantially, with hybrid systems outperforming any standalone intervention. Tree–green wall combinations consistently provide some of the strongest integrated cooling within dense urban morphologies (Hosseinzadeh et al., 2022), and mixed systems incorporating trees, shrubs, green walls, and green roofs often produce additive or synergistic reductions in thermal load (Herath et al., 2018; Irie, 2022; Lin & Zhang, 2024). Empirical observations further demonstrate that hybrid designs involving trees and water features can exceed the cooling levels of vegetation-only systems (Tariq, 2023). Taken together, the literature demonstrates that multi-layered GI configurations consistently yield the most effective and resilient cooling outcomes, substantially outperforming single-strategy approaches.

### 3.3 Key Factors Shaping Cooling Outcomes

The cooling outcomes reported across the 31 reviewed studies vary substantially, and this variability reflects not the inconsistency of GI itself, but the diverse mechanisms, measurement practices, and environmental contexts through which GI interacts with the urban thermal environment. One of the most influential determinants is the structural and biophysical character of the vegetation deployed. Numerous studies demonstrate that attributes such as canopy cover, leaf area index or leaf area density, species morphology, and tree height jointly define the magnitude of shading and evapotranspiration, the two primary mechanisms responsible for temperature reduction. Modelling and field studies that explicitly manipulate canopy or LAD values consistently report disproportionately large gains in cooling as vegetation becomes denser or more vertically complex, especially in tree-dominated systems (Esfehankalateh et al., 2021; Semenzato & Bortolini, 2023). By contrast, groundcover or grass-dominated systems exhibit minimal cooling unless accompanied by shrubs or tree canopies, underscoring the central role of vegetation structure rather than typology alone in determining thermal performance (Tariq, 2023; Tiwari et al., 2021; Wang et al., 2015). These findings show that vegetation's physical and biological attributes are foundational determinants of GI cooling performance.

Spatial configuration further shapes the magnitude and distribution of cooling by modulating shading footprints, radiative exchange, and local airflow within the urban canopy layer. Comparative studies consistently show that clustered, polygonal, or multi-strata vegetation patches generate deeper and more spatially extensive cooling than linear or dispersed arrangements (Ananyeva, 2021; Park et al., 2017). The interaction between vegetation and street-canyon geometry also plays a decisive role: green walls provide shading directly within the pedestrian microclimate, often outperforming green roofs in canyons where vertical radiation exchange dominates (Galagoda et al., 2018; Herath et al., 2018; Hosseinzadeh et al., 2022; Lin & Zhang, 2024). At larger scales, several modelling studies highlight that meaningful neighborhood- and city-scale cooling only emerges once vegetation coverage reaches sufficiently high proportions of the urban surface, with some showing non-linear improvements as coverage approaches continuity (Esfehankalateh et al., 2021; Mohammed et al., 2023). These results underscore that spatial arrangement and connectivity are critical to unlocking the full cooling potential of GI at both local and mesoscale spatial domains.

Hydrological and meteorological conditions additionally govern the degree to which vegetation can express its cooling capacity. In water-limited environments, suppressed evapotranspiration frequently reduces the cooling effectiveness of grass, shallow vegetation, or untreated green roofs, occasionally even generating slight nocturnal warming compared to non-vegetated surfaces (Mutani & Todeschi, 2020; Tiwari et al., 2021). Conversely, in humid or irrigated contexts, vegetation can fully realize its evapotranspirative function, enabling substantially stronger cooling relative to shading alone (Herath et al., 2018; Tariq, 2023). Atmospheric conditions such as wind speed, stability, and diurnal radiative regimes regulate whether these cooling signals remain locally concentrated or diffuse downstream, with calm daytime environments enhancing shading-driven gradients and stable nights enabling parks to develop cold-air pools (Irie, 2022; Morakinyo et al., 2021; Zölch et al., 2016). Thus, the expression of cooling is tightly coupled to water availability and local meteorology, which determine how fully vegetation can perform its biophysical cooling functions.

Finally, methodological and modelling differences are among the most prominent sources of variation in reported cooling magnitudes. Field measurements conducted beneath canopy shade typically capture larger instantaneous cooling signals than simulation studies or remote-sensing products, which aggregate over broader spatial scales and different thermal layers (Park et al., 2018; Semenzato & Bortolini, 2023). ENVI-met tends to highlight fine-scale pedestrian-level gradients (Ali et al., 2021; Herath et al., 2018), while CFD approaches prioritize airflow dynamics and often yield more conservative temperature reductions (Hosseinzadeh et al., 2022). Satellite-based LST analyses measure surface temperature rather than ambient air temperature, often registering ample surface cooling that cannot be compared directly with near-surface air temperature reductions (Razzaghmanesh et al., 2016; Sánchez-Cordero et al., 2025). Some studies use thermal-comfort indices such as PET or UTCI, which integrate multiple thermal variables, producing outcomes that are meaningful but not directly comparable to air-temperature metrics (Morakinyo et al., 2021; Zölch et al., 2016). These methodological divergences highlight the importance of interpreting reported cooling magnitudes within the specific thermal metric, scale, and modelling framework from which they arise.

In summary, the wide range of cooling outcomes reported across the literature does not reflect inconsistency in the effectiveness of GI, but rather reflects the complexity of interactions among vegetation characteristics, spatial configuration, hydrological and meteorological conditions, and the methodological frameworks used to measure cooling. These factors jointly determine whether a GI intervention expresses only a fraction of its potential or achieves substantial reductions in thermal load at the pedestrian, neighborhood, or city scale. Recognizing these interacting determinants is therefore essential for interpreting the diverse findings of previous studies and for designing GI strategies that are responsive to the specific physical and climatic conditions in which they are deployed. This synthesis also sets the stage for examining the broader climatic context within which GI operates, as large-scale environmental regimes can further mediate or amplify the cooling outcomes identified here.

### 3.4 Climatic Context and Its Influence on GI Cooling Performance

Climatic context exerts a fundamental influence on how GI delivers cooling, shaping not only the absolute magnitude of thermal reduction but also the dominant mechanisms through which different typologies operate. The 31 reviewed studies span a diverse range of climatic zones, demonstrating that GI-based UHI mitigation is a globally relevant concern, with the literature distributed across tropical, temperate, continental, and dry settings (Figure 4). Temperate climates constitute the largest share of research, particularly studies conducted in Europe and East Asia, followed by work in continental regions, represented mainly by South Korea. Dry-zone studies constitute another substantial segment of the literature and underscore the need to address extreme heat in the Middle East and other dryland regions. Tropical environments appear least frequently in the sample but offer valuable insights into high-evapotranspiration contexts where GI can perform very differently from temperate or arid settings. Across these varied climatic regimes, vegetation functions under distinct radiative and hydrological conditions, with evapotranspiration potential, atmospheric moisture, solar exposure, and seasonal dynamics jointly modulating the cooling performance of GI.

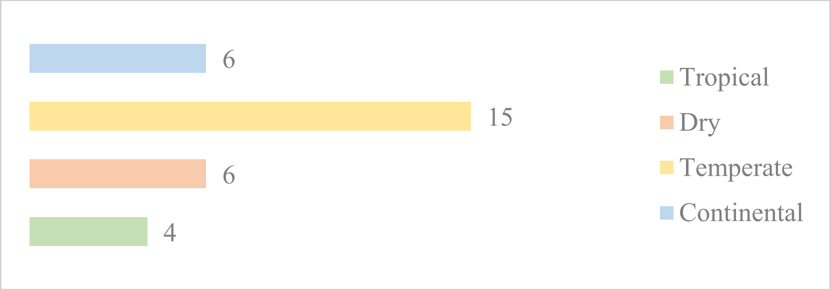

*Figure 5.* Climate Distribution Graph
*Source: (Reviewed studies, 2025)*

In tropical climates, cooling performance is strongly amplified by high humidity, persistent solar radiation, and strong evaporative demand. Studies from Sri Lanka and Singapore show that trees and multilayer vegetation consistently deliver some of the highest observed reductions in air temperature because shading and evapotranspiration operate synergistically (Galagoda et al., 2018; Herath et al., 2018; Tan et al., 2021). Field evidence from West Africa further demonstrates that dense vegetation produces deep daytime cooling and retains nighttime cooling due to moist-air retention and reduced thermal diffusivity (Morakinyo et al., 2021). Thus, tropical climates maximize the combined shading and evapotranspirative mechanisms that underpin GI cooling.

In temperate climates, cooling is primarily governed by shading rather than evapotranspiration. Studies in Germany, the Netherlands, and Italy show that trees remain the strongest typology, but cooling magnitudes are more modest and sensitive to seasonal leaf development, canyon geometry, and solar angle (Palme et al., 2020; Semenzato & Bortolini, 2023; Wang et al., 2015; Zölch et al., 2016). Seasonal climates such as Tokyo, Glasgow, and Adelaide display strong diurnal and seasonal contrasts: trees reduce summer heat substantially, yet allow winter solar access when deciduous canopies shed their leaves (Ananyeva, 2021; Irie, 2022; Razzaghmanesh et al., 2016). As a result, temperate climates moderate GI cooling intensity, yielding reliable but seasonally variable cooling dominated by shading processes.

In continental climates, the significant temperature seasonality and strong diurnal contrasts produce distinctive cooling behavior. Studies from multiple Korean cities reveal that GI effectively reduces extreme summer heat, particularly when canopy cover or LAD is high, but evapotranspiration is constrained during cold seasons, causing cooling performance to fluctuate substantially over the year (Esfehankalateh et al., 2021; Park et al., 2017, 2018, 2022; Piao, 2022; Yun, 2023). Continental climates also show strong sensitivity to spatial configuration: deeper street canyons and multilayer vegetation improve cooling efficiency, while dispersed vegetation performs weakly under high radiation loads. Consequently, continental climates enhance shading-driven cooling in summer while imposing seasonal limits on evapotranspiration, producing highly seasonal GI performance.

In arid climates, evapotranspiration is theoretically high but practically limited by severe water scarcity, shallow soils, and plant stress. Studies from the UAE and Iran show that grass or non-irrigated green roofs provide slight cooling, while drought-tolerant trees and green walls offer more reliable performance by relying primarily on shading and surface insulation (Ali et al., 2021; Fallahi & Ayvazian, 2016; Mohammed et al., 2023). Phoenix and Peshawar studies similarly highlight that shading is the dominant cooling mechanism, with evapotranspiration contributing only when irrigation is available (Tariq, 2023; Yang & La Roche, 2025). Overall, arid climates favor shading-based GI strategies and underscore the critical role of irrigation and drought resilience in sustaining meaningful cooling.

Climatic context also governs the spatial reach and persistence of cooling. Tropical cities exhibit extended cooling plumes due to moist-air retention, whereas temperate and continental cities experience faster dilution of cooling effects under stronger winds and greater seasonal variability (Ananyeva, 2021; Herath et al., 2018). In arid regions, rapid surface reheating limits nighttime cooling, especially where vegetation is sparse or moisture-limited (Moreno-García & Baena, 2019; Razzaghmanesh et al., 2016). Together, these spatial and temporal patterns confirm that climate not only conditions the magnitude of GI cooling but also determines how far and how long its benefits extend into the urban environment.

## 4. Conclusion

This review demonstrates that GI-based UHI mitigation research is dominated by simulation-driven approaches, with tools such as ENVI-met, CFD, and mesoscale models forming the methodological backbone of the field. While modelling enables controlled evaluation of complex thermal processes, empirical measurements remain indispensable for calibration and validation, ensuring that simulated results remain grounded in real environmental behavior. Across the 31 reviewed studies, a clear hierarchy of cooling performance emerges: trees consistently provide the strongest and most scalable temperature reductions, followed by green walls, green roofs, and ground-level vegetation. Multi-layered and hybrid GI systems outperform single interventions, confirming that structural complexity, canopy density, and vertical layering are critical for achieving effective, resilient cooling.

Variability in reported cooling magnitudes arises not from inconsistencies in GI itself but from the interactions among vegetation structure, spatial configuration, hydrological and meteorological conditions, and differing measurement frameworks. These factors collectively determine whether a GI intervention expresses minimal or substantial cooling, highlighting the need for context-sensitive interpretation of results. Climatic conditions further mediate GI performance: tropical climates amplify evapotranspirative and shading cooling, temperate and continental climates introduce substantial seasonal variability, and arid climates constrain evaporative cooling while prioritizing shading and irrigation-supported strategies. Overall, the findings underscore that effective UHI mitigation requires aligning GI typologies and configurations with local climatic and spatial conditions. The synthesis presented here establishes the conceptual foundation for designing climate-responsive, structurally optimized GI interventions across diverse urban environments.

### Acknowledgment

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

## References

Ali, M. A., Alawadi, K., & Khanal, A. (2021). The role of green infrastructure in enhancing microclimate conditions: A case study of a low-rise neighborhood in Abu Dhabi. *Sustainability*, *13*(8), 4260. https://doi.org/10.3390/su13084260

Ananyeva, O. (2021). *Green infrastructure cooling strategies for urban heat island mitigation in cities: case study of Glasgow city centre*. https://urn.fi/URN:NBN:fi:amk-2021110219147

Antoszewski, P., Świerk, D., & Krzyżaniak, M. (2020). Statistical review of quality parameters of blue-green infrastructure elements important in mitigating the effect of the urban heat island in the temperate climate (C) zone. *International Journal of Environmental Research and Public Health*, *17*(19), 7093. https://doi.org/10.3390/ijerph17197093

Apritasari, Y. D., Triyadi, S., Wonorahardjo, S., & Indraprastha, A. (2022). Review on appropriateness of urban heat island mitigation technologies at several climates condition. *IOP Conference Series: Earth and Environmental Science*, *1058*(1), 012011. https://doi.org/10.1088/1755-1315/1058/1/012011

Bahadori, E., Rezaei, F., He, B.-J., Heiranipour, M., & Attia, S. (2025). Evaluating urban heat island mitigation strategies through coupled UHI and building energy modeling. *Building and Environment*, 113111. https://doi.org/10.1016/j.buildenv.2025.113111

Balany, F., Ng, A. W. M., Muttil, N., Muthukumaran, S., & Wong, M. S. (2020). Green infrastructure as an urban heat island mitigation strategy—a review. *Water*, *12*(12), 3577. https://doi.org/10.3390/w12123577

Battista, G., Evangelisti, L., Guattari, C., De Lieto Vollaro, E., De Lieto Vollaro, R., & Asdrubali, F. (2020). Urban heat island mitigation strategies: Experimental and numerical analysis of a university campus in Rome (Italy). *Sustainability*, *12*(19), 7971. https://doi.org/10.3390/su12197971

Budzik, G., Sylla, M., & Kowalczyk, T. (2025). Understanding Urban Cooling of Blue–Green Infrastructure: A Review of Spatial Data and Sustainable Planning Optimization Methods for Mitigating Urban Heat Islands. *Sustainability*, *17*(1), 142. https://doi.org/10.3390/su17010142

Chaney, M. A. (2021). So You Want to Write a Narrative Review Article? *Journal of Cardiothoracic and Vascular Anesthesia*, *35*(10), 3045–3049. https://doi.org/10.1053/j.jvca.2021.06.017

Esfehankalateh, A. T., Ngarambe, J., & Yun, G. Y. (2021). Influence of tree canopy coverage and leaf area density on urban heat island mitigation. *Sustainability*, *13*(13), 7496. https://doi.org/10.3390/su13137496

Fallahi, S., & Ayvazian, S. (2016). *The analysis of the role of green walls in reduction of heat islands in Tehran*. https://www.sid.ir/paper/339265/en

Fu, Q., Zheng, Z., Sarker, M. N. I., & Lv, Y. (2024). Combating urban heat: Systematic review of urban resilience and adaptation strategies. *Heliyon*, *10*(17). https://doi.org/10.1016/j.heliyon.2024.e37001

Galagoda, R. U., Jayasinghe, G. Y., Halwatura, R. U., & Rupasinghe, H. T. (2018). The impact of urban green infrastructure as a sustainable approach towards tropical micro-climatic changes and human thermal comfort. *Urban Forestry & Urban Greening*, *34*, 1–9. https://doi.org/10.1016/j.ufug.2018.05.008

Habibi, A., & Kahe, N. (2024). Evaluating the role of green infrastructure in microclimate and building energy efficiency. *Buildings*, *14*(3), 825. https://doi.org/10.3390/buildings14030825

Herath, H., Halwatura, R. U., & Jayasinghe, G. Y. (2018). Evaluation of green infrastructure effects on tropical Sri Lankan urban context as an urban heat island adaptation strategy. *Urban Forestry & Urban Greening*, *29*, 212–222. https://doi.org/10.1016/j.ufug.2017.11.013

Hosseinzadeh, A., Bottacin-Busolin, A., & Keshmiri, A. (2022). A parametric study on the effects of green roofs, green walls and trees on air quality, temperature and velocity. *Buildings*, *12*(12), 2159. https://doi.org/10.3390/buildings12122159

Imran, H. M., Shammas, M. I., Rahman, A., Jacobs, S. J., Ng, A. W. M., & Muthukumaran, S. (2021). Causes, modeling and mitigation of urban heat island: a review. *Earth Sciences*, *10*(6), 244–264. https://doi.org/10.11648/j.earth.20211006.11

IPCC. (2023). *Climate change 2023 synthesis report*. Intergovernmental Panel on Climate Change (IPCC). https://doi.org/10.59327/IPCC/AR6-9789291691647.001

Irie, T. (2022). The cooling effect of green infrastructure in mitigating nocturnal urban heat islands: a case study of Yoyogi Park and Meiji Jingu Shrine in Tokyo. *Landscape Research*, *47*(5), 559–583. https://doi.org/10.1080/01426397.2022.2050195

Jabbar, H. K., Hamoodi, M. N., & Al-Hameedawi, A. N. (2023). Urban heat islands: a review of contributing factors, effects and data. *IOP Conference Series: Earth and Environmental Science*, *1129*(1), 012038. https://doi.org/10.11648/j.earth.20211006.11

Kabisch, N., Korn, H., Stadler, J., & Bonn, A. (Eds.). (2017). *Nature-based solutions to climate change adaptation in urban areas: Linkages between science, policy and practice*. Springer Cham. https://doi.org/10.1007/978-3-319-56091-5

Koc, C. B., 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. https://doi.org/10.1016/j.solener.2018.03.008

Li, X., Zhou, Y., Yu, S., Jia, G., Li, H., & Li, W. (2019). Urban heat island impacts on building energy consumption: A review of approaches and findings. *Energy*, *174*, 407–419. https://doi.org/10.1016/j.energy.2019.02.183

Lin, C., & Zhang, S. (2024). Impact of Green Roofs and Walls on the Thermal Environment of Pedestrian Heights in Urban Villages. *Buildings*, *14*(12), 4063. https://doi.org/10.3390/buildings14124063

Mohammed, A., Khan, A., & Santamouris, M. (2023). Numerical evaluation of enhanced green infrastructures for mitigating urban heat in a desert urban setting. *Building Simulation*, *16*(9), 1691–1712. https://doi.org/10.1007/s12273-022-0940-x

Morakinyo, T. E., Adegun, O. B., Adegbie, M. O., & Olusoga, O. O. (2021). *Micro-Climatic Benefits of Green Infrastructure (Trees) in a Housing Estate in Abuja, Nigeria*. https://waberconference.com/wp-content/themes/waberconference/assets/images/conference_papers/50.pdf

Moreno-García, M. del C., & Baena, I. (2019). The microclimatic effect of green infrastructure (GI) in a Mediterranean city: the case of the urban park of Ciutadella (Barcelona, Spain). *Arboriculture & Urban Forestry (AUF)*, *45*(3), 99–107. https://doi.org/10.48044/jauf.2019.009

Mutani, G., & Todeschi, V. (2020). The effects of green roofs on outdoor thermal comfort, urban heat island mitigation and energy savings. *Atmosphere*, *11*(2), 123. https://doi.org/10.3390/atmos11020123

Nguyen, T. M., Lin, T.-H., & Chan, H.-P. (2019). The environmental effects of urban development in Hanoi, Vietnam from satellite and meteorological observations from 1999–2016. *Sustainability*, *11*(6), 1768. https://doi.org/10.3390/su11061768

Nuruzzaman, M. (2015). Urban heat island: causes, effects and mitigation measures-a review. *International Journal of Environmental Monitoring and Analysis*, *3*(2), 67–73. https://doi.org/10.11648/j.ijema.20150302.15

Oğuztürk, G. E., Sünbül, S., & Alparslan, C. (2025). The effect of green areas on urban microclimate: A university campus model case. *Applied Sciences*, *15*(8), 4358. https://doi.org/10.3390/app15084358

Palme, M., Privitera, R., & La Rosa, D. (2020). The shading effects of Green Infrastructure in private residential areas: Building Performance Simulation to support urban planning. *Energy and Buildings*, *229*, 110531. https://doi.org/10.1016/j.enbuild.2020.110531

Park, J., Kim, J.-H., Dvorak, B., & Lee, D. K. (2018). The role of green roofs on microclimate mitigation effect to local climates in summer. *International Journal of Environmental Research*, *12*(5), 671–679. https://doi.org/10.1007/s41742-018-0124-9

Park, J., Kim, J.-H., Lee, D. K., Park, C. Y., & Jeong, S. G. (2017). The influence of small green space type and structure at the street level on urban heat island mitigation. *Urban Forestry & Urban Greening*, *21*, 203–212. https://doi.org/10.1016/j.ufug.2016.12.005

Park, J., Shin, Y., Kim, S., Lee, S.-W., & An, K. (2022). Efficient plant types and coverage rates for optimal green roof to reduce urban heat island effect. *Sustainability*, *14*(4), 2146. https://doi.org/10.3390/su14042146

Piao, Z. (2022). *Multi-objective Optimization Model for 3D Urban Green Space to Reduce Urban Heat Island*. https://hdl.handle.net/10371/187962

Raymond, C. M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M. R., Geneletti, D., & Calfapietra, C. (2017). A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental Science & Policy*, *77*, 15–24. https://doi.org/10.1016/j.envsci.2017.07.008

Razzaghmanesh, M., Beecham, S., & Salemi, T. (2016). The role of green roofs in mitigating Urban Heat Island effects in the metropolitan area of Adelaide, South Australia. *Urban Forestry & Urban Greening*, *15*, 89–102. https://doi.org/10.1016/j.ufug.2015.11.013

Sánchez-Cordero, F., Nanía, L., Hidalgo-García, D., & López-Chacón, S. R. (2025). Assessing the Spatial Benefits of Green Roofs to Mitigate Urban Heat Island Effects in a Semi-Arid City: A Case Study in Granada, Spain. *Remote Sensing*, *17*(12), 2073. https://doi.org/10.3390/rs17122073

Santamouris, M. (2020). 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*, *207*, 109482. https://doi.org/10.1016/j.enbuild.2019.109482

Semenzato, P., & Bortolini, L. (2023). Urban heat island mitigation and urban green spaces: testing a model in the city of Padova (Italy). *Land*, *12*(2), 476. https://doi.org/10.3390/land12020476

Tan, J. K. N., Belcher, R. N., Tan, H. T. W., Menz, S., & Schroepfer, T. (2021). The urban heat island mitigation potential of vegetation depends on local surface type and shade. *Urban Forestry & Urban Greening*, *62*, 127128. https://doi.org/10.1016/j.ufug.2021.127128

Tariq, M. (2023). *A Comparative analysis of the Cooling effects of Green Infrastructure Types on Peshawar's Urban Microclimate in Public Squares*. https://urn.fi/URN:NBN:fi:amk-2023101327506

Tiwari, A., Kumar, P., Kalaiarasan, G., & Ottosen, T.-B. (2021). The impacts of existing and hypothetical green infrastructure scenarios on urban heat island formation. *Environmental Pollution*, *274*, 115898. https://doi.org/10.1016/j.envpol.2020.115898

Wang, Y., Bakker, F., de Groot, R., Wörtche, H., & Leemans, R. (2015). Effects of urban green infrastructure (UGI) on local outdoor microclimate during the growing season. *Environmental Monitoring and Assessment*, *187*(12), 732. https://doi.org/10.1007/s10661-015-4943-2

Wardana, L. M. F., Rizaldi, M. A., Joko, T., & Nurjazuli, N. (2025). Urban Heat Islands, Rising Temperatures, and Their Impacts on Global Public Health: A Narrative Review. *Jurnal Ilmiah Kesehatan Masyarakat: Media Komunikasi Komunitas Kesehatan Masyarakat*, *17*(2), 102–119. https://doi.org/10.52022/jikm.v17i2.742

Wong, L. P., Alias, H., Aghamohammadi, N., Aghazadeh, S., & Sulaiman, N. M. N. (2018). Physical, psychological, and social health impact of temperature rise due to urban heat island phenomenon and its associated factors. *Biomed Environ Sci*, *31*(7), 545–550. https://doi.org/10.3967/bes2018.074

Yang, S., & La Roche, P. (2025). Microclimate Analysis of Tree Canopies and Green Surface Combinations for Urban Heat Island Mitigation in Los Angeles and Phoenix. *Buildings*, *15*(9), 1573. https://doi.org/10.3390/buildings15091573

Yun, S. H. (2023). *Development of a 3D Urban Surface Model for Evaluating Cooling Effect of Green Infrastructure*. https://hdl.handle.net/10371/197475

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. https://doi.org/10.1016/j.ufug.2016.09.011