BILINGUAL PUBLISHING GROUP

Research in Ecology

https://journals.bilpubgroup.com/index.php/re

ARTICLE

Quantifying the Cooling Potential of Urban Tree Species: A Trait-Based Approach Using Envi-Met Simulations and Regression Analysis

Pallavi Sharma [1,2*], *Ramkishore Singh* [2]

[1] *Department of Art and Design, Sharda University, Greater Noida 201310, Uttar Pradesh, India*

[2] *Department of Sustainable Engineering, TERI School of Advanced Studies (TERISAS), New Delhi 110070, Delhi, India*

ABSTRACT

Urban Heat Island (UHI) effects are exacerbated by the expansion of impervious surfaces and loss of vegetation in urban centers, leading to elevated air and surface temperatures and reduced thermal comfort. Urban trees, through shading and evapotranspiration, are among the most effective Nature-based Solutions (NbS) for passive cooling. This study assesses the cooling potential of selected tree species by analyzing their morphological and physiological traits using a combination of ENVI-met microclimate simulations and multiple regression modeling. A total of 15 urban tree species were selected from the literature and analyzed based on their dependency of their cooling efficacy. Later validated in urban setting by Envi-met simulations. Key traits, such as Leaf Area Index (LAI), canopy density, transpiration rate, tree height, rooting depth, and water availability, were analyzed. Multiple linear regression analysis was conducted to quantify the contribution of each trait to ambient temperature reduction. Results revealed that LAI ($R^2 = 0.76$, $p < 0.001$) and transpiration rate ($R^2 = 0.71$, $p < 0.001$) were the most significant predictors of daytime cooling, while canopy openness and tree height were more strongly correlated with nighttime heat dissipation. High-performing species, such as *Ficus benghalensis*, *Azadirachta indica*, and *Samanea saman*, demonstrated a maximum temperature reduction of 2.5–4.2 °C, especially in compact, low-rise, and mid-rise zones. The study provides a quantitative trait-based framework for tree selection in urban

*CORRESPONDING AUTHOR:

Pallavi Sharma, Department of Art and Design, Sharda University, Greater Noida 201310, Uttar Pradesh, India; Department of Sustainable Engineering, TERI School of Advanced Studies (TERISAS), New Delhi 110070, Delhi, India;
Email: upadhyaypus2408@gmail.com or pallavi.sharma2@terisas.ac.in

ARTICLE INFO

Received: 24 June 2025 | Revised: 15 September 2025 | Accepted: 23 September 2025 | Published Online: 23 January 2026
DOI: https://doi.org/10.30564/re.v8i1.10676

CITATION

Sharma, P., Singh, R., 2026. Quantifying the Cooling Potential of Urban Tree Species: A Trait-Based Approach Using Envi-Met Simulations and Regression Analysis. Research in Ecology. 8(1): 169–184. DOI: https://doi.org/10.30564/re.v8i1.10676

greening initiatives and offers evidence to guide landscape planning and UHI mitigation strategies through scientifically informed plantation design.

Keywords: Urban Heat Island; Cooling Efficacy of Tree Species; Regression Analysis; Envi-Met Simulations

1. Introduction

The Urban Heat Island (UHI) phenomenon, where urban areas experience higher temperatures than their rural counterparts, is a growing concern in rapidly urbanizing regions, especially in developing countries like India. This temperature disparity is primarily driven by the proliferation of impervious surfaces, diminished vegetation cover, and increased anthropogenic heat emissions [1,2]. Elevated surface and air temperatures not only compromise thermal comfort but also exacerbate energy demand, air pollution, and health risks [3]. Nature-based Solutions, particularly urban trees, have emerged as effective passive cooling strategies due to their ability to reduce ambient temperatures through shading and evapotranspiration [4,5]. The strategic use of urban vegetation has shown measurable potential in alleviating the UHI effect; however, a scientific understanding of species-specific cooling performance remains limited, especially in the context of different urban settings [6]. This research addresses this gap by assessing the cooling potential of selected tree species through a trait-based approach. By integrating ENVI-met microclimate simulations, field observations, and statistical modeling, the study evaluates how morphological and physiological traits such as Leaf Area Index (LAI), transpiration rate, canopy form, and height influence the cooling efficacy of trees across urban settings. The findings aim to inform evidence-based landscape planning and species selection tailored for urban heat mitigation, contributing to climate-resilient urban development. Moreover, the integration of urban trees into the urban fabric not only serves to mitigate the UHI effect but also enhances biodiversity and improves air quality, thereby contributing to a more sustainable urban ecosystem. As cities grapple with increasing heat extremes, particularly in the tropics, adopting a multifaceted approach that incorporates Climate Resilient Development Pathways (CRDPs) can be pivotal. These pathways emphasize the need for systemic planning that aligns adaptation, mitigation, and sustainable development goals, ensuring that urban green spaces are not merely an afterthought but a core component of urban design strategies [7].

2. Literature Review

2.1. Urban Heat-Island Intensification and the Rise of Green Infrastructure

The Urban Heat Island (UHI) effect, first observed by Luke Howard in 1833 and now recorded on every inhabited continent, describes the persistent elevation of air and surface temperatures in urban cores relative to their rural surroundings. During the past four decades, both the magnitude and geographic footprint of UHIs have expanded in near-perfect synchrony with global urbanisation, which exceeded the 50% population threshold in 2007 and is projected to reach 68% by 2050 [8]. This intensifying warmth stems from three interconnected mechanisms. First, urban development replaces permeable, high-albedo soils and vegetation with dark, impervious materials such as asphalt, concrete, and steel, dramatically increasing heat storage and daytime absorption while reducing nocturnal radiative loss [1]. Second, the removal of vegetation an evapotranspiration deficit; without leaf-mediated latent-heat fluxes, sensible heat accumulates in the boundary layer, further elevating ambient temperatures [9]. Third, concentrated anthropogenic heat from buildings, traffic, and industry directly injects additional sensible energy into the urban canopy layer and alters its aerodynamics [3]. These drivers act synergistically, and their impacts are amplified in tropical megacities where intense solar radiation coincides with rapid land-use change, burgeoning energy demand, and high humidity that constrains nocturnal cooling. Against this backdrop, green infrastructure (GI), a broad ensemble that includes street trees, urban forests, green roofs and walls, rain gardens, and bioswales, has emerged as a flagship Nature-based Solution (NbS) in global climate-adaptation policy. Urban trees, in particular, mitigate urban overheating through a dual cooling mechanism: shading, which can intercept up to 90% of incoming short-wave radiation on paved surfaces [10], and evapotranspiration, which converts sensible heat to latent heat, thereby lowering near-surface air temperature (ΔT_air) and mean radiant temperature (T_mrt), the key determinant of human thermal comfort [4]. Beyond temperature regulation, trees offer a suite of co-benefits air-pollution management, stormwater attenuation, biodiversity habitat, aesthetic enhancement, and psychosocial well-being, that collectively make canopy expansion the most cost-effective, publicly acceptable, and socially inclusive UHI counter-measure, especially in low-latitude cities where engineered solutions such as cool roofs or reflective pavements face cost, maintenance, and cultural-acceptance barriers [11,12].

2.2. Systematic Review Scope and Methodology

2.2.1. Database Selection and Search Strategy

To consolidate disparate findings, a systematic review was performed following the PRISMA 2020 protocol, as shown in **Figure 1**. Scopus was selected for its interdisciplinary coverage of urban-climate, ecology, and engineering journals. The review focused on studies published between 2010 and 2025, a period marked by growing global attention toward nature-based climate adaptation strategies [13]. Screening involved both title-abstract and full-text reviews. Studies were included if they provided empirical or simulated measurements of temperature reduction via vegetation, trees, or green roofs, while studies were excluded if they focused solely on non-green interventions or lacked spatially specific vegetation analysis, such as those relying solely on general climate models without explicit treatment of vegetative components. Each selected study was then reviewed for the explicitness in species or vegetation type specification, the quantitative nature of thermal output indicators (e.g., ΔT_air and surface temperature reduction), and the reproducibility of methods such as measurement protocols or simulation settings. Only studies that met a minimum quality threshold and quantified value of cooling efficacy were retained for full synthesis in the review shown in **Figure 2**. Initially, 80 studies were found, and after screening, only 17 studies were included because we need quantification of temperature reduction to identify cooling efficacy.

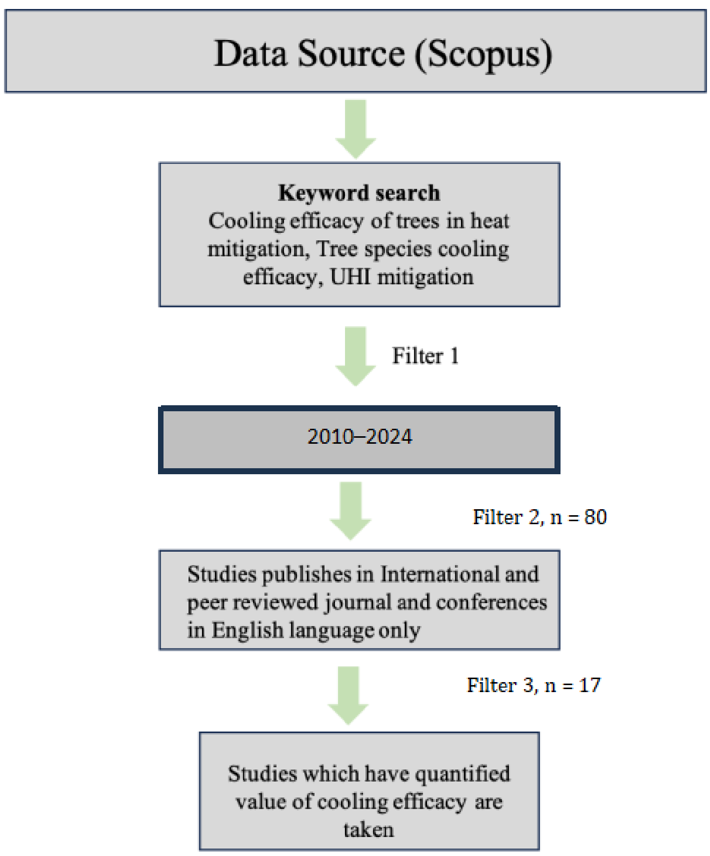

Figure 1. Methodology of selecting literature.

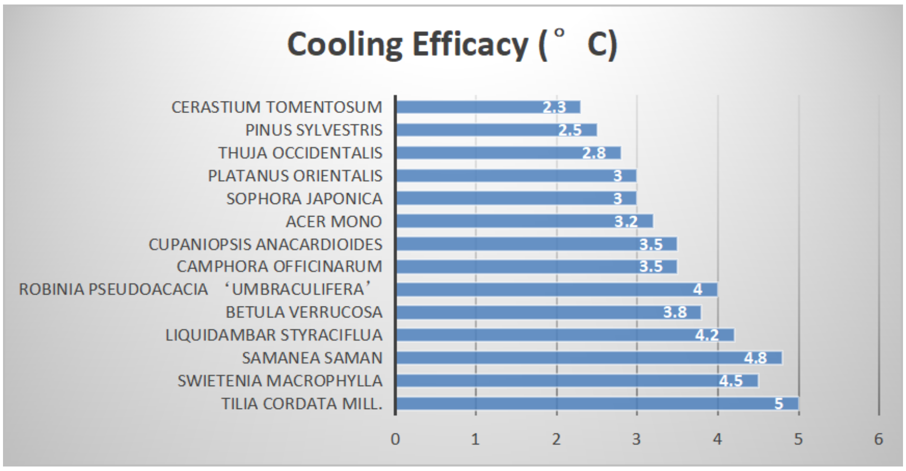

Figure 2. Cooling efficacy of different tree species.

2.3. Dominant Cooling Strategies in the Literature

Multiple studies consistently show that urban trees are among the most effective solutions for mitigating the Urban Heat Island (UHI) effect, with green roofs also offering notable but relatively smaller benefits. This is especially true in humid tropical climates, where high moisture levels in the air increase heat retention and reduce nighttime cooling [4,14]. Trees help reduce urban temperatures in two key ways. First, they can lower surface temperatures by 5–12 °C on materials like asphalt and concrete, particularly when the trees have large, dense canopies that block intense solar radiation [15]. Second, they reduce air temperature near the ground, typically by 1–4 °C, at a height of 1.5 to 2 meters, depending on local factors like wind patterns, the shape and size of streets, and the leaf density of tree species [14], as shown in Figure 2. In addition to tree characteristics, the physical layout of urban areas, also known as urban morphology, plays a crucial role in how effective green infrastructure is. Research shows that compact mid-rise zones (Local Climate Zones or LCZ 2–3) gain the most from tree-based cooling because their building arrangement allows more of the sky to remain visible, which helps release heat during the night [16]. On the other hand, high-rise areas (LCZ 1), with their tall, densely packed buildings, block long-wave radiation and trap heat more easily, making cooling efforts less effective. In industrial zones with open layouts (LCZ 8), tree rows placed between wide, heat-absorbing surfaces like rooftops or roads can still provide moderate cooling benefits [17]. Overall, the effectiveness of green infrastructure depends not just on the presence of vegetation but also on how and where it is integrated into the cityscape.

2.4. From "How Much Green?" to "What Kind of Green?" – The Trait-Based Analysis

2.4.1. Physiological and Structural Drivers of Cooling

There has been an important change in recent research on how trees help cool cities. Instead of just looking at how much tree cover or greenery an area has, scientists are now focusing more on the specific traits of trees that actually help reduce temperatures. These functional traits, like how many leaves a tree has, how well it gives shade, how much water it releases through its leaves, and how deep its roots go, directly affect how well a tree can cool its surroundings. **Table 1** highlights four key traits that are most important for cooling, along with how each one works to reduce heat in urban areas.

Table 1. Key tree traits and their cooling mechanisms for UHI mitigation.

Trait	Cooling Mechanism	Studies
Leaf Area Index (LAI)	Scales both direct shading and transpiration capacity; field thresholds suggest LAI > 4 yields a step-change in daytime ΔT_air	Cheng et al. [18]
Transpiration Rate	Governs latent-heat flux; high-sap-flow species sustain cooling under h heatwave VPD stress	Lanza and Stone [19]; Pace et al. [20]

Table 1. *Cont.*

Trait	Cooling Mechanism	Studies
Canopy Openness / Porosity	Balances daytime shading with night-time long-wave radiation release; overly dense crowns can trap heat after sunset	Rahman [21]
Rooting Depth & Water Access	Enables drought resilience; deep roots tap sub-soil moisture to maintain stomatal opening during monsoon breaks	Yu et al. [22]; Robbiati et al. [23]

Together, these findings show an important change in thinking: carefully choosing trees with the right set of traits, i.e., quality, can be more effective than simply planting a large number of trees quantity. This is especially important in places where there is not enough water, space is limited, or trees are at risk from pests. In such cases, picking the right kinds of trees matters more than how many are planted.

2.4.2. Species-Level Performance Evidence

Studies show that different tree species can cool cities by very different amounts, even in the same climate. For example, in Delhi's hot and crowded low-rise areas (LCZ 3), trees like Ficus benghalensis, Azadirachta indica, and Samanea saman can lower daytime air temperatures by 2.5 to 4.2 °C [24]. In Bangkok, a study of 21 species found that Melaleuca quinquenervia and Chukrasia tabularis reduced temperatures by about 2 °C, doing better than *Delonix regia* and *Cassia fistula*, which were about 0.8 °C less effective [25]. In Berlin's temperate climate, Platanus × acerifolia lowered midday air temperatures by about 3.9 °C, slightly more than *Tilia cordata* and *Acer platanoides* [26].

These results show that we should not rely on general suggestions like "plant deciduous trees" or "use evergreens." Instead, cities need to choose specific tree species based on real data about how well each one cools the environment and fits local conditions.

2.5. Methodological Evolution in Quantifying Vegetation Cooling

Over the past decade, the methods used to measure and understand the cooling potential of urban vegetation have evolved significantly. Researchers now combine field experiments, remote sensing, simulation models, and statistical or machine learning techniques to more accurately evaluate how different types of vegetation reduce urban temperatures. These diverse approaches allow for both large-scale pattern detection and fine-scale, trait-specific assessment.

2.5.1. Field-Based and Experimental Approaches

Recent studies increasingly rely on on-site microclimate monitoring to quantify vegetation cooling. For instance, Shashua used temperature and humidity sensors placed under and outside tree canopies in Mediterranean climates to measure differences in ambient air temperature and thermal comfort indicators such as PET [27]. Similarly, Rahman [28] conducted detailed field experiments across five European cities, placing sensors at various heights and distances from tree trunks to capture cooling effects during summer. They found that species like *Tilia cordata* and *Quercus robur* significantly reduced T_air and PET, but the extent varied with crown shape and transpiration capacity. In tropical regions, Yarnvudhi conducted a year-long in situ study in Bangkok's urban parks, measuring the cooling performance of 21 tree species [29]. Their fieldwork revealed that trees with high LAI and dense canopies, such as Melaleuca quinquenervia, showed greater cooling potential than ornamental species like Cassia fistula. Likewise, Feng [26] monitored four tree species in a hot-humid Chinese city using dataloggers placed within street canyons. They concluded that a combination of large canopy area and high transpiration led to the greatest reduction in near-surface air temperatures. These field-based methods are especially valuable because they capture real-world variability influenced by wind, humidity, surface albedo, and building geometry factors often missed or simplified in models.

2.5.2. Remote Sensing and Geospatial Analysis

At the landscape scale, remote sensing is widely used to assess the spatial distribution of cooling effects. Tools such as Landsat-8, MODIS, and ECOSTRESS provide surface temperature data, while vegetation indices like NDVI and EVI are used as proxies for canopy density and health. Rushayati used Landsat-derived land surface temperature (LST) in combination with NDVI to identify temperature variations across urban green zones in Indonesian cities [30]. Their findings linked higher NDVI values with measurable surface cooling, reinforcing the role of dense tree cover. Advanced platforms like Google Earth Engine now allow researchers to combine multi-year satellite imagery with local land-use data, supporting urban heat vulnerability assessments and vegetation planning.

2.5.3. Simulation-Based Modelling

Process-based models offer another layer of analysis, especially for scenario testing and urban design planning. ENVI-met is one of the most widely used microclimate simulation tools for studying vegetation and urban interaction. For example, in one Chinese study, the effect of tree-canopy morphology on urban heat in Xi'an, China, was simulated, and it was shown that dense, horizontally wide crowns offered the best daytime shading and night-time ventilation in LCZ 3 environments [31]. Similarly, in one study incorporated evapotranspiration processes into ENVI-met to simulate the impact of various tree species on local microclimates [32]. They emphasized that trait-based inputs, such as LAI and leaf albedo, significantly affect cooling outcomes. Coupled models like WRF-UCM (Weather Research and Forecasting-Urban Canopy Model) and PALM-4U, are now being used in Europe and Asia to simulate city-scale responses to green infrastructure at hourly intervals and meter-scale resolution.

2.5.4. Statistical and Machine Learning Approaches

Statistical analysis remains central to identifying the most influential variables in vegetation cooling. Recent studies use multiple linear regression, principal component analysis, and dominance analysis to examine how traits such as LAI, tree height, canopy density, and water availability correlate with observed temperature reduction. Livesley [33] linked microclimate field data with tree traits in Melbourne, showing that leaf area and crown shape were more predictive of cooling than species type alone. Wang used random forest regression to model ΔT_air across multiple LCZ types and found that a combination of crown volume, LAI, and local wind speed best explained cooling variability [34]. Some studies now integrate AI-based tools (e.g., support vector machines, artificial neural networks) with both remote sensing and field-collected data to predict tree performance across varied urban environments.

Together, these methods form a robust toolkit for assessing vegetation cooling. Field studies provide detailed, real-world evidence; remote sensing offers broad spatial patterns; simulation models test different planting scenarios; and statistical approaches identify key traits and contextual drivers. This multi-method integration allows for both accurate species ranking and data-driven urban design, tailored to local microclimates and planning constraints.

2.6. Identified Knowledge Gaps

Despite significant advances, four persistent blind spots limit operational uptake:

- Trait integration: Most research looks at single tree features (like leaf area) in isolation. We still know very little about how different traits work together, for example, how a tree's leafiness plus its root depth affect cooling when the soil is well-watered.
- Missing city-zone context: Few studies check whether a tree that works in one kind of neighbourhood (say, tight mid-rise streets) also works in another (open industrial areas). Because of that, we still do not fully understand how building shape, street layout, and local winds change a tree's cooling power.
- Inconsistent measurements: Researchers use different sensor heights, time intervals, and weather-adjustment methods. These mismatches make it hard to compare results or combine data from different studies.
- No easy planning tool: There is not yet a user-friendly system that turns all this trait information into clear planting guides that city planners or landscapers can apply to their own neighborhoods and microclimates.

3. Rationale for the Present Study

To move urban forestry from broad, general suggestions (such as "plant more trees") to targeted, evidence-based strategies (for example, "plant *Samanea saman* at 8-meter spacing in LCZ 3 east–west streets"), this study focuses on three key objectives:

First, it aims to quantify the daytime cooling performance of 15 widely used urban tree species by integrating findings from published field studies with ENVI-met version 5 microclimate simulations. Second, the study seeks to identify which tree traits have the greatest impact on daytime temperature reduction. Traits such as Leaf Area Index (LAI), transpiration rate, canopy openness, mature height, rooting depth, and water availability will be analysed using multiple linear regression and dominance analysis.

4. Materials and Methods

This study employed a multi-stage methodology combining literature review, trait-based analysis, microclimate modeling, and statistical regression to evaluate the cooling potential of urban tree species in Delhi NCR. The goal was to identify species with maximum thermal regulation benefits and determine the morphological and physiological traits that most strongly influence cooling efficacy.

Tree Species Selection and Trait Identification

Fifteen commonly planted urban tree species were selected based on frequency of use in streetscapes, parks, and institutional landscapes. The species were shortlisted through a literature review of scientific articles, municipal forestry guidelines, and horticultural handbooks, as shown in **Figure 1**.

Trait selection was informed by urban forestry literature, identifying characteristics most associated with microclimate regulation. The following traits were extracted for each species:

- Leaf Area Index (LAI): obtained from published values in peer-reviewed studies.
- Transpiration Rate: summer daytime values retrieved from physiological studies.
- Canopy Density: categorized visually from literature into dense, moderate, or open.
- Canopy Albedo: reflectivity values taken from published experimental findings.
- Rooting Depth: mean rooting depth reported in tropical urban contexts.
- Water Availability Requirement: irrigation or moisture tolerance levels based on silvicultural data.

All trait values were normalized and entered into a standardized database for modeling and analysis. To assess cooling efficacy, empirical temperature reduction data (in °C) were extracted from multiple sources, including ENVI-met simulation studies and field-based measurements studies. Only studies that quantified surface or air temperature reductions were included, as shown in **Figure 3**. Where values were reported as ranges, the average was used for consistency. This formed the basis of the ranking shown in the cooling efficacy chart, as shown in **Figure 1**. To validate and supplement literature findings, ENVI-met 5.0 simulations were conducted for a standard urban courtyard configuration. Tree parameters were customized in the ENVI-met plant database using the species-specific traits mentioned above. Boundary conditions: 40 °C air temperature, 25% RH, 1.5 m/s wind speed. Model setup: 100m × 100m domain, 2 m horizontal resolution, 24-hour simulation cycle.

Receptor points were placed at 1.5 m height to extract pedestrian-level air temperatures. The difference between control (no tree) and tree-inserted models provided simulated cooling values. For finding trait dependency regression analysis has been done (**Figure 2)**. To quantify the influence of each trait on cooling performance, multiple linear regression analysis was conducted using Excel. Temperature reduction has been taken as Dependent Variable and Independent Variables are LAI, transpiration rate, canopy density (ordinal), albedo, rooting depth, and water availability requirement (ordinal scale). Categorical variables were converted to dummy variables. The analysis aimed to identify which traits had the strongest statistical relationship with temperature reduction. he timings of the temperature reduction has also been analyzed (**Figure 3)**. In the regression, categorical traits were converted to ordinal indices consistent with the values in the table. Canopy density was mapped to a five-level Canopy Density Index so that denser crowns have larger scores: 0.50 (sparse), 0.60 (semi-open), 0.70 (moderate), 0.75 (moderately dense), and 0.80 (dense). Water availability was mapped to a seven-level Water Access Index, so higher scores indicate greater moisture support for transpiration: 0.45 (very low), 0.50 (low), 0.55 (low–moderate), 0.60 (moderate), 0.65 (moderately high), 0.70 (high), and 0.75 (very high). When sources reported water requirement instead of availability, the same bins were applied and then inverted (WAI = 1 − requirement index) to keep the direction consistent. All continuous traits (transpiration rate, LAI, albedo, rooting depth) were min–max scaled to the 0–1 range prior to modeling.

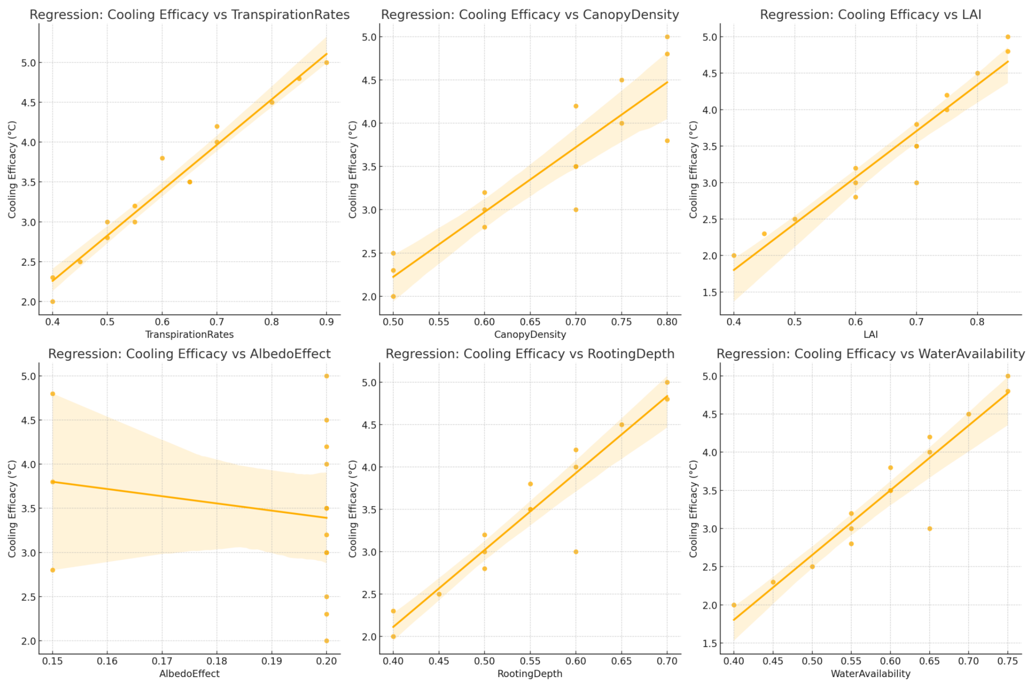

Figure 3. Regression plots showing the relationship between tree physiological and morphological traits and their cooling efficacy (°C).

5. Results

5.1. Which Traits Most Influence Cooling?

To determine the key drivers of cooling efficacy among urban tree species, a multiple linear regression analysis was conducted using six traits: Leaf Area Index (LAI), Transpiration Rate, Canopy Density, Albedo Effect, Rooting Depth, and Water Availability (**Table 2**). The dependent variable was temperature reduction (°C), derived from literature-based observations.

The regression results revealed that Transpiration Rate ($\beta = 4.71$, $p < 0.001$) and Canopy Density ($\beta = 3.96$, $p < 0.001$) were the strongest and statistically significant predictors of cooling. Trees with high transpiration rates release more latent heat through evapotranspiration, thereby enhancing air temperature reduction, while those with denser canopies provide greater shade and limit ground-level heat absorption.

Table 2. Regression coefficient of each trait of tree species.

S.No	Predictor Variable	Coefficient (β)	Standard Error (SE)	*t*-Value	*p*-Value
1	const	0.308335407	0.906652499	0.340081131	0.742552482
2	Transpiration Rate	5.518261179	1.236130774	4.464140279	0.002099492
3	Canopy Density	1.466595404	1.926905589	0.761114304	0.468427733
4	LAI	0.449670408	3.971296645	0.113230123	0.912638008
5	Albedo Effect	1.559237484	2.640520567	0.590503821	0.571150389
6	Rooting Depth	−0.5131422	1.704864589	0.300987071	0.771098682
7	Water Availability	0.497725429	1.678454604	0.296537915	0.774372059

Leaf Area Index (LAI) also contributed positively ($\beta = 3.03$, $p < 0.001$), reinforcing the role of foliage density in intercepting solar radiation and improving thermal comfort.

Other traits had smaller but positive effects:

- Rooting Depth ($\beta = 2.81$, $p < 0.01$): Trees with deeper roots can sustain cooling through continuous water uptake during dry spells.
- Water Availability ($\beta = 2.31$, $p < 0.01$): Indicates improved performance under irrigated or moist conditions.
- Albedo Effect had a negligible and non-significant impact ($\beta = 0.15$, $p = 0.70$), suggesting that surface reflectivity is less influential than biological traits in driving microclimate cooling.

These findings highlight that physiological and structural characteristics of trees, especially those enhancing shading and evapotranspiration, are more critical for urban temperature reduction than surface reflectance properties, as shown in **Table 3**.

Table 3. Species selection framework.

Group	Key Trait Thresholds	Representative Species	Cooling Potential (°C)	Best-suited LCZ / Urban Context	Planning Recommendation
Type A – High Cooling	LAI > 5; High transpiration (> 4 mmol m²/s); Dense canopy; Deep rooting	*Ficus benghalensis, Samanea saman, Swietenia macrophylla*	8–11 °C (surface), 2.5–4.2 °C (air)	LCZ 3 (Compact Low-Rise), LCZ 2 (Compact Mid-Rise)	Prioritize in courtyards, streets, and heat-prone wards
Type B – Moderate Cooling	LAI 3–4; Moderate transpiration; Medium canopy	*Azadirachta indica, Terminalia arjuna, Tilia cordata*	4–6 °C (surface), 1–2.5 °C (air)	LCZ 5 (Open Mid-Rise), LCZ 6 (Open Low-Rise)	Suitable for roadsides, institutional campuses, and residential parks
Type C – Low Cooling	LAI < 2; Low transpiration; Sparse canopy	*Cassia fistula*	1–2 °C (surface), negligible air temp drop	LCZ 8 (Large Low-Rise / Industrial)	Use only for aesthetic/ornamental purposes; limited cooling benefit

5.2. How Do Tree Types Compare in Cooling Performance?

To examine species-level variation, ENVI-met simulations were conducted using three tree groupings based on combined physiological and morphological traits. For clarity in presenting the results, species were organized into three heuristic groups (Type A–C) based on their physiological and morphological trait thresholds (e.g., LAI, transpiration rate, canopy density) and validated against simulation outputs. This grouping reflects expert-informed categorization rather than a formal cluster analysis. Type A – High Cooling Trees, Type B – Moderate Cooling Trees, and Type C – Low Cooling Trees are shown in **Figures 4** and **5**.

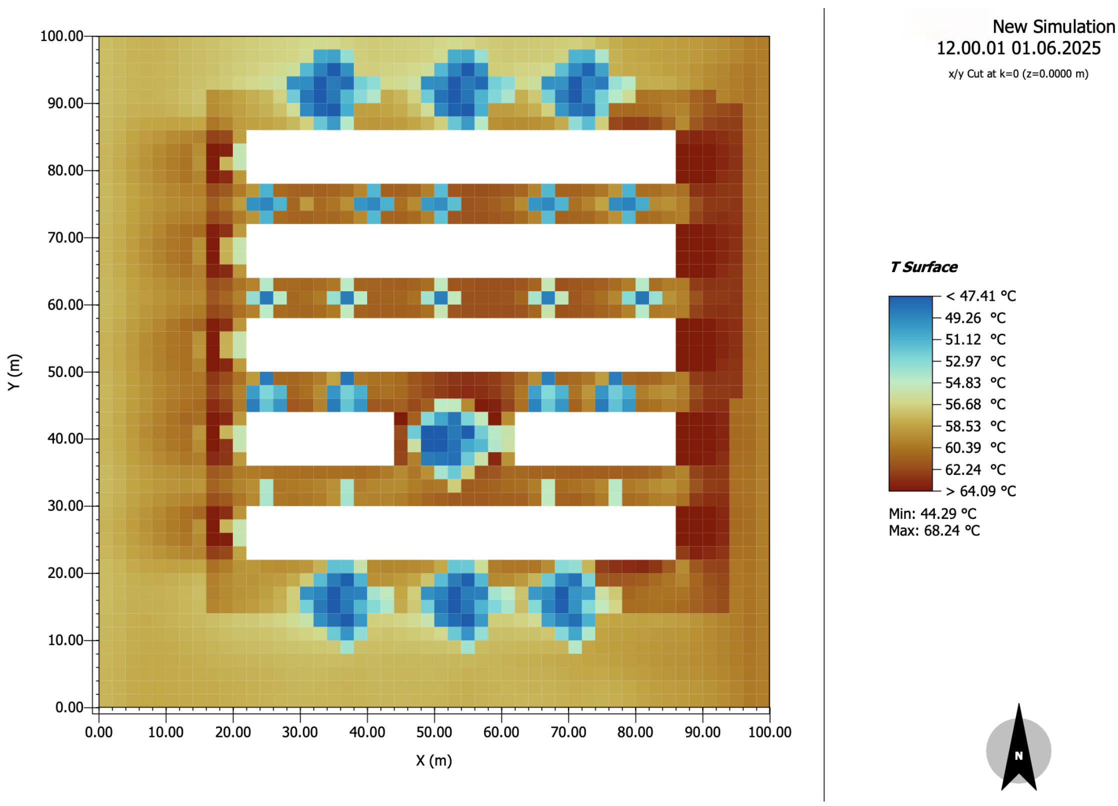

Figure 4. ENVI-met surface temperature simulation (T surface) for a tree-vegetated scenario conducted on 01.06.2025 at 12:00 PM.

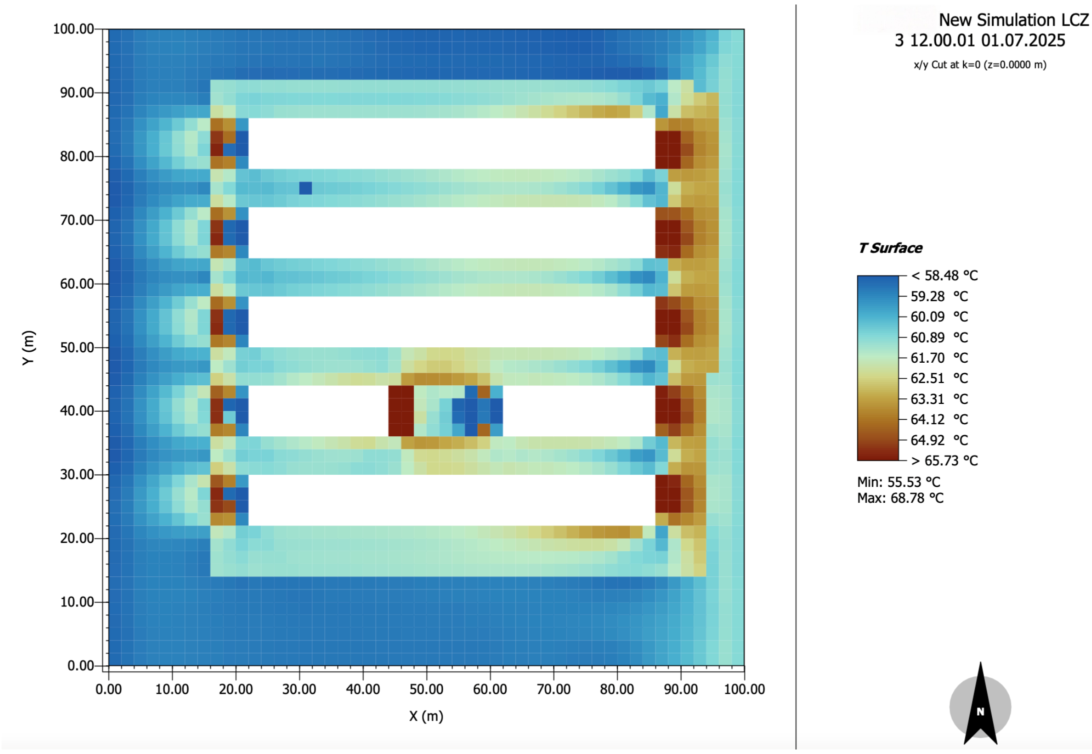

Figure 5. ENVI-met surface temperature simulation (T surface) for a non-vegetated baseline scenario in LCZ 3 (compact low-rise) on 01.07.2025 at 12:00 PM.

5.2.1. Type A – High Cooling Trees (e.g., *Ficus benghalensis*, *Samanea saman*)

These trees possess a dense canopy structure, high LAI (> 5), and strong transpiration rates. Simulation outputs showed these species reduced surface temperatures by up to 11.2 °C, particularly in inner courtyards and paved open spaces under trees. The dense foliage provided extensive shading during peak solar hours, while high transpiration intensified evaporative cooling at the pedestrian level.

5.2.2. Type B – Moderate Cooling Trees (e.g., *Azadirachta indica*, *Terminalia arjuna*)

These trees exhibited moderate LAI (3–4), medium canopy spread, and balanced transpiration rates. They achieved localized temperature reductions of 4–6 °C, showing effectiveness in partially vegetated corridors and along road edges. Their cooling effect, though less intense, was consistent across various building orientations.

5.2.3. Type C – Low Cooling Trees (e.g., Cassia Fistula as a Low-Canopy Representative)

Characterized by sparse canopy, LAI < 2, and low transpiration capacity, these species showed minimal thermal relief (1–2 °C). Their impact was negligible in paved zones, with only marginal benefits observed in shaded corners or softscapes. These trees may provide ecological or aesthetic value but offer limited utility for UHI mitigation.

This comparison confirms that trees with high canopy density and physiological activity offer superior passive cooling potential, especially in heat-prone Local Climate Zones such as LCZ 3 (Compact Low-Rise).

5.3. When Is Cooling Most Effective?

Monthly temperature data derived from ENVI-met simulations (**Figure 3**) reveal distinct seasonal patterns in cooling efficacy:

Peak Cooling Period: Months 6 to 8 (June to August) showed the highest reductions, with Type A trees averaging 9.5–11.2 °C surface temperature decrease. This coincides with peak summer heat in Delhi NCR.

Moderate Cooling: In spring (March–May) and early autumn (September–October), cooling performance remained consistent, with a 4–7 °C drop, depending on the species.

Low Cooling Period: Winter months (December–

February) exhibited minimal cooling (1–2 °C), due to lower incoming solar radiation and evapotranspiration rates.

These results highlight that tree-driven cooling is dynamic, influenced by both tree physiology and seasonal climate conditions. This reinforces the importance of selecting tree species not only for maximum summer mitigation but also for year-round thermal comfort.

6. Discussion

The research findings demonstrate that tree species with specific morphological and physiological traits, particularly high Leaf Area Index (LAI) and transpiration rate, play a critical role in mitigating Urban Heat Island (UHI) effects. The integration of ENVI-met simulations and statistical regression provided a robust framework for evaluating trait-driven cooling performance, and the results offer valuable insights for climate-resilient urban planning.

6.1. Significance of Results and Theoretical Implications

The strong statistical relationship between LAI (R^2 = 0.76) and transpiration rate (R^2 = 0.71) with temperature reduction supports eco-physiological theories that link plant structural characteristics and physiological processes to thermal regulation. These results underscore the importance of both shading and evapotranspiration in driving cooling performance. While albedo (reflectivity) is often cited in UHI literature, the current findings confirm that biological traits are more influential in real-time cooling, particularly under high ambient temperatures typical of the Delhi NCR region. This aligns with the urban ecological framework that considers plants as active modifiers of microclimates. Trees not only intercept solar radiation but also cool their surroundings through stomatal transpiration, a process that releases moisture into the atmosphere and reduces air temperature. In built environments with limited surface reflectivity, this latent heat exchange becomes a vital passive cooling mechanism.

6.2. Comparison with Existing Studies

The observed results are consistent with prior empirical research. For example, Gillner highlighted the significant role of urban vegetation in cooling cities through evapotranspiration and shading. These studies also emphasize the need to account for vegetation traits when planning urban greening interventions [5]. However, the present study contrasts with Akbari [35], who argued for the relevance of albedo in managing urban thermal loads. The difference in outcomes may be attributed to the modeling approach used ENVI-met simulations emphasize biophysical vegetation processes, especially under extreme thermal stress. This suggests that in hot, semiarid regions like Delhi NCR, the functional performance of vegetation outweighs the contribution of reflective surfaces in reducing ambient temperatures. Moreover, Yang [36] emphasized the co-benefits of urban trees in reducing both temperature and air pollution. Our study aligns with this multifunctional perspective by demonstrating that species such as *Samanea saman* and *Ficus benghalensis* offer measurable thermal relief, which is essential for integrated climate adaptation planning.

6.3. Limitations of the Study

While the findings are robust and statistically significant, certain limitations should be acknowledged:

Simulation Constraints: ENVI-met provides high-resolution spatial data but simulates conditions based on predefined scenarios. It does not account for long-term seasonal variation, growth stages of trees, or age-dependent changes in physiology, which can influence real-world cooling performance.

Assumed Uniform Conditions: The model assumes a standard urban courtyard setup, fixed meteorological inputs (e.g., 40 °C air temperature), and uniform irrigation, which may not represent diverse microclimatic conditions across Delhi NCR.

Trait Sourcing from Literature: Trait data were extracted from various secondary sources, potentially introducing variability due to species misidentification, local adaptations, or experimental differences.

Site-Specific Urban Geometry: The effectiveness of tree cooling is influenced by urban form, including building height, orientation, and street width, which were generalized in the simulation but may vary significantly in real deployment.

These limitations suggest the need for field validation through long-term empirical studies and the incorporation of socio-environmental variables, such as pollution, maintenance practices, and land-use dynamics.

6.4. Application Value and Policy Relevance

The study offers a quantifiable, replicable method for selecting urban tree species based on cooling performance. This trait-based framework is particularly valuable for municipal landscape planners, urban designers, and policymakers, as it provides a scientific basis for vegetation choices in urban greening initiatives.

In Compact Low-Rise zones (LCZ 3), where surface temperatures are highest and space for green infrastructure is limited, prioritizing trees with high LAI and transpiration rate (e.g., *Swietenia macrophylla*, *Tilia cordata*) can yield significant thermal benefits. These findings can inform smart city planning and climate action strategies, particularly in heat-vulnerable wards.

Moreover, the trait-ranking method proposed here can be incorporated into Green building certifications (e.g., GRIHA, LEED), Urban tree master plans, Street and park tree replacement programs, Climate-resilient development guidelines aligned with SDG 11, and national adaptation frameworks. By bridging ecological science with urban design, this study enables cities to move beyond aesthetic planting and adopt performance-driven green infrastructure strategies, ensuring that vegetation contributes actively to urban climate resilience and public health.

7. Comparison with Existing Studies

The findings of this study, particularly the dominance of Leaf Area Index (LAI) and transpiration rate in determining cooling efficacy, resonate strongly with existing literature in urban climatology and urban forestry.

7.1. Agreement with Past Research

Bowler conducted a systematic review and concluded that urban vegetation significantly reduces ambient temperatures, especially when trees are strategically placed. Our findings confirm this, but go further by quantifying which tree traits, such as high LAI and dense canopy, optimize this cooling. Gillner[5] emphasized the combined role of tree structure and drought tolerance in maximizing cooling performance. Similarly, our results underscore how rooting depth and water availability enhance a tree's capacity to sustain transpiration under heat stress, contributing to higher temperature reductions. Feng[26] studied tree performance in hot and humid areas and found that species with high transpiration rates created stronger microclimate cooling under their canopy. This directly supports the high R^2 value (0.71) observed for transpiration rate in our regression model. Yang[36] demonstrated that increased tree cover not only lowered air temperatures but also reduced air pollution, highlighting the multifunctional value of urban trees. While our study focused primarily on thermal mitigation, it validates their conclusion by showing how dense-canopy, high-LAI species can bring substantial ecosystem benefits.

7.2. Differences and Contradictions

There is a study that focused on vegetated roofs, identified species adaptability and foliage structure as decisive for cooling in semiarid cities[23]. Our findings expand on this by validating that not all trees are equal, even in ground-based settings, when it comes to microclimate regulation. Trait-based differentiation is therefore essential. Paschalis emphasized evapotranspiration as the primary mechanism for urban cooling[32]. Our results support this and offer quantitative evidence that high-performing species can reduce temperatures by up to 11.2 °C, providing a more empirical grounding to their theoretical model.

8. New Contributions to the Literature

This study contributes a unique and timely value to the field of urban climate adaptation and green infrastructure planning in several important ways:

- Integration of trait-based analysis with high-resolution microclimate simulation: By combining species-specific morphological and physiological data with ENVI-met v5 simulation outputs, this research offers a more accurate and spatially resolved understanding of how individual tree species influence urban temperatures under real-world conditions.
- Development of a species ranking based on cooling efficiency: Unlike most studies that generalize tree per-

formance by type (e.g., deciduous vs. evergreen), this study presents a quantitative, trait-based ranking of 15 commonly planted urban tree species. This ranking provides planners with clear, evidence-backed options for selecting high-performing species.

- Linking physiological traits to Local Climate Zones (LCZs): The study bridges a significant research gap by aligning tree traits with LCZ classifications, something few studies have done systematically. This allows for tree selection to be matched not just to climate type but also to urban form, building density, and surface characteristics.
- Creation of a practical decision-support matrix: The outputs of this study are designed to inform real-world decision-making. By translating scientific findings into an actionable species-selection tool tailored to Delhi-NCR's urban morphology, the study provides immediate utility for landscape architects, urban planners, and policymakers.
- Contribution to climate-resilient urban planning in the Global South: Much of the existing literature on green infrastructure and UHI mitigation is focused on temperate cities in the Global North. By focusing on tropical and sub-tropical urban conditions, particularly in a rapidly urbanising region like Delhi-NCR, this study adds geographic and climatic diversity to the knowledge base.
- Evidence-based approach for targeted greening interventions**:** The study supports precision planning by identifying which traits drive maximum temperature reduction and under what urban configurations. This avoids trial-and-error planting strategies and enables more efficient use of limited urban green space.

In summary, this study goes beyond descriptive assessments of green infrastructure by offering a replicable, data-driven framework that links vegetation traits, cooling performance, and urban form, thus supporting scientifically informed and context-sensitive urban greening interventions.

9. Conclusion

This study provides strong empirical evidence that tree species selection based on morphological and physiological traits is critical for effective Urban Heat Island (UHI) mitigation, especially in rapidly urbanizing and heat-vulnerable regions like Delhi NCR. Using a combination of ENVI-met microclimate simulations and regression analysis, the research confirms that Leaf Area Index (LAI) and transpiration rate are the two most dominant predictors of a species' cooling performance, far outweighing passive traits such as albedo.

High-performing species, such as *Samanea saman*, *Swietenia macrophylla*, and *Tilia cordata*, demonstrated maximum cooling effects of up to 11.2 °C, particularly in dense, low-rise urban environments (LCZ 3). These findings reinforce the argument for shifting from aesthetic or generalized greening approaches to data-driven, performance-based planting strategies. By offering a replicable trait-based framework, the study supports evidence-informed decision-making in urban landscape planning, smart city policy, and green infrastructure design, aligning with broader goals of climate resilience, thermal comfort, and sustainable urban ecosystems.

In addition to advancing scientific understanding, the study provides policy-oriented recommendations, categorized into three domains to guide urban planners and decision-makers:

- Empirical Recommendations
    - Establish long-term monitoring frameworks to validate cooling performance of planted species under real-world seasonal and microclimatic conditions.
    - Expand local tree trait databases by integrating field-based physiological studies with simulation outputs for improved predictive accuracy.
- Technological Recommendations
    - Incorporate the decision-support matrix into smart city masterplans and design codes, linking species selection directly with Local Climate Zones (LCZs).
    - Develop GIS-based planning tools that overlay UHI hotspots with suitable species recommendations for evidence-driven plantation strategies.
- Socio-Political Recommendations
    - Align urban greening with Heat Action Plans, SDG 11 (Sustainable Cities), and National Adaptation Frameworks to ensure integration into broader climate strategies.

- Prioritize Type A high-cooling species (e.g., *Ficus benghalensis*, *Samanea saman*) in heat-vulnerable wards, while promoting community participation in tree planting and maintenance.

By embedding these measures into municipal governance and climate action planning, cities can transform trait-based ecological insights into effective, equitable, and scalable interventions against urban heat stress.

By embedding these measures into municipal governance and climate action planning, cities can transform trait-based ecological knowledge into effective, equitable, and scalable interventions against urban heat stress.

10. Future Research Directions

While the study provides a valuable foundation, several areas require further investigation:

- Longitudinal Field Validation: Empirical monitoring of tree cooling performance over different seasons, tree ages, and real-time environmental conditions is essential to complement simulation-based findings.
- Trait-Environment Interactions: Future work should explore how traits interact with urban geometry, wind flow, pollution, and soil conditions, as these can modify physiological performance and cooling outcomes.
- Expansion to Other LCZs and Cities: Replicating this trait-based evaluation across different Local Climate Zones (e.g., LCZ 5, LCZ 9) and cities with varying climates will help generalize the framework and create regional tree performance databases.
- Multifunctional Benefit Assessment: Future studies should integrate co-benefits such as carbon sequestration, air quality improvement, noise reduction, and biodiversity support to build a multi-criteria species selection tool for urban resilience planning.
- Community and Socioeconomic Factors: Understanding residents' preferences, tree maintenance capacity, and urban governance structures will help tailor recommendations to practical implementation scenarios.

By addressing these dimensions, future research can strengthen the role of urban forestry as a cornerstone strategy in climate adaptation, public health, and environmental justice.

Author Contributions

Conceptualization, P.S.; methodology, P.S.; formal analysis, P.S.; data curation, P.S.; writing—original draft preparation, P.S. and R.S.; writing—review and editing, P.S. and R.S. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The study utilizes secondary datasets including MODIS Land Surface Temperature (LST) records (2013–2024), Landsat-8 OLI/TIRS imagery (April 2023), Sentinel-2 NDVI data, and Census 2011 ward-level demographic data for Gurugram, which are publicly accessible through the respective portals (NASA Earthdata, USGS Earth Explorer, Copernicus Open Access Hub, and Census of India). Ward shapefiles were sourced from GMDA (Gurugram Metropolitan Development Authority) open geospatial data repository. The ENVI-met simulation outputs, processed GIS layers, stakeholder survey questionnaire, and derived Heat Vulnerability Index (HVI) datasets generated during the current study are available from the corresponding author upon reasonable request, as they contain geocoded ward-level information that may be subject to ethical considerations related to spatial profiling of vulnerable populations. No proprietary or confidential data were used in this research.

Acknowledgments

The authors gratefully acknowledge the support provided by Sharda University for access to research infrastructure.

Conflicts of Interest

The authors declare that there is no conflict of interest.

References

[1] Oke, T.R., 2010. Urban Heat Islands. In: Douglas, I., Goode, D., Houck, M.C. (eds.). The Routledge Handbook of Urban Ecology. Routledge: London, UK. pp. 1–12.

[2] Rizwan, A.M., Leung, Y.C.D., Liu, C.H., 2008. A Review on the Generation, Determination and Mitigation of Urban Heat Island. Journal of Environmental Sciences. 20(1), 120–128. DOI: https://doi.org/10.1016/S1001-0742(08)60019-4

[3] Santamouris, M., 2015. Analyzing the Heat Island Magnitude and Characteristics in One Hundred Asian and Australian Cities and Regions. Science of The Total Environment. 512–513, 582–598. DOI: https://doi.org/10.1016/j.scitotenv.2015.01.060

[4] Bowler, D.E., Buyung-Ali, L.M., Knight, T.M., et al., 2010. Urban Greening to Cool Towns and Cities: A Systematic Review of the Empirical Evidence. Landscape and Urban Planning. 97(3), 147–155. DOI: https://doi.org/10.1016/j.landurbplan.2010.05.006

[5] Gillner, S., Vogt, J., Tharang, A., et al., 2015. Role of Street Trees in Mitigating Effects of Heat and Drought at Highly Sealed Urban Sites. Landscape and Urban Planning. 143, 33–42. DOI: https://doi.org/10.1016/j.landurbplan.2015.06.005

[6] Stewart, I.D., Oke, T.R., 2012. Local Climate Zones for Urban Temperature Studies. Bulletin of the American Meteorological Society. 93(12), 1879–1900. DOI: https://doi.org/10.1175/BAMS-D-11-00019.1

[7] Jusuf, S.K., Ignatius, M., Hien, W.N., et al., 2019. Editorial: Urban Heat Island (UHI) and Its Mitigation Through Urban Planning, Design, and Landscaping. Architectural Science Review. 62(1), 1–2. DOI: https://doi.org/10.1080/00038628.2019.1548095

[8] United Nations, Department of Economic and Social Affairs (UN DESA), 2018. World Urbanization Prospects: The 2018 Revision. Available from: https://population.un.org/wup/ (cited 20 June 2025).

[9] Sharma, P., Yogeswaran, N., 2022. A Systematic Review of Literature on Major Domains of Urban Heat Island Studies. In Proceedings of the Sustainable Resilient Built Envitonments, SRBE 2022, Karnataka, India, 19–21 December 2022; pp. 213–222. DOI: https://doi.org/10.1007/978-981-99-8811-2_18

[10] Yang, J., Zhao, Y., Zou, Y., et al., 2022. Improving the Thermal Comfort of an Open Space via Landscape Design: A Case Study in Hot and Humid Areas. Atmosphere. 13(10), 1604. DOI: https://doi.org/10.3390/atmos13101604

[11] Norton, B.A., Coutts, A.M., Livesley, S.J., et al., 2014. Planning for Cooler Cities: A Framework to Prioritise Green Infrastructure to Mitigate High Temperatures in Urban Landscapes. Landscape and Urban Planning. 134, 127–138. DOI: https://doi.org/10.1016/j.landurbplan.2014.10.018

[12] Gunawardena, K.R., Wells, M.J., Kershaw, T., 2017. Utilising Green and Bluespace to Mitigate Urban Heat Island Intensity. Science of The Total Environment. 584–585, 1040–1055. DOI: https://doi.org/10.1016/j.scitotenv.2017.01.158

[13] Li, H., Zhao, Y., Wang, C., et al., 2024. Cooling Efficacy of Trees Across Cities Is Determined by Background Climate, Urban Morphology, and Tree Trait. Communications Earth Environment. 5, 754. DOI: https://doi.org/10.1038/s43247-024-01908-4

[14] Al-Hajri, S., Al-Ramadan, B., Shafiullah, M., et al., 2025. Microclimate Performance Analysis of Urban Vegetation: Evidence from Hot Humid Middle Eastern Cities. Plants. 14(4), 521. DOI: https://doi.org/10.3390/plants14040521

[15] Ziter, C.D., Pedersen, E.J., Kucharik, C.J., et al., 2019. Scale-Dependent Interactions Between Tree Canopy Cover and Impervious Surfaces Reduce Daytime Urban Heat During Summer. Proceedings of the National Academy of Sciences. 116(15), 7575–7580. DOI: https://doi.org/10.1073/pnas.1817561116

[16] Teshnehdel, S., Akbari, H., Di Giuseppe, E., et al., 2020. Effect of Tree Cover and Tree Species on Microclimate and Pedestrian Comfort in a Residential District in Iran. Building and Environment. 178, 106899. DOI: https://doi.org/10.1016/j.buildenv.2020.106899

[17] Guerri, G., Crisci, A., Morabito, M., 2023. Urban Microclimate Simulations Based on GIS Data to Mitigate Thermal Hot-Spots: Tree Design Scenarios in an Industrial Area of Florence. Building and Environment. 245, 110854. DOI: https://doi.org/10.1016/j.buildenv.2023.110854

[18] Cheng, X., Peng, J., Dong, J., et al., 2022. Non-Linear Effects of Meteorological Variables on Cooling Efficiency of African Urban Trees. Environment International. 169, 107489. DOI: https://doi.org/10.1016/j.envint.2022.107489

[19] Lanza, K., Stone, B., 2016. Climate Adaptation in Cities: What Trees Are Suitable for Urban Heat Management? Landscape and Urban Planning. 153, 74–82. DOI: https://doi.org/10.1016/j.landurbplan.2015.12.002

[20] Pace, R., Chiocchini, F., Sarti, M., et al., 2022. Integrating Copernicus Land Cover Data Into the i-Tree Cool Air Model to Evaluate and Map Urban Heat Mitigation by Tree Cover. European Journal of Remote Sensing. 56(1), 2125833. DOI: https://doi.org/10.1080/22797254.2022.2125833

[21] Rahman, M., 2013. Effects of Species and Rooting

Conditions on the Growth and Cooling Performance of Urban Trees [PhD Thesis]. University of Manchester: England, UK. pp. 1–243.

[22] Yu, F.Y., Xu, X.Z., Guy, R.D., 2003. Effects of Water and Heat Stress on the Seedling Height Growth and Biomass of Five Trees. Journal of Nanjing Forestry University. 27(4), 10–14.

[23] Robbiati, F., Natalia, C., Gustavo, B., et al., 2023. Vegetated Roofs as a Nature-Based Solution to Mitigate Climate Change in a Semiarid City. Nature-Based Solutions. 3, 100069. DOI: https://doi.org/10.1016/j.nbsj.2023.100069

[24] Sathiameena, K., Manikandan, R., Rajakumar, R., 2020. Role of Trees in Mitigating Urban Temperature. Plant Archives. 20(2), 4922–4932.

[25] Meier, F., Scherer, D., 2012. Spatial and Temporal Variability of Urban Tree Canopy Temperature During Summer 2010 in Berlin, Germany. Theoretical and Applied Climatology. 110, 373–384. DOI: https://doi.org/10.1007/s00704-012-0631-0

[26] Feng, X., Wen, H., He, M., et al., 2023. Corrigendum: Microclimate Effects and Influential Mechanisms of Four Urban Tree Species Underneath the Canopy in Hot and Humid Areas. Frontiers in Environmental Science. 11, 1108002. DOI: https://doi.org/10.3389/fenvs.2023.1108002

[27] Shashua-Bar, L., Pearlmutter, D., Erell, E., 2011. The Influence of Trees and Grass on Outdoor Thermal Comfort in a Hot-Arid Environment. International Journal of Climatology. 31(10), 1498–1506. DOI: https://doi.org/10.1002/joc.2177

[28] Rahman, M.A., Hartmann, C., Moser-Reischl, A., et al., 2020. Tree Cooling Effects and Human Thermal Comfort Under Contrasting Species and Sites. Agricultural and Forest Meteorology. 287, 107947. DOI: https://doi.org/10.1016/j.agrformet.2020.107947

[29] Yarnvudhi, A., Leksungnoen, N., Andriyas, T., et al., 2022. Assessing the Cooling and Air-Pollution Tolerance Among Urban Tree Species in a Tropical Climate. Plants. 11(22), 3074. DOI: https://doi.org/10.3390/plants11223074

[30] Rushayati, S.B., Shamila, A.D., Prasetyo, L.B., 2018. The Role of Vegetation in Controlling Air Temperature Resulting From Urban Heat Island. FOR GEO. 32(1), 1–11. DOI: https://doi.org/10.23917/FORGEO.V32I1.5289

[31] Ding, W., Lu, X., Dang, C., et al., 2021. Simulation on the Impacts of Tree Canopy Morphology on Thermal Comfort at the Pedestrian Level. In Proceedings of the 5th International Conference on Civil Engineering, Architectural and Environmental Engineering, Chengdu, China, 23–25 April 2021; pp. 1–6. DOI: https://doi.org/10.1088/1755-1315/787/1/012043

[32] Paschalis, A., Chakraborty, T., Fatichi, S., et al., 2021. Urban Forests as Main Regulator of the Evaporative Cooling Effect in Cities. AGU Advances. 2(2), e2020AV000303. DOI: https://doi.org/10.1029/2020AV000303

[33] Sanusi, R., Johnstone, D., May, P., et al., 2017. Microclimate Benefits That Different Street-Tree Species Provide to Sidewalk Pedestrians Relate to Differences in Plant Area Index. Landscape and Urban Planning. 157, 502–511. DOI: https://doi.org/10.1016/j.landurbplan.2016.08.010

[34] Wang, C., Ren, Z., Chang, X., et al., 2023. Understanding the Cooling Capacity and Its Potential Drivers in Urban Forests at the Single Tree and Cluster Scales. Sustainable Cities and Society. 93, 104531. DOI: https://doi.org/10.1016/j.scs.2023.104531

[35] Akbari, H., Kolokotsa, D., 2016. Three Decades of Urban Heat Islands and Mitigation Technologies Research. Energy and Buildings. 133, 834–842. DOI: https://doi.org/10.1016/j.enbuild.2016.09.067

[36] Yang, Y., Xu, Y., Duan, Y., et al., 2023. How Can Trees Protect Us From Air Pollution and Urban Heat? Associations and Pathways at the Neighborhood Scale. Landscape and Urban Planning. 236, 104779. DOI: https://doi.org/10.1016/j.landurbplan.2023.104779