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Performance-Based Planting Systems for Urban Heat Mitigation: Assessing Plant Species, Canopy Cover and Rooftop Microclimates in Chennai, India

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Abstract - *In tropical cities, rapid urbanization and the replacement of vegetated land with impermeable surfaces contribute to urban heat and increased thermal exposure. In Chennai, India, heat mitigation requires planting strategies that consider local climatic conditions, water availability, rooftop exposure, and limited ground-level planting space. This study develops a literature-based framework to evaluate the potential of plant species, canopy cover, and rooftop planting systems for urban heat mitigation in Chennai. The proposed framework integrates plant characteristics, canopy density, surface temperature, near-surface air temperature, relative humidity, substrate moisture, irrigation requirements, plant survival, and maintenance needs. Four assessment conditions are considered: exposed conventional roofs, terrace gardens, outdoor areas beneath tree canopies, and comparable exposed outdoor hardscape. A standardized monitoring methodology is proposed to support future comparisons under similar measurement conditions and weather patterns. The literature review indicates that vegetation can mitigate heat through shading and evapotranspiration, although its effectiveness varies with plant characteristics, canopy structure, planting configuration, climatic conditions, and water availability. Existing research also indicates that reductions in roof-surface temperature do not necessarily correspond to equivalent reductions in ambient air temperature. Based on these considerations, the study proposes a Planting System Heat Mitigation Performance Index (PSHMPI) incorporating thermal performance, canopy cover, plant survival, water efficiency, and maintenance efficiency. The framework aims to support evidence-based landscape planning and climate-responsive rooftop greening in Chennai. However, the proposed assessment methodology and performance index require field validation before quantitative performance targets or species-level rankings can be established.*

Key Words: Urban heat island, heat mitigation, planting systems, canopy cover, terrace garden, rooftop microclimate, landscape architecture, Chennai.

1. INTRODUCTION

As buildings, highways, and other impermeable surfaces replace vegetation and disrupt the exchange of energy, moisture, and heat within cities, urban heat is becoming a more significant environmental design concern. By absorbing solar radiation, providing shade for building surfaces, and releasing water vapor through evapotranspiration, vegetation can lessen exposure to heat. However, its cooling efficiency varies with plant structure, canopy density, water availability, background climate and the spatial layout of planting [1]–[4]. Reviews of urban greening highlight the need to discern between changes in air temperature, surface temperature, and human thermal comfort, while also reporting generally good cooling effects.

Planting methods that provide quantifiable environmental benefits without requiring extra irrigation or upkeep are necessary in Chennai due to the city's hot climate, humid weather, dense construction and vast hardscape. When there is enough room for roots, ground-level trees can offer shade, roof gardens and green roofs can bring vegetation into densely populated regions with little land. While rooftop vegetation predominantly impacts roof-surface heat exchange and may also alter the building's thermal behavior, trees have an impact on adjacent surfaces and shaded outdoor spaces [2], [5], and [6].



Fig- 1. Shaded and exposed urban surfaces

Plants are frequently described in conventional landscape specifications based on their look, availability, and maintenance needs. Instead, a performance-based approach evaluates whether the chosen planting strategy meets certain environmental goals. Instead of assuming that more green cover always results in the same cooling advantage, this implies assessing plant characteristics, canopy coverage, thermal sensitivity, water demand, and survival all at once for heat mitigation.

An organized approach for evaluating Chennai's planting systems' performance is presented in this research. It integrates a field-monitoring protocol, a literature-based review, and a comparative evaluation technique that may be used for rooftop and landscape design projects.

1.1 Aim

To develop a performance-based framework for evaluating how plant species, canopy cover and rooftop planting systems contribute to urban heat mitigation in Chennai, India.

1.2 Objectives

1. Identify plant traits associated with thermal performance, evapotranspiration, and shade availability based on existing research literature.
2. Review published evidence on the relationship between canopy cover and temperatures beneath or near vegetation.
3. Develop a proposed monitoring methodology for comparing exposed conventional roofs with vegetated rooftop systems.
4. Identify water requirements, plant survival, and maintenance as key indicators for evaluating planting-system performance alongside thermal benefits.
5. Propose a composite performance index for the literature-informed evaluation of planting systems, subject to future field validation.

2. LITERATURE REVIEW

2.1 Urban vegetation and heat mitigation

Through evapotranspiration and shade, urban vegetation affects the local temperature. While evapotranspiration transforms some of the available energy into latent heat, shading lessens the amount of direct solar radiation that reaches people, walls, paving, and soil. Climate, water availability, and vegetation structure all affect how much each process contributes [1], [2], and [7]. Although findings vary by study type and location, Bowler et al. [1] concluded that the empirical literature typically supports cooler conditions in urban green spaces compared to comparable non-green environments.

The energy consumption of buildings as well as the temperature of roadways and pedestrian zones can be impacted by urban trees. However, the overall green area should not be the only metric used to assess vegetation. The cooling provided at a particular place is influenced by the distribution of canopy, the amount of shade during pertinent periods, and the availability of water [2], [3], and [8].

2.2 Plant species and functional characteristics

Crown form, leaf area, foliage density, leaf size, phenology, transpiration capacity, and heat and water stress tolerance are all different among plant species. These features affect both the potential for evaporative cooling and the quantity of radiation intercepted. A meta-analysis of urban tree characteristics revealed that leaf and tree properties interact with planting conditions and climate, and that canopy density is a significant factor in cooling [3]. Crown density, planting patterns, species morphology, and the interaction between plants and wind are all identified as important elements in research on outdoor thermal comfort [4].

Therefore, choosing species for Chennai should take into account more than just whether a species is native or foreign. Local adaptability, non-invasive behavior, shade characteristics, rooting requirements, water requirements, structure safety, and maintenance requirements should all be taken into consideration when evaluating suitability. Individual performance must still be evaluated in relation to the intended site and function, even when native species can sustain local ecological connections [9], [10].

2.3 Canopy cover and planting configuration

The percentage of a certain ground or site area that is covered by the vertical projection of plant crowns is known as canopy cover. Because canopy affects shade distribution and solar exposure, it is a useful design variable. However, depending on crown height, leaf density, canopy continuity, orientation, surrounding building geometry, and the type of surface being shaded, equivalent canopy percentages may result in varied thermal consequences [3], [4], and [8].

Along with the location and timing of temperature readings, canopy cover should be recorded for field evaluation. It is not appropriate to compare an exposed planted-soil region with a shaded paved area without first noting the variations in surface material, moisture content, and solar exposure. Regardless of the type of plant, these variables can affect the observed temperature.

2.4 Rooftop planting and Terrace garden

Through plant shade, evapotranspiration, and the growing medium's thermal characteristics, terrace gardens can lessen the quantity of solar radiation that reaches the roof surface. The quantity and kind of potted plants, foliage density, plant coverage, growing medium, irrigation, terrace flooring, roof construction, wind exposure, and seasonal circumstances all affect how well they cool. Terrace gardens can lower roof surface temperatures in Chennai's hot, humid climate, albeit the degree of cooling depends on the features of the garden and the surrounding circumstances. The ambient air temperature does not always drop in proportion to a cooler roof surface.

Additionally, the plant layouts, pot sizes, rooting volume, growth media, water retention, vegetation species, and maintenance needs of terrace gardens vary. Terrace gardens frequently consist of individual pots, containers, raised beds, or other planting arrangements, in contrast to green roofs, which usually have a vegetation and growing-medium system built over a roof structure. Therefore, rather than treating all terrace gardens as a single system, the study should document various features, such as plant density, shadow covering, and watering techniques.

2.5 Research gap

Existing research shows that vegetation can help reduce heat, but direct comparison of results is hampered by differences in measurement heights, monitoring periods, weather conditions, plant characteristics, terrace garden arrangements, and cooling performance definitions [1], [3], and [6]. A Chennai-focused approach should take these aspects into account and evaluate both thermal outcomes and the resources needed to sustain terrace gardens, such as water, plant care, and maintenance.

This study addresses the identified research gap by proposing a standardized, literature-based assessment framework for evaluating tree-canopy areas and terrace gardens under Chennai's climatic conditions. The framework is intended to support future comparative field studies of their heat-mitigation performance.

The principal contribution of this study is the development of a literature-informed framework for comparing urban tree-canopy planting and rooftop gardens using consistent thermal, vegetation, water-management, and maintenance indicators. By distinguishing surface-temperature reduction from air-temperature changes and incorporating resource requirements alongside cooling potential, the framework provides a basis for future field investigations and performance-based landscape design in Chennai.

3. RESEARCH METHODOLOGY

3.1 Research design

In order to create a suggested framework for assessing the heat-mitigation capability of urban planting systems in Chennai, India, this study used a literature-based research design. Relevant plant traits, canopy-cover indicators, microclimatic variables, irrigation needs, and maintenance parameters are identified using the body of existing research literature. For the evaluation of these indicators in the future, a standardized field-monitoring approach is suggested. This study does not produce species-level performance rankings or statistical findings because it does not incorporate original field measurements.

3.2 Study area

The study area is Chennai, Tamil Nadu, India. Included are typical developed environments with different levels of vegetation and roof exposure. Institutional structures, residential rooftops, and paved outside areas with established tree canopies are examples of feasible settings.



Fig. 2. Rooftop planting systems

Permission, accessibility, safety, roof structural capacity, vegetation availability, and the viability of monitoring similar circumstances should all be taken into consideration when choosing final locations. Building height, roof material, surrounding building density, orientation, shading, vegetation coverage, and adjacent sources of heat or obstruction should all be included in the site description.

3.3 Comparative planting conditions

Table- 1. Classification of Rooftop and Outdoor Planting Conditions for Urban Heat-Mitigation Assessment

Code	Planting condition	Main assessment
C1	Exposed conventional roof	Baseline roof-surface and near-surface air temperatures
C2	Terrace garden	Roof-surface temperature,

		indoor air temperature, indoor relative humidity, and terrace air temperature and relative humidity.
C3	Outdoor area beneath tree canopy	Shade conditions, surface temperature and air temperature beneath the canopy
C4	Comparable exposed outdoor hardscape	Reference condition for tree-canopy cooling assessment

C1 and C2 should ideally be located on comparable roof structures with similar orientation and exposure. C3 and C4 should have comparable paving or surface materials wherever possible. Because these conditions represent different physical settings, rooftop and tree-canopy results should be analysed separately before any broader comparison is made.

3.4 Plant species and trait assessment

Relevance to Chennai's climate and site availability should be taken into consideration when choosing species. Shade trees, bushes, ground coverings, and rooftop plants that are appropriate for the area may be included in the final sample. A consistent trait sheet should be used to reliably identify each species.

Table- 2. Plant Traits and Performance Indicators for Assessing Urban Heat-Mitigation Planting Systems

Trait	**Measurement or classification**	**Relevance**
Crown width	Metres	Approximate horizontal shade extent
Canopy cover	Percentage of study area	Proportion of area covered by crowns
Leaf area or foliage density	Measured or standardised category	Potential solar interception
Plant height	Metres	Vertical structure and shade position
Leaf habit	Evergreen, deciduous or seasonal	Seasonal continuity of shade
Water requirement	Recorded irrigation volume and frequency	Resource demand
Plant condition	Survival and health assessment	Long-term system reliability
Maintenance	Labour, pruning and replacement records	Practical implementation cost

3.5 Temperature and microclimate monitoring

The proposed monitoring variables are:

- Air temperature (°C)
- Relative humidity (%)
- Surface temperature (°C)
- Solar radiation or a documented proxy for solar exposure, if available
- Substrate moisture for rooftop planting
- Irrigation volume and frequency
- Canopy cover and plant condition



Fig- 3. Microclimate monitoring

Installed at constant heights, air-temperature sensors should be protected from direct sunlight. The same technique and similar surface locations should be used to record surface temperature. Documentation is required for sensor models, calibration processes, recording intervals, installation height, and maintenance. Surface emissivity and measuring distance should be taken into account when using infrared thermometers.

Monitoring should repeat observations at similar times of day and cover representative hot-weather periods. When possible, continuous logging is preferred. Unusual weather occurrences, cloud cover, irrigation, and rainfall should all be noted since they may have an impact on the comparison.

3.6 Sampling and data management

For every planting situation, a realistic pilot may employ many measurement points and repeat measurements over a few days. Access, equipment, and the variability found during an initial survey should be taken into consideration when determining the final number of locations, sensors, and monitoring days. There would be little data to support generalizing the findings from a single sensor or measurement day.

Time-stamped data should be examined for anomalous readings, missing observations, and sensor faults. The

pertinent site, planting condition, surface type, and weather record should all be linked to each measurement.

3.7 Data analysis

The temperature difference between a reference and a planting condition can be calculated as:

$$\Delta T = T_{reference} - T_{planting}$$

A positive value indicates that the measured temperature at the planting condition was lower than at the reference condition. Air temperature and surface temperature must be analysed separately.

Percentage canopy cover can be estimated as:

$$C = A_{canopy}/A_{study} X100$$

Where A_{canopy} is the projected canopy-covered area and A_{study} is the defined study area.

Weather, surface material, irrigation, and site geometry should be taken into consideration as potential confounders. If sample size and study design allow inferential testing, appropriate statistical methods can be used to examine differences among conditions and associations between canopy cover and temperature. The mean, minimum, maximum, and variation in temperature should be reported for comparable monitoring periods.

4. LITERATURE SYNTHESIS AND PROPOSED PERFORMANCE ASSESSMENT FRAMEWORK

This section presents a literature-based discussion of the potential heat-mitigation performance of urban planting systems and the proposed methods for evaluating them. The discussion draws on existing published research and identifies the indicators required for future field assessment. As no original field measurements have been collected for this study, the proposed framework does not establish new species-level performance rankings or measured cooling values for Chennai.

4.1 Plant species and thermal performance

Plant characteristics and observed temperature variations should be compared in the initial analysis. While plants with little foliage may offer less protection from direct sunlight, species with wide, deep crowns may offer significant shade. However, because transpiration depends on water availability, plant physiology, and meteorological conditions, crown density cannot determine total performance on its own [3], [4]. The results table should distinguish measured performance from descriptive plant traits.

Soil moisture, leaf size, and canopy spread can all affect how well vegetation cools. Variations in cooling effects can be explained by keeping track of these variables in addition to temperature readings.

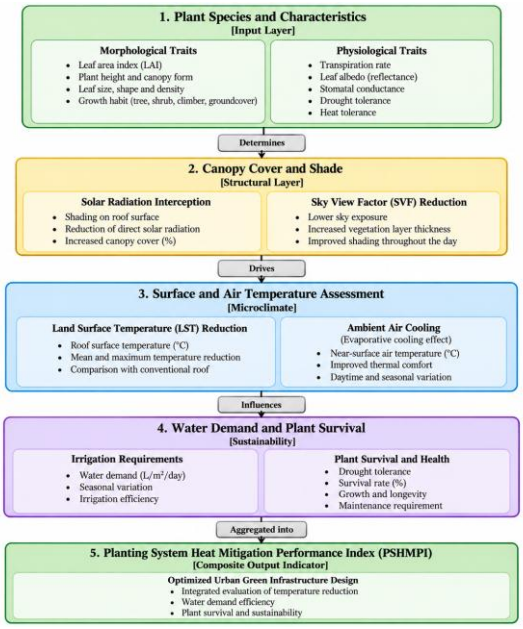


Figure 4. Proposed Framework for Assessing Planting-System Heat-Mitigation Performance

Table- 3. Functional Characteristics of Selected Tree Species for Urban Heat Mitigation

Source: Authors' synthesis of verified botanical and scientific literature.

Species	Crown characterstics	Shade potential	Key assessment parameters
Neem (Azadirachta indica)	Broad crown at maturity	Potentially high	Crown spread, canopy density, water requirements
Pongam (Pongamia pinnata)	Spreading crown	Potentially high	Canopy cover, plant health, irrigation
Indian almond (Terminalia catappa)	Broad, spreading crown	Potentially high	Seasonal foliage, shade distribution, rooting space

Whether observed cooling is more strongly correlated with plant size, moisture availability, canopy density, or a combination of these factors should be determined in the

final debate. General descriptions alone should not be used to rank species.

4.2 Canopy cover and outdoor heat mitigation

In comparison to similar exposed regions, the canopy analysis should determine whether areas with more overhead vegetation have lower surface temperatures and, where detectable, lower air temperatures. Instead of relying on a single noon reading, the link should be assessed through repeated observations.

Trends can be found using a scatter plot of canopy cover versus surface temperature difference. A second plot might compare the canopy cover to the difference in air temperature. Because shade can lower the temperature of exposed surfaces without causing an equally significant decrease in the surrounding air temperature, these correlations may differ [1], [3], [4].

Planting geometry should also be documented in the study. Shade may be distributed variously by a continuous canopy, solitary trees, and staggered tree rows. In order to prevent their influence from being mistakenly attributed to species choice, roadway direction and wind conditions should be noted when they differ.

4.3 Rooftop microclimate assessment

The rooftop analysis should compare exposed roofs and terrace gardens under similar weather conditions. The principal variables are roof-surface temperature, near-surface air temperature, relative humidity, soil moisture in plant containers and irrigation volume.

Terrace gardens can influence roof-surface temperatures through plant shading and evapotranspiration, but their cooling performance varies with plant coverage, container size, growing medium, irrigation and weather conditions [5], [6]. In a hot-humid environment, the study should avoid assuming that a terrace garden will always produce a large reduction in ambient air temperature. Results should report roof-surface temperature and air temperature independently.

The following table can be populated after monitoring.

Table- 4. Proposed Comparison of Conventional Roofs and Terrace Gardens

Parameter	Conventional roof	Terrace garden roof	Difference
Mean daytime surface temperature (°C)	To be measured	To be measured	To be calculated
Maximum surface temperature (°C)	To be measured	To be measured	To be calculated
Mean near-surface air temperature (°C)	To be measured	To be measured	To be calculated
Relative humidity (%)	To be measured	To be measured	To be calculated
Irrigation demand (L/m²/day)	Usually none for roof surface	To be measured	To be calculated
Plant survival (%)	Not applicable	To be monitored	Not applicable

Source: Proposed monitoring framework developed by the authors.

4.4 Water demand and maintenance

Terrace gardens' thermal performance should be assessed in addition to the water and labor needed to keep the plants healthy. Rooftop plants are subjected to wind, high temperatures, and intense sunlight, all of which can increase water demand and moisture loss. Water-stressed plants may show less growth and transpiration, which could lessen the terrace garden's cooling effects. On the other hand, if rooftop waterproofing and drainage systems are insufficient, excessive watering can raise water consumption, maintenance expenses, and the risk of water leakage.

When possible, the assessment should include information on watering frequency, maintenance needs, plant replacement rates, and general plant health in addition to irrigation requirements expressed in liters per square meter per day (L/m²/day). These indicators aid in determining if a terrace garden can continue to be water-efficient, useful, and sustainable over time while maintaining its thermal performance under local climate conditions.

4.5 Proposed Planting System Heat Mitigation Performance Index

To compare potential planting systems, a composite index is suggested. Only after enough field data has been gathered and normalized should it be computed.

$$PSHMPI = wT\ Tn + wC\ Cn + wS\ Sn + wW\ Wn + wM\ Mn$$

Where:

- Tn= normalised thermal-mitigation performance
- Cn = normalised canopy-cover or shade performance
- Sn = normalised plant-survival performance
- Wn = normalised water-efficiency score
- Mn = normalised maintenance-efficiency score
- w_T,w_C,w_S,w_W,w_M = weights assigned to each indicator.

All indicators will be normalized using a defined and justified method. Higher thermal mitigation, effective shade and plant survival should receive higher scores. Water demand and maintenance burden should be scored so that lower resource requirements receive higher efficiency scores. The weights must be justified, and sensitivity analysis should be undertaken before interpreting the index. The index remains proposed until it has been tested using field data.

The total of the weights ought to be one. The scoring direction for water demand and maintenance load should be reversed to give lower resource demand a higher efficiency score. The index should not be given as a verified scientific statistic until the weighting method, normalization, and sensitivity have been investigated.

4.6 Design implications for Chennai

The proposed framework supports five practical design principles:

1. Prioritise Effective Shade: Optimising plant placement for maximum shade and reduced heat gain.
2. Select Suitable Plants: Choosing heat-tolerant, climate-adapted plants with appropriate water requirements.
3. Ensure Terrace Safety: Checking structural capacity, waterproofing, drainage and safe planter placement.
4. Use Water Efficiently: Monitoring soil moisture and optimising irrigation to maintain plant health.
5. Measure Cooling Performance: Comparing roof-surface and indoor air temperatures in vegetated and non-vegetated areas.

These ideas are consistent with broader research showing that vegetation in terrace gardens can assist regulate roof temperatures and enhance indoor thermal comfort. However, plant traits, shading, site conditions, watering techniques, and continuing upkeep all affect how much and how long these benefits last.

4.7 Limitations

The proposed literature-based framework has several limitations, particularly the absence of original field measurements and the need to validate its indicators and performance index under Chennai's local climatic conditions. First, weather, wind, rooftop surface materials, building geometry, plant arrangement, irrigation, and sensor site can all have an impact on temperature readings. Second, it is not always possible to extrapolate findings from one terrace garden to all terrace gardens in Chennai. Third, age, seasonal growth, water stress, and management techniques can all affect how well a plant performs. Fourth, if the scoring system and weighting standards are unclear, a composite index might mask trade-offs. Lastly, in addition to climatic data, terrace gardens need proper evaluations of structural load-bearing capacity, waterproofing, drainage, and safe pot and planter placement.

Therefore, repeatable measurements, comparable techniques, well-documented site characteristics, and adequate monitoring time are all necessary for a valid study. Unless greater sampling supports broader conclusions, the results should be stated as site-specific.

5. CONCLUSION

This study proposes a literature-based framework for assessing the heat-mitigation potential of urban planting systems in Chennai, India. The framework integrates plant characteristics, canopy cover, rooftop microclimates, temperature variations, irrigation requirements, plant survival, and maintenance needs through a proposed Planting System Heat Mitigation Performance Index (PSHMPI). By considering both thermal performance and resource requirements, the framework supports performance-based planting decisions. However, field validation is necessary to verify cooling effectiveness, compare plant species, and establish reliable performance indicators. Evaluating tree canopies and rooftop gardens as separate but complementary systems can support climate-responsive urban design and sustainable landscape architecture in Chennai.

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