Towards Sustainable Housing: Integrating UHI Mitigation for Heatwave-Resilient Urban Design

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Table of Contents

Nomenclature

Symbol / Abbreviation	Description
UHI	Urban Heat Island
LST	Land Surface Temperature
NDVI	Normalized Difference Vegetation Index
UTFVI	Urban Thermal Field Variation Index
FAR	Floor Area Ratio
EUI	Energy Use Intensity ($kWh/m^2 \cdot yr$)
kWh	Kilowatt-hour
sqm / m^2	Square meter
CEA	City Energy Analyst (urban building energy modelling tool)
TIRS	Thermal Infrared Sensor (Landsat sensor band)
Pv	Proportion of Vegetation
ε (epsilon)	Surface Emissivity
σ (sigma)	Standard Deviation (statistical measure)
μ (mu)	Mean (statistical average)
RCC	Reinforced Cement Concrete (roof type)

Symbol / Abbreviation	**Description**
NSGA-II	Non-dominated Sorting Genetic Algorithm II (optimization method)
ML	Machine Learning
RF	Random Forest (machine learning algorithm)
ROI	Return on Investment
INR	Indian Rupee (currency)

Abstract

This research systematically investigates the occurrence and mitigation of Urban Heat Island (UHI) effects to enhance heatwave resilience in Indian urban housing across varying climatic, morphological, and regulatory contexts. Focusing on Mumbai, Faridabad, and Udaipur—representing diverse city tiers, climates, and urban forms—the study employs a robust mixed-methods approach integrating multi-temporal satellite-based land surface temperature (LST) analysis, detailed urban neighbourhood morphometric characterization using GIS and Google Building Footprints, and dynamic energy simulations with a state-of-the-art urban building energy modelling tool. The study starts with the temporal mapping of LST (2015–2025) which reveals significant expansion and intensification of UHI hotspots, especially in dense and vegetatively sparse zones. Regression-based optimisation of urban variables (street width, vegetation coverage, building density, distance from highways) demonstrates substantial deviations at building scale from prevailing regional bylaws, indicating regulatory insufficiency in current UHI management. City-specific scenario simulations show that proximity to traffic corridors, building height, and spatial compactness are principal drivers of elevated UHI intensity. Energy simulation results indicate that UHI exposure leads to an 7.6% increase in annual cooling energy demand for a single-building in Mumbai. Similarly, the effects of proximity to a highway, building heights and inter-building compactness is observed on cooling energy demand. Mitigation analyses reveal that retrofitting with cool and green roofs reduces cooling demand by up to 12%, enhances annual comfort hours, and is economically viable within typical building lifecycles. Comparative policy review highlights convergence between optimised Indian strategies and global mandates (e.g., Toronto, Paris, Sydney), highlighting the need for codified, context-reflexive interventions. Findings advocate for immediate policy reform to embed evidence-based UHI mitigation—optimised urban form parameters, prioritization of retrofits, and targeted interventions in hotspots—within India's urban housing codes, thereby advancing long-term urban climate resilience and public health protection.

Keywords: UHI, Energy Demand, Urban Building Energy Modelling, Mitigation

1. Introduction

1.1 Urban Heat Island (UHI) effect

The Urban Heat Island (UHI) effect, defined as the elevation of urban temperature relative to surrounding rural areas, is a pronounced consequence of rapid urbanization, surface sealing, and anthropogenic heat emissions [1]. This phenomenon is particularly acute in dense tropical and sub-tropical cities, where impervious materials and the loss of vegetative cover amplify thermal load, attenuate nocturnal cooling, and elevate the risk of heat stress. In India, the UHI effect is further intensified by high population density, sprawling urban forms, and a proliferation of high-rise and compact residential clusters [2]. Cumulative impacts have resulted in a marked increase in both frequency and intensity of urban heatwaves, carrying significant implications for urban health, liveability, and resource efficiency.

1.2 UHI Mechanisms

UHI mechanisms encompass multiple interacting factors that elevate urban temperatures relative to surrounding rural areas. Principal processes include thermal storage by built environment materials characterized by low albedo and high heat capacity, which absorb and slowly release solar energy, leading to elevated daytime and nocturnal temperatures [3]. Equally significant is the absence of green space, which reduces shading and evapotranspiration, further amplifying thermal build-up in urban zones [4]. Urban configurations such as dense buildings and narrow streets intensify the trapping of heat, while anthropogenic emissions and impervious surfaces suppress natural cooling mechanisms [1]. Collectively, these mechanisms reveal UHI as a complex phenomenon driven by land cover transformation, material properties, and human activity, necessitating integrated mitigation strategies addressing both urban design and technology interventions. Figure 1 shows the temperature profile across a city due to the UHI effect.

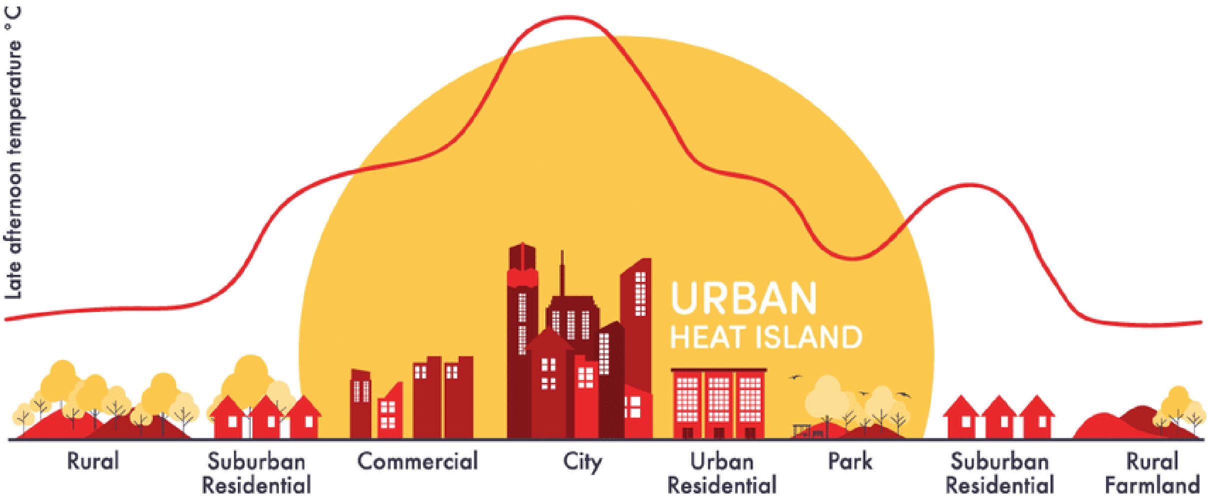

Figure 1 Temperature profile across a city due to the UHI effect [5]

Remote sensing approaches, particularly retrieval of Land Surface Temperature (LST) from satellites such as Landsat, provide a powerful, spatially-resolved proxy for UHI assessment at city scales [6]. These measurements capture surface thermal heterogeneity and inform analyses of temporal trends and hotspot mapping which are critical for urban climate management. Building upon the fundamental thermal processes driving urban heat accumulation, urban geometry - including building density, height, street width, and vegetation distribution—plays a critical role in modulating LST and spatial variability of the UHI effect [1]. As demonstrated in global studies, the intensity of UHI grows with urban sprawl, excessive impervious surface fraction, and absence of coherent green infrastructure [7,8]. In warm climates, these factors are frequently compounded by climate change-induced heatwaves, exacerbating thermal exposure and discomfort.

1.3 UHI in India

Indian cities, ranging from megacities like Mumbai to secondary and tertiary centres, have exhibited rapid, often unregulated, urbanisation and significant reductions in per capita green cover [9]. Multi-temporal remote sensing analyses confirm a consistent upward trajectory in both summer and winter LST values, most prominently in high-density and industrial precincts. Studies identify that the UHI intensity in Indian contexts is positively correlated with built-up area ratio, Floor Area Ratio (FAR), surface imperviousness, and the degree of vegetation loss, with some cities showing increases in annual mean urban temperature by over 2°C between 2000 and 2020 [2]. The UHI phenomenon in the Indian context presents a compounding risk: increased frequency and extremity of heatwaves and corresponding growth in cooling energy demand. Urban morphology - such as tall, closely-packed buildings and reduced street widths - further amplifies night-time heat retention and impedes ventilation, aggravating indoor and outdoor heat stress [10,11].

1.4 Best Practices in UHI Mitigation

Mitigation of UHI has evolved globally from isolated technical fixes to multi-scalar, integrative urban policies [8,12]. Strategies include increasing urban vegetation through parks, green roofs and walls, and street canopies; improving surface reflectance via high-albedo materials and cool roofs; utilizing permeable surfaces; and optimizing urban geometry to improve airflow and shading. Empirical evaluations have shown green roofs can reduce rooftop surface temperatures by up to 40°C, and cool roofs can lower mean indoor temperatures by 1–2°C and decrease cooling energy use by 10–15% in subtropical climates as shown in Table 1 [13–15].

In the Indian policy landscape, UHI mitigation remains nascent: pilot initiatives in Hyderabad have demonstrated the heat reduction and public health benefits of reflective roofing [16], but integration into codes and mainstream housing policy is limited. Recent reviews highlight the need for context-specific approaches, especially in morphologically diverse and rapidly growing cities [17].

Table 1 Comparative Summary of UHI Mitigation Strategies

Mitigation Strategy	Mechanism	Evidence of Effectiveness
Green roofs and walls	Thermal insulation, evapotranspiration cooling	Proven to reduce surface temperatures, enhance thermal comfort, and provide co-benefits like biodiversity support
Cool or reflective roofs	Increased solar reflectance reducing heat absorption	Effective in lowering roof surface and indoor temperatures; reduces cooling energy demand
Urban greening & tree planting	Shading, evapotranspiration, wind channelling	Localized temperature reductions, improved outdoor comfort; significant welfare benefits
Urban form and zoning	Optimized building height, street width, orientation to enhance airflow, shading	Demonstrated mitigation of nocturnal heat accumulation, urban ventilation improvements

1.5 Research Gap and Problem Statement

Indian metropolises are witnessing unprecedented rates of land-use change, manifesting in the encroachment of green spaces, reduction in vegetation coverage, and unregulated built-up expansion. The UHI effect leads to disproportionately high cooling energy demand, electrical peak loads, and diminished outdoor and indoor comfort, particularly affecting lower-income and vulnerable populations [18]. For instance, UHI-driven temperature differentials have been linked to annual urban electricity consumption increases upwards of 10–11% in megacities [19]. With the confluence of climate change and urban growth, these risks are projected to escalate, posing substantive challenges to thermal resilience and sustainable urban development.

1.6 Need of the study

Despite increased awareness of the UHI effect and its consequences, most Indian housing and urban regulations still overlook the specific microclimatic impacts of their standards. Existing policy measures often prescribe general norms for setbacks, built-up area, FAR, and open space, but do not leverage spatial UHI mapping or energy simulation to identify urban heat hotspots or evaluate which mitigation strategies work best at the neighbourhood or building scale.

The key research gap is a lack of targeted, data-driven mitigation. Simply introducing broad measures, such as a cool roof policy, is not enough - cities must first identify where UHI intensity is highest, determine which intervention (e.g., cool roof, green roof, urban greening, water bodies, or high-albedo pavements) is most effective in each hotspot, and develop context-specific plans for implementation. The relative effectiveness and cost of each solution can vary widely across different urban forms, population densities, climatic zones, and local land use.

Therefore, there is an urgent need for an empirically grounded, locally adaptable framework that guides Indian cities in:

- Mapping UHI hotspots,
- Evaluating and comparing mitigation options using robust scientific evidence and energy simulations,
- Designing focused interventions that maximise cooling, resilience, and long-term cost-effectiveness.

This targeted approach will close the policy-response gap and help cities move beyond generic guidelines towards customized, climate-sensitive urban design—ensuring measurable reductions in thermal stress and improved health and comfort for residents, especially during extreme heat events.

1.7 Objectives

By explicitly linking urban morphometrics, regulatory context, remote sensing, and building energy demand, this research aims to provide actionable policy recommendations that advance the science and practice of UHI mitigation within the Indian urban housing sector through the following objectives -

1) **UHI Impact Assessment in Indian Cities:** Identify high UHI intensity zones using satellite-derived temperature maps across three cities representing different urban tiers, and analyze the thermal environment of housing clusters in these UHI hotspots.
2) **Urban Variable Analysis for UHI:** Investigate how factors such as road density, building geometry, and vegetation affect UHI variations at the building level to identify key modifiable parameters.
3) **Evaluating UHI Mitigation Strategies:** Test and compare the impact of cool roofs, green roofs, and hybrid strategies using CEA simulations to model microclimatic changes and temperature reduction across different building typologies.
4) **Energy and Economic Impact Analysis:** Simulate cooling energy savings due to UHI mitigation measures, quantify reductions in air-conditioning loads for different urban housing types, and provide data-driven insights on cost-effectiveness of interventions.
5) **Urban Design Recommendations:** Develop data-driven recommendations for minimizing UHI through passive design interventions and identify low-cost, scalable solutions for heat mitigation in urban housing contexts.

2 Methodology

This study adopts a staged methodology beginning with the identification of UHI hotspots across three Indian cities exhibiting contrasting development scales and climates, followed by micro-scale analysis of urban factors influencing UHI intensity, culminating in energy simulation assessments for targeted mitigation strategies.

2.1 City and Site Selection

Three cities as shown in Figure 2 and Table 2, representative of transmission, climate, and development gradients, were selected:

Table 2 Selected City Characteristics

City	Tier	Climate	Urban Form
Mumbai	I	Warm-humid	High-density, vertical
Faridabad	II	Composite	Mixed-use, highrise/lowrise
Udaipur	III	Hot and Dry	Medium-density, clustered

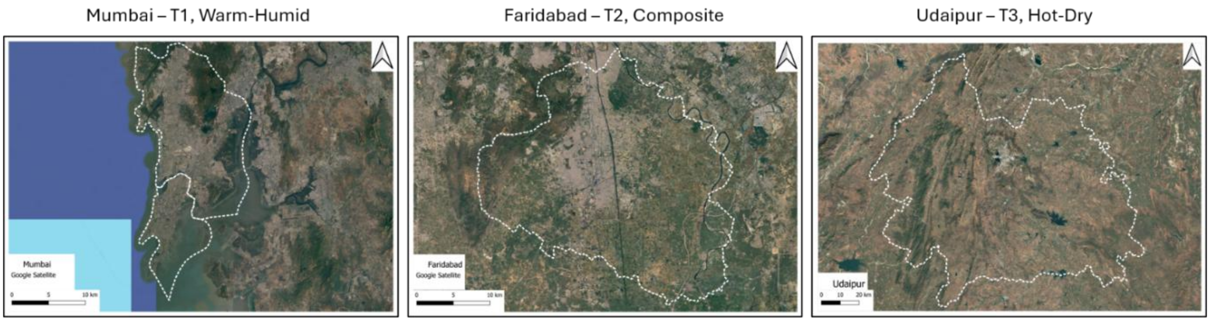

Figure 2 Study area

2.2 Data Collection and UHI Mapping

The process to retrieve LST from Landsat data involves several key steps, executed here via Google Earth Engine for temporal consistency and spatial resolution. First, Landsat 8 Thermal Infrared Sensor (TIRS) bands (notably band 10) are converted from digital numbers to at-sensor brightness temperature using radiometric calibration coefficients. Next, surface emissivity, a critical parameter accounting for material-specific thermal radiation, is derived through the Normalized Difference Vegetation Index (NDVI) using a threshold method that differentiates vegetated, mixed, and bare soil pixels. The proportional vegetation (P_v) and emissivity (ε) are estimated accordingly. Finally, the LST is calculated by correcting brightness temperature for emissivity and atmospheric effects using a split-window or mono-window algorithm, providing surface temperature estimates at spatial resolution of ~100m (resampled to 30m).

For hotspot delineation, the LST data over the urban extent is statistically analysed by calculating the mean μ and standard deviation σ of the temperature distribution. Pixels with temperature values exceeding the threshold:

$$LST_{threshold} = \mu + 2\sigma$$

are classified as UHI hotspots, indicating areas with significantly elevated thermal signatures. This thresholding filters out background variability, isolating the most critical heat-affected zones for further analysis.

2.3 Neighbourhood and Urban Variable Analysis with respect to UHI

In the neighbourhood and urban variable analysis, each building is treated as a distinct analytical unit, enabling precise quantification of Urban Thermal Field Variation Index (UTFVI)-derived UHI intensity at micro-scale resolution. Building footprints, extracted from google open buildings shapefiles, provide area (m²) for each structure.

$$Intensity = f(\mathbf{NDVI_{500}}, \mathbf{Street\ Width}, \mathbf{Building\ Density_{500}}, \mathbf{Highway\ Distance}, \mathbf{Nearest\ Building\ Distance}, \mathbf{Building\ Area})$$

Street width (m) is computed using buffered road centreline shapefiles, representing the minimum perpendicular distance between facing building frontages. Mean NDVI within a 500-metre buffer is derived from Landsat multispectral imagery, capturing surrounding vegetative index for each building through zonal statistics. Building density is calculated as the number of building footprints intersecting a 500-metre buffer around the building centroid, normalized by buffer area. Proximity to highway is assessed as the shortest Euclidean distance from each building centroid to the nearest segment of digitized highway polyline shapefile. Proximity to the nearest building edge is computed as the minimum distance from the building footprint perimeter to that of any neighbouring structure. These variables serve as predictors in a machine learning-based regression framework, with UHI intensity as the output. Optimization routines then identify variable thresholds that minimize UHI intensity, guiding targeted urban retrofit or planning interventions. The overall methodology of the study is described in Figure 3.

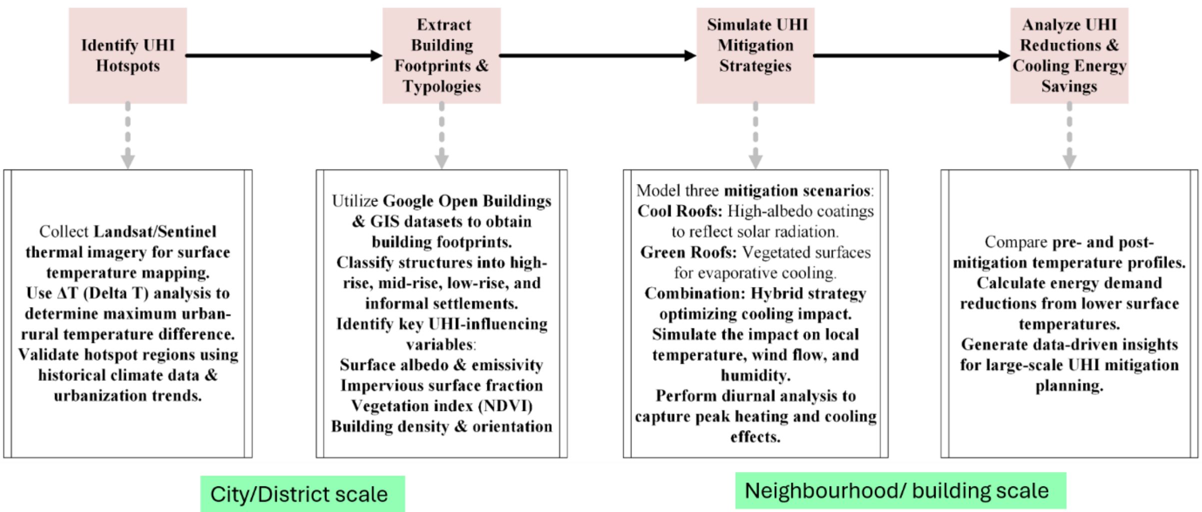

Figure 3 Flowchart of multi-scale methodology

2.4 Simulation and Scenario Design

Cooling energy demand simulations for multiple urban neighbourhoods were executed in an open-source urban building energy modelling tool – City Energy Analyst (CEA) for each city across two cases: existing baseline and mitigation (applying cool/green roofs). Parameterization reflected empirical observations from hotspot neighborhoods. The detailed simulation framework is shown in Figure 4.

2.5 Case-Specific Experimental Design

The study areas were divided into groups based on city specific context variables as shown in Table 3.

- Mumbai: Cooling demands in neighborhoods adjacent vs distant to major highways.
- Faridabad: High-rise (> 10 floors) vs low-rise (<4 floors) neighbourhoods.
- Udaipur: Compact (city-centre) vs dispersed (periphery) building arrangements.

Table 3 Experimental Groups and Interventions

City	Group A	Group B	Mitigation Applied
Mumbai	Neighbourhood near highway	Neighbourhood far from highway	Cool/Green roof
Faridabad	High-rise cluster	Low-rise cluster	Cool/Green roof
Udaipur	Dense, centre	Sparse, periphery	Cool/Green roof

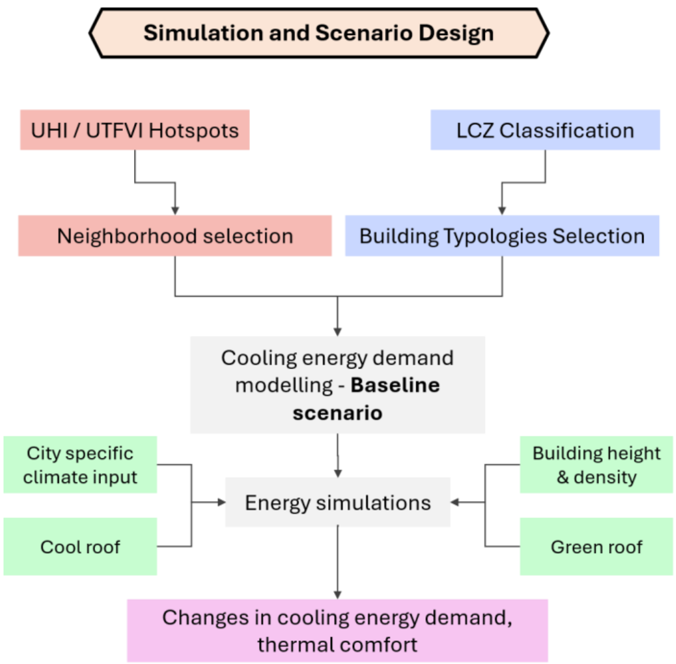

Figure 4 Urban Building Energy Modelling framework

3 Results

3.1 UHI Trends and Hotspot Dynamics

The decadal analysis of Landsat-derived LST data from 2015 to 2025 demonstrates clear amplification and spatial expansion of UHI hotspots in Mumbai, Faridabad, and Udaipur. Trends observed in the attached figures indicate a consistent increase in hotspot area over time for each city. In Mumbai, the hotspot area has grown from 20.58 km² in 2015 to 39.21 km² in 2024, with trendline projections suggesting further increase beyond 2025 (Figure 5). Faridabad exhibits a similar trajectory, with hotspot area rising from 16.66 km² in 2018 to 29.22 km² in 2024 (Figure 7). Udaipur, while starting at a lower baseline, has also expanded its hotspot zone from 16.66 km² to 29.22 km² over the same period (Figure 9), following a comparable upward trend.

This quantified spatial growth in hotspot areas underscores intensifying thermal stress driven by factors such as densification, accelerated industrialization, and ongoing loss of vegetative cover, particularly in Mumbai and Faridabad. Udaipur's expansion further reflects the vulnerabilities of tier-3 cities experiencing rapid urbanization in hot-dry climates. The close alignment between observed data and forecasted trendlines in all three cities reinforces the reliability of these patterns and highlights the need for proactive, targeted UHI mitigation.

Altogether, these spatial-temporal trends validate the critical importance of integrating remote sensing, urban morphological analysis, and predictive modelling in formulating effective climate-adaptive housing and infrastructure strategies. Priority should be given to densely developed, vegetation-deficient urban cores where hotspot amplification is most pronounced, to reduce long-term exposure to heat stress and mitigate increased energy demands.

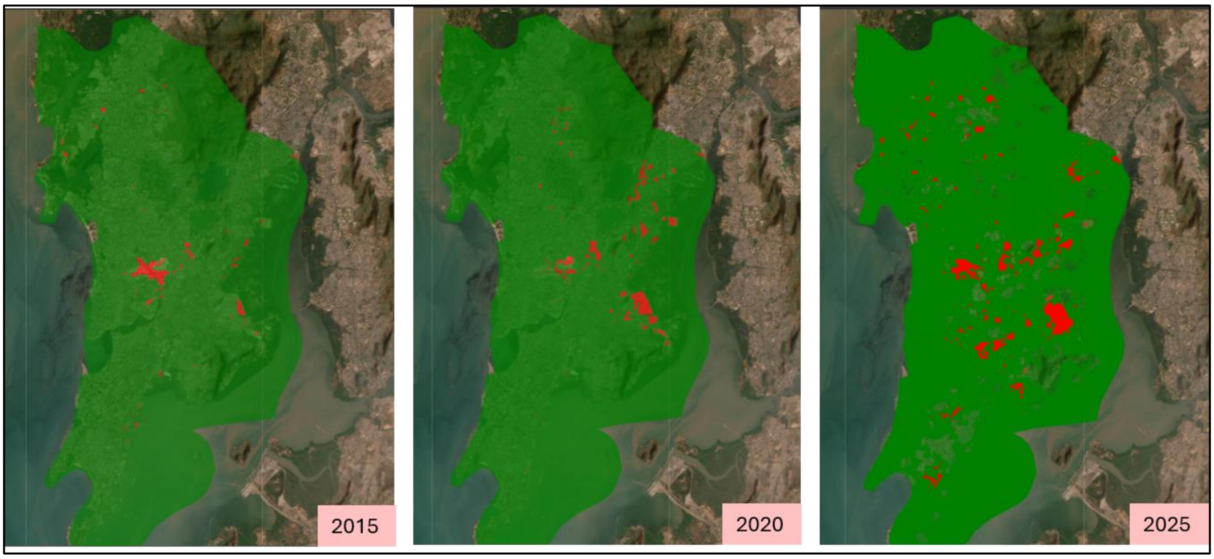

Figure 5 Hotspot increase in Mumbai for the years 2015, 2020, 2025

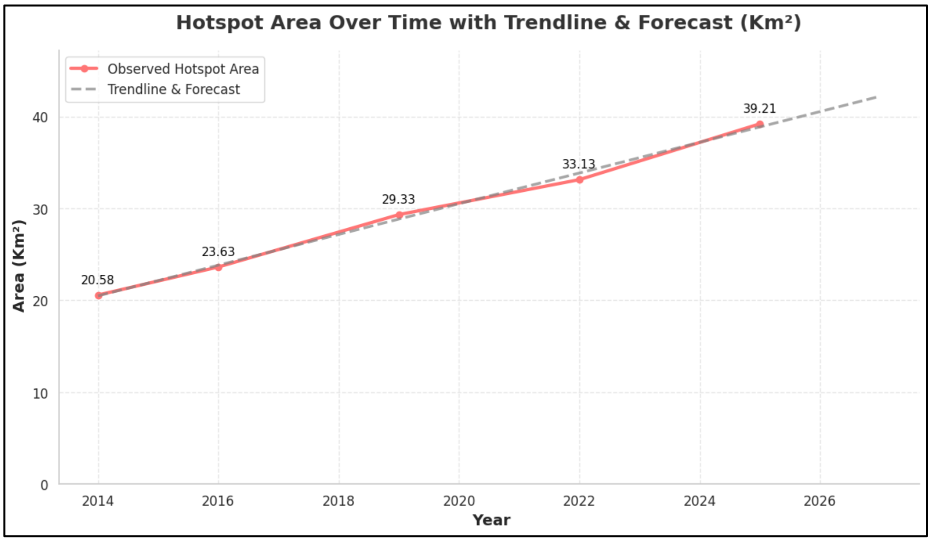

Figure 6 Hotspot area increase trend for Mumbai

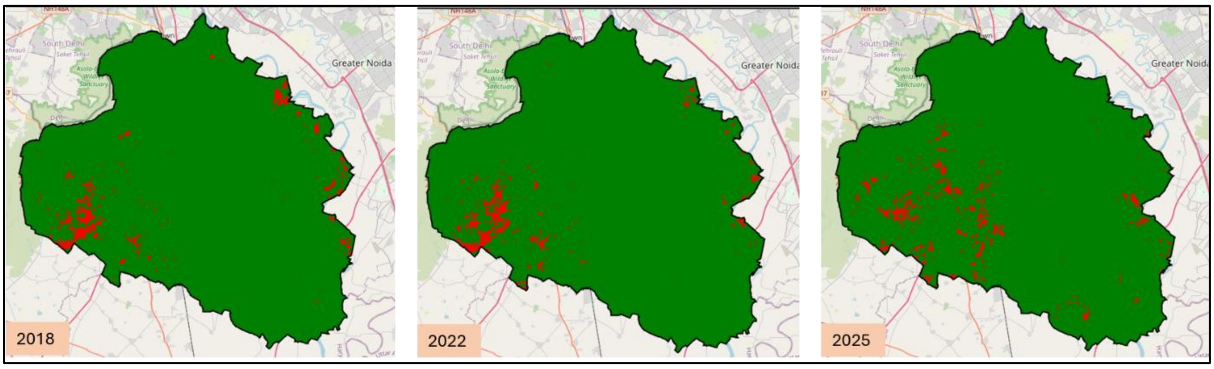

Figure 7 Hotspot increase in Faridabad for the years 2018, 2022, 2025

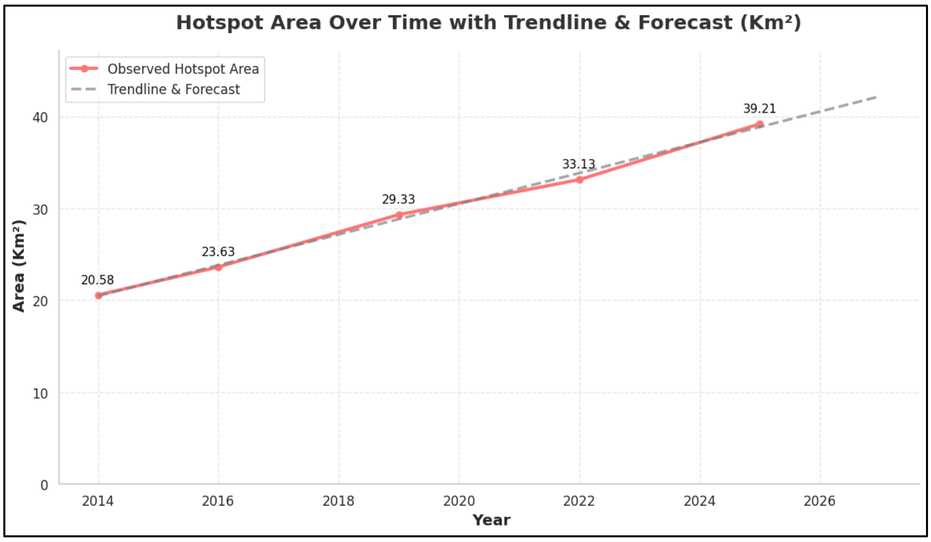

Figure 8 Hotspot area increase trend for Faridabad

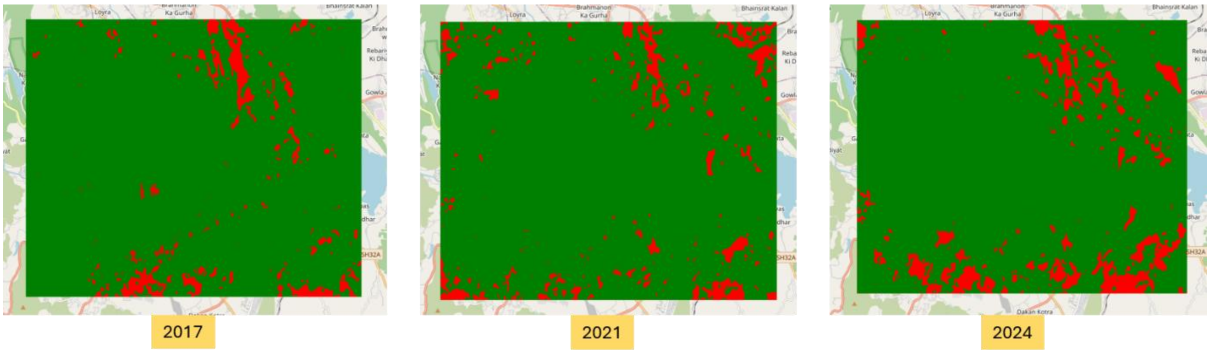

Figure 9 Hotspot increase in Udaipur for the years 2017, 2021, 2024

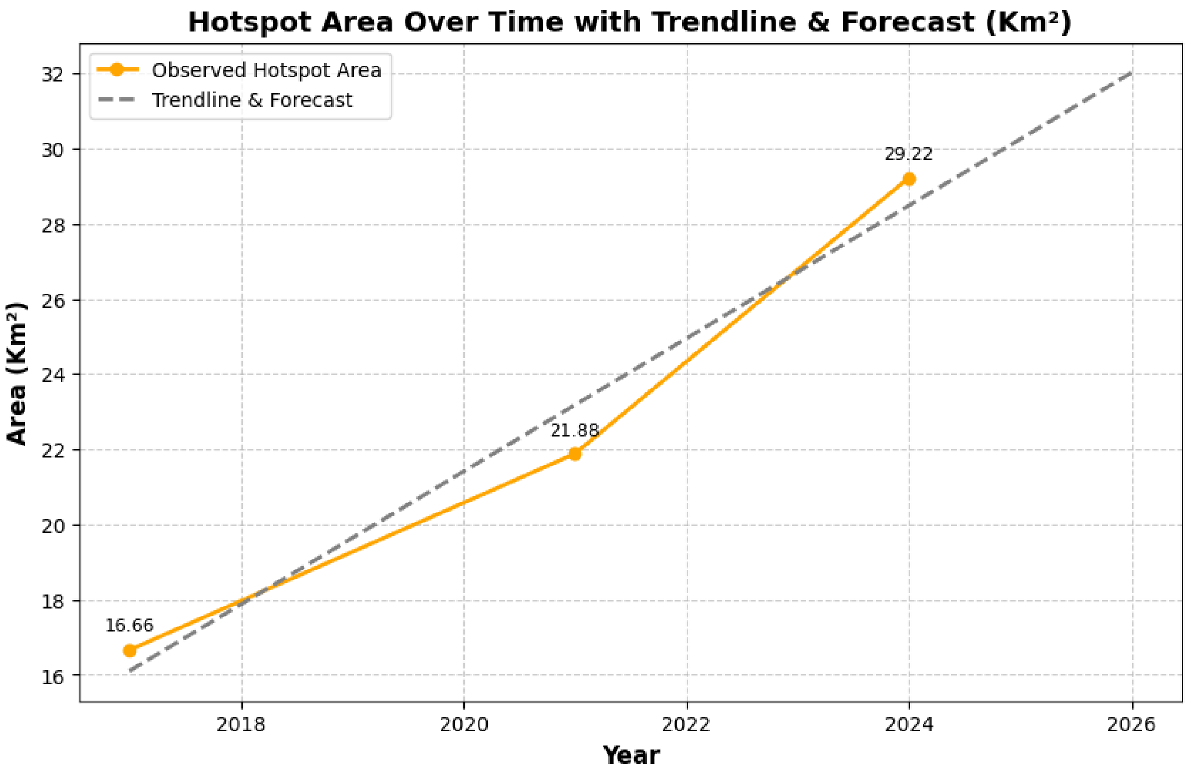

Figure 10 Hotspot area increase trend for Udaipur

3.2 Optimised Urban Variables

Random Forest regression model correlate UHI magnitude with key geometric and morphological variables. For each city, optimum values were identified for each factor as shown in Figure 11 and juxtaposed against existing state bylaws for Maharashtra, Haryana, and Rajasthan. This methodological workflow illustrates the sequential integration of urban data collection, variable processing, machine learning modelling, and optimization for UHI mitigation. Multi-source thermal and morphological datasets are pre-processed to extract spatial variables. A Random Forest algorithm is then trained to model thermal exposure at the building scale. Optimization is achieved via Bayesian search, iteratively identifying urban design solutions that minimize UHI while respecting real-world constraints. This scalable pipeline enables data-driven, robust urban heat mitigation strategies adaptable to diverse city contexts.

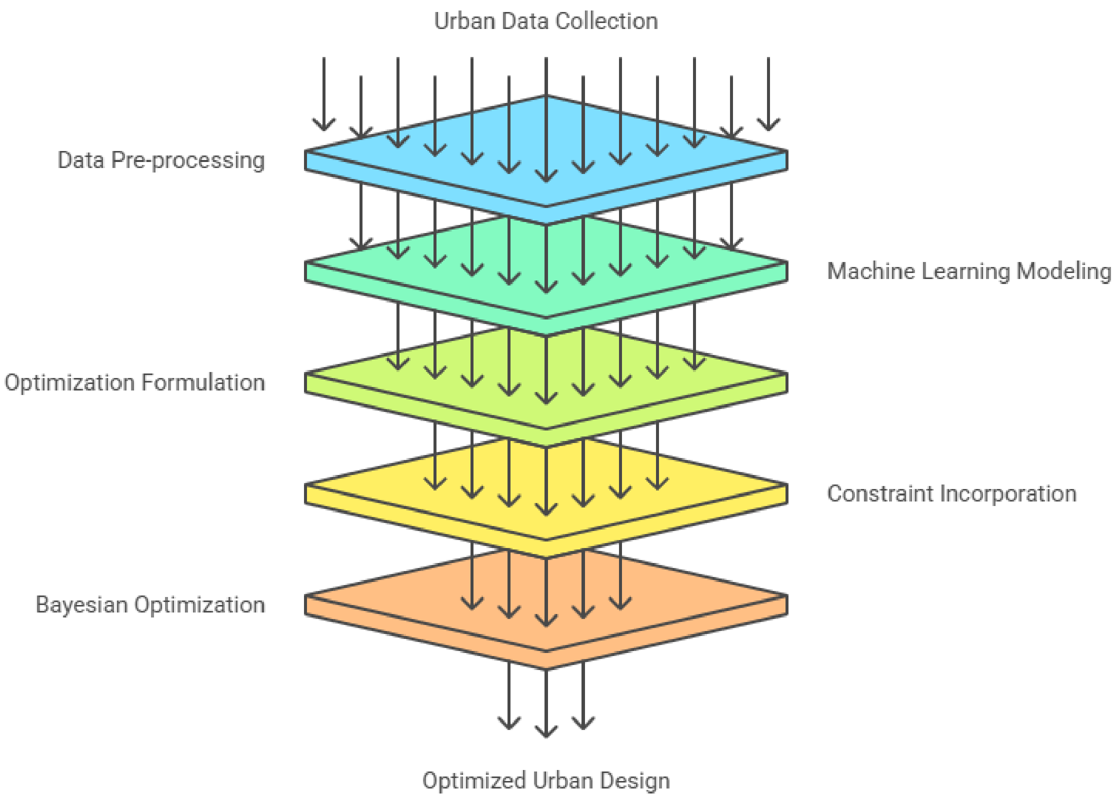

Figure 11 Neighbourhood level optimisation workflow

The analysis of optimised urban parameters against existing state bylaws reveals notable discrepancies and insights for urban heat mitigation. While Mumbai shows an increased recommendation for minimum street width compared to current UDCPR standards, facilitating better airflow and reduced heat accumulation, Faridabad's existing norms for street widths remain stricter than optimised values, indicating regulatory gaps in practical application. In terms of built density, Mumbai's present FAR bylaws far exceed the optimised thresholds, potentially exacerbating UHI intensity through densification, whereas Udaipur's FAR aligns more closely with modelled optimal levels. Vegetation measures, represented as NDVI or plantation density, highlight significant underperformance across all cities, with the conversion between NDVI values and tree counts suggesting deficient green cover relative to thermal mitigation benchmarks. Notably, setback distances from highways are consistently lower than optimal in Mumbai and Faridabad, potentially intensifying heat exposure in adjacent buildings. Cross-comparison of metrics with varying units necessitates careful interpretation: for example, NDVI values infer vegetative health but require contextual translation to physical tree counts and canopy cover mandated in bylaws. Overall, the divergence between optimised and legal parameters underscores the urgency for regulatory revisions incorporating scientific insights, tailored to local contexts for effective UHI mitigation as shown in Table 4.

Table 4 Optimised Urban Variables vs. State Building Bylaws and Specifications as per [a]: Maharashtra UDCPR, [b]: Haryana Building Code, [c]: Rajasthan ULB/Building Guidelines

Variable	City	Specification	Optimised (This Study)	State By-Law Value	Comment
Minimum Street Width (m)	Mumbai	Collector's road, arterial	20	18 (arterial), 12 (collector)[a]	Current bylaws lower than optimum
	Faridabad	Sector road, internal	18.63	24 (sector), 12 (internal)[b]	Internal streets below optimum
	Udaipur	Main road, internal	10.89	18 (main), 9 (internal)[c]	Internal roads close to optimum
Building Density	Mumbai	Bylaws use FAR	0.0355	3.0 (max, varies) [a]	FAR is calculated per plot, does not take into account the surroundings
	Faridabad	Bylaws use FAR	0.0271	2.5–3.5 (varies)[b]	
	Udaipur	Bylaws use FAR	0.307	2.0–2.5[c]	
NDVI (Avg. 0–1)	Mumbai	% plot/colony area	0.1162	10% (open space min)[a]	NDVI ~0.1 ≈ sparse cover, just at minimum requirement
	Faridabad	trees per area	0.1337	15 trees per 1000 sqm[b]	NDVI ~0.13 ≈ sparse, not necessarily healthy/dense trees

Variable	City	Specification	Optimised (This Study)	State By-Law Value	Comment
	Udaipur	% colony/site area	0.104	8–12%[c]	NDVI ~0.1 ≈ bare minimum required green
Distance to Highway (m)	Mumbai	Setback from highway	231.63	30m (major roads) [a]	Lower setbacks than optimal
	Faridabad	Setback from state highway	470	30m (major), 6m (others)[b]	Inner city often less
	Udaipur	Setback from principal road	18	15m–30m[c]	May align

3.3 Energy Simulation Outcomes

The energy simulation outcomes provide a comprehensive assessment of cooling energy demand variations across Mumbai, Faridabad, and Udaipur, driven by distinct urban typologies and microclimatic contexts. For each case study city, simulations quantify the effects of UHI zones, building proximity to anthropogenic heat sources, and neighbourhood morphological characteristics on annual cooling energy intensity. Table 5 summarizes these key results, including the measured impacts of cool and green roof mitigation strategies. These findings highlight the critical influence of localized design features and retrofitting interventions on reducing thermal loads and enhancing energy performance in diverse Indian urban environments.

3.3.1 Case I: Mumbai

3.3.1.1 ***Single Building UHI vs Non-UHI Comparison***

A single building energy demand simulation comparing a building situated within a UHI zone versus a non-UHI zone in Mumbai indicated a 7.6% increase in annual cooling energy demand intensity attributable to the elevated ambient temperatures caused by the UHI effect as shown in Figure 12. This quantifies the direct thermal penalty faced by buildings within heat-affected zones.

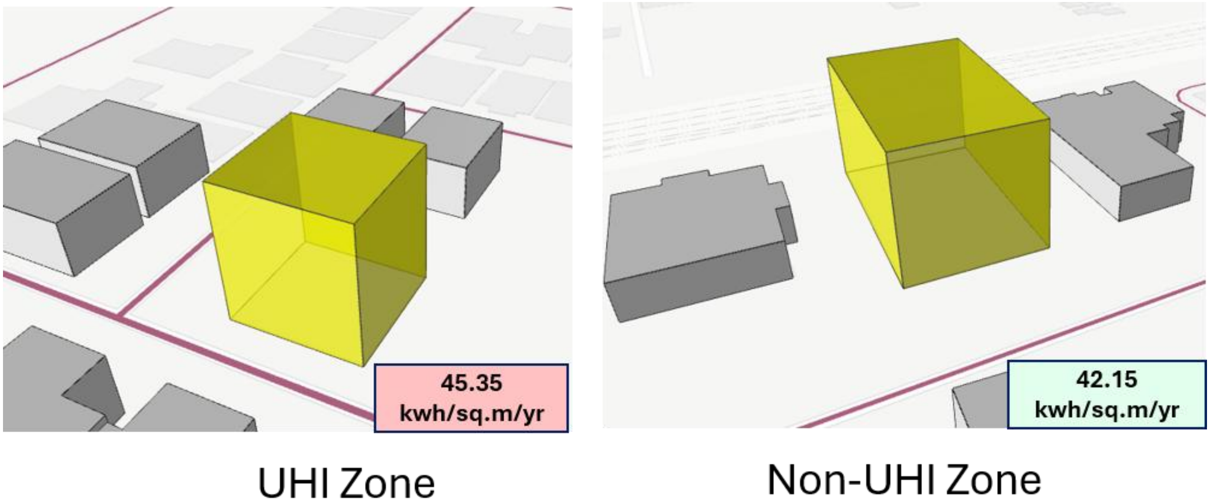

Figure 12 Comparison of annual cooling energy demand intensity (kWh/m²·yr) for a representative building located in a UHI zone versus a non-UHI zone in Mumbai. The visual demonstrates that the building in the UHI zone exhibits higher cooling demand intensity (45.35 kWh/m²·yr) compared to its counterpart in a non-UHI zone (42.15 kWh/m²·yr), quantifying the energy penalty associated with localized urban heat effects.

3.3.1.2 Neighbourhood-Level Comparison: UHI Zone Close to Highway vs Non UHI Zone Far from Highway

At the neighbourhood scale, cooling energy demand varies with local UHI intensity linked to proximity to traffic-related heat sources. Buildings in the UHI zone close to the highway registered an end-use space cooling demand intensity of 36.5 kWh/m² per year, compared to 34.35 kWh/m² per year for buildings in the Non UHI zone farther from the highway as shown in Figure 13 and Figure 16. This reflects the incrementally greater thermal burden imposed by increased anthropogenic heat, reduced indoor thermal comfort and higher cooling hours near highways.

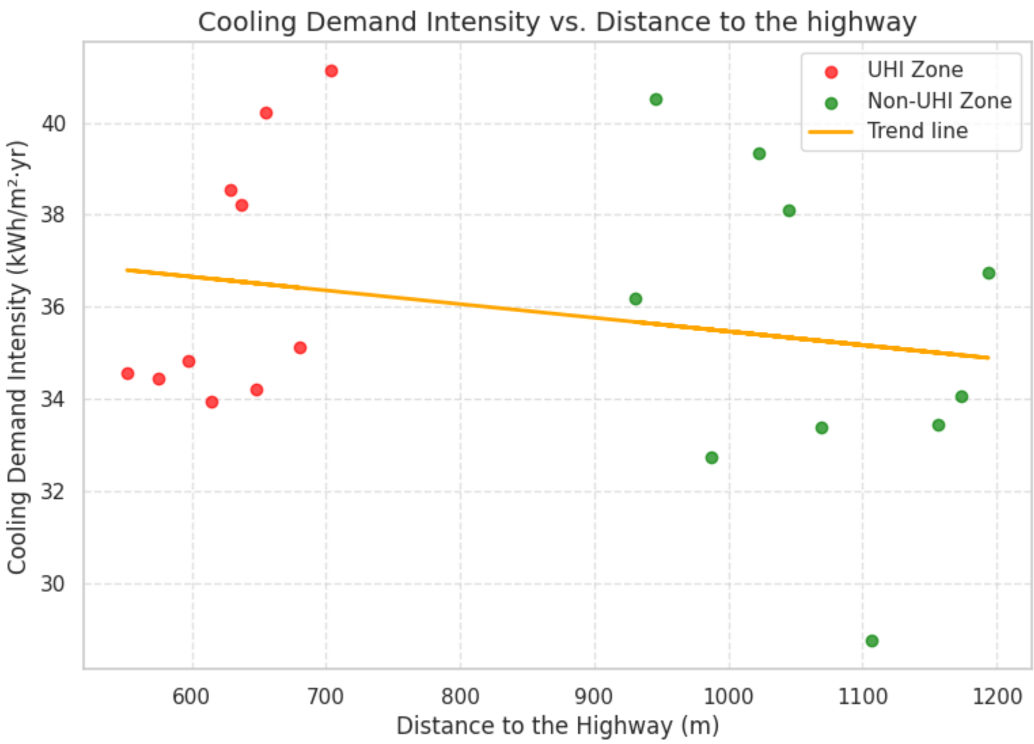

Figure 13 Relationship between building distance from the highway and annual cooling demand intensity (kWh/m²·yr) in Mumbai neighbourhoods. The scatter plot and trend line indicate a slight increase in cooling energy requirements with greater distance from the highway, suggesting that proximity to major heat sources and associated urban morphology influence local thermal loads. This underscores the interplay between spatial configuration and UHI-driven energy demand in dense metropolitan contexts.

The correlation analysis for Mumbai reveals that cooling energy demand intensity decreases slightly as the distance from the highway increases. Buildings located in UHI zones closer to highways experience higher cooling loads, attributed to intensified anthropogenic heat, diminished indoor air quality and higher air conditioning hours, while those in non-UHI zones and farther from traffic corridors show reduced cooling intensity. This pattern underscores the impact of proximity to major heat sources and urban traffic on local microclimates, emphasizing the importance of strategic mitigation for neighbourhoods adjacent to highways.

3.3.2 Case II: Faridabad

3.3.2.1 Neighbourhood-Level Comparison: UHI Zone Low-Rise vs High-Rise

In Faridabad, building typology significantly impacts cooling demand under UHI conditions. Low-rise clusters (3–4 floors) exhibited a notably high cooling demand intensity of 64.5 kWh/m² per year, reflecting higher exposure due to larger envelope-to-volume ratios and heat gain. Conversely, high-rise clusters (15+ floors) had a lower cooling demand intensity of 42.55 kWh/m² per year, possibly due to shading effects and reduced envelope exposure per unit floor area as shown in Figure 14.

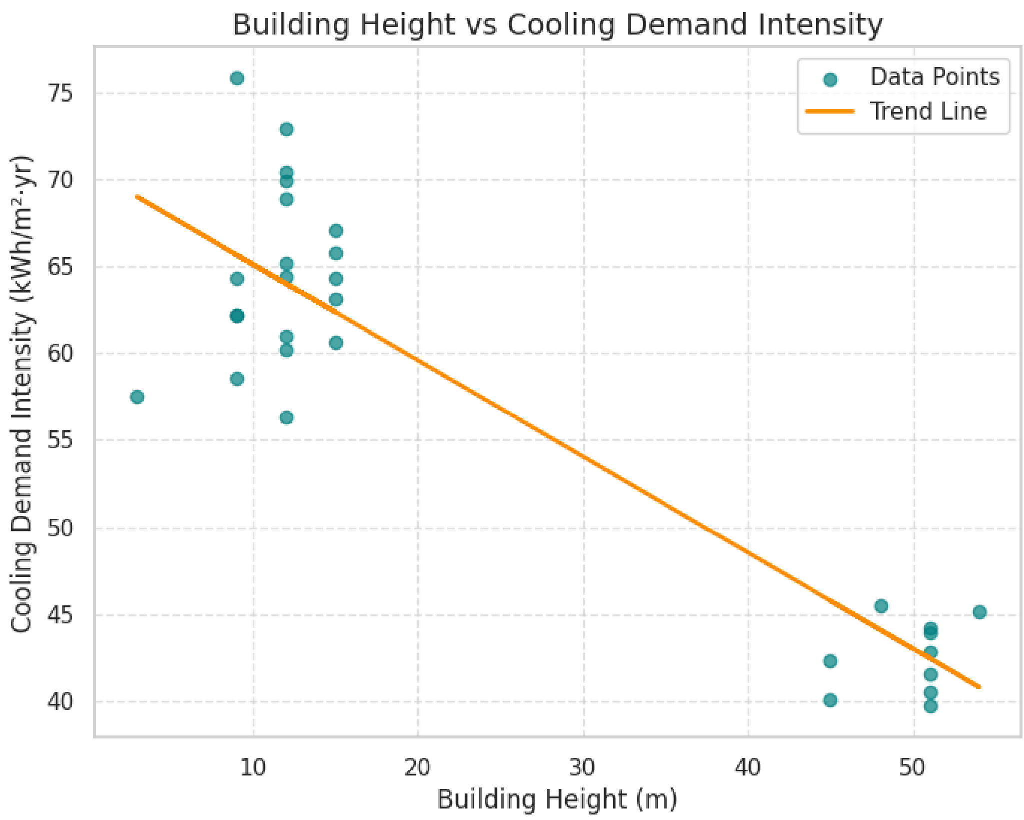

Figure 14 Correlation between building height and annual cooling demand intensity (kWh/m²·yr) in Faridabad neighbourhoods. The plot demonstrates that taller buildings are associated with lower cooling energy requirements per unit area, as illustrated by the negative trend line. This suggests that increasing building height can improve thermal efficiency, likely due to favourable volume-to-envelope ratios and enhanced shading effects in high-rise typologies.

In Faridabad, there is a clear negative correlation between building height and annual cooling demand. Low-rise buildings tend to exhibit substantially higher cooling loads compared to high-rise counterparts as shown in Figure 14. Taller typologies benefit from improved volume-to-envelope ratios and mutual shading, resulting in more efficient thermal performance per unit area. These findings indicate that increasing building height, within appropriate planning limits, can be an effective design strategy for reducing energy demand under UHI conditions in composite climates.

3.3.3 Case III: Udaipur

3.3.3.1 Neighbourhood-Level Comparison: UHI Zone Compact Spacing vs Sparse Spacing

In Udaipur's hot and dry context, compactly spaced buildings within the city core exhibited an end-use space cooling demand intensity of 61.55 kWh/m² per year, suggestive of cumulative heat retention effects. Interestingly, dispersed buildings in less dense peripheral areas showed an even higher cooling demand intensity of 83.65 kWh/m² per year, potentially driven by lesser mutual shading and higher direct solar exposure as shown in Figure 15.

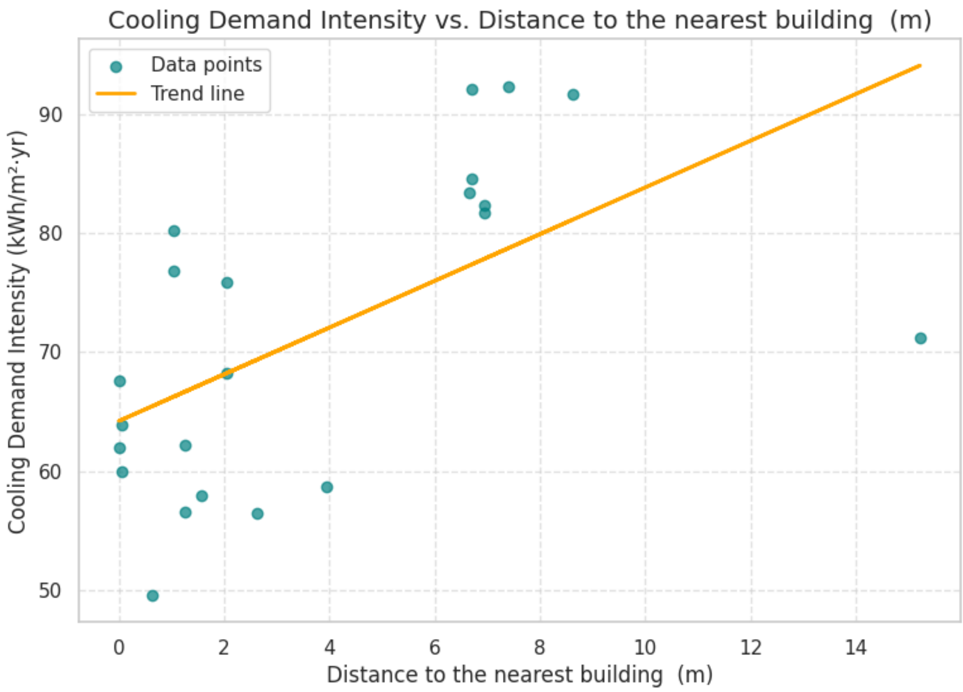

Figure 15 Relationship between building compactness (measured as nearest edge distance) and annual cooling demand intensity (kWh/m²·yr) for Udaipur neighbourhoods. The scatter plot illustrates that greater spacing between buildings is associated with higher cooling energy requirements, as shown by the upward trend line. This highlights the thermal efficiency benefits of compact urban forms in hot and dry contexts.

For Udaipur, the analysis demonstrates that cooling demand increases with greater spacing between buildings. Compact neighbourhoods, characterized by closely spaced structures, exhibit lower cooling energy requirements due to collective shading and reduced exposure to direct solar radiation. Conversely, sparse urban layouts result in heightened thermal loads as buildings receive more solar gain and experience limited mutual protection. These results highlight the thermal advantages of compact city design in hot-dry climates, supporting denser urban morphologies as an effective UHI mitigation strategy.

3.3.4 Summary of simulation results

The energy use intensity (EUI) analysis across Mumbai, Faridabad, and Udaipur reveals significant variability in cooling demand driven by urban context and built form. Mumbai demonstrates lower baseline cooling loads in neighbourhoods near highways, attributable to microclimatic factors, with an 8–13% reduction potential via cool and green roof retrofits. Faridabad's high-rise clusters consume less cooling energy than low-rise due to volumetric and shading effects, with up to ~11% savings from cool roofs. Udaipur's compact clusters show beneficial impacts from both interventions, achieving reductions nearing 16%, underscoring the efficacy of vegetation and reflective surfaces in hot and dry climates. Notably, cool roofs consistently outperform green roofs in percentage energy savings but trade off eco-benefits. The data substantiates the critical role of tailored retrofit solutions within diverse urban morphologies to optimize heat mitigation and energy efficiency as shown in Table 5.

Table 5 EUI and cooling load reductions for baseline and mitigated scenarios across study cities and neighbourhood typologies. The table presents annual cooling demand intensity (kWh/m²-yr) for reference buildings under baseline conditions, alongside EUI values following *cool roof and green roof retrofits. Corresponding percentage reductions quantify energy savings attributable to each intervention. The variation between zones—such as proximity to highways in Mumbai or building height typologies in Faridabad—illustrates context-specific thermal load differences critical to targeted mitigation planning. Data underpin regionally calibrated energy modelling supporting climate-responsive urban design strategies.*

City	Group	Base-case EUI	EUI with Cool roof	% Reduction by cool roof	Cooling EUI with Green roof	% Reduction by green roof
Mumbai	Near to highway	36.58	32.7	10.606	31.54	13.77
	Far from highway	39.02	33.6	13.890	36.1	7.48
Faridabad	High rise	42.55	38.95	8.460	39.13	8.037
	Low rise	67.9	60.17	11.384	61.57	9.322
Udaipur	Compact	61.56	51.48	16.374	52.22	15.172
	Sparse	83.65	75.6	9.623	78.64	5.989

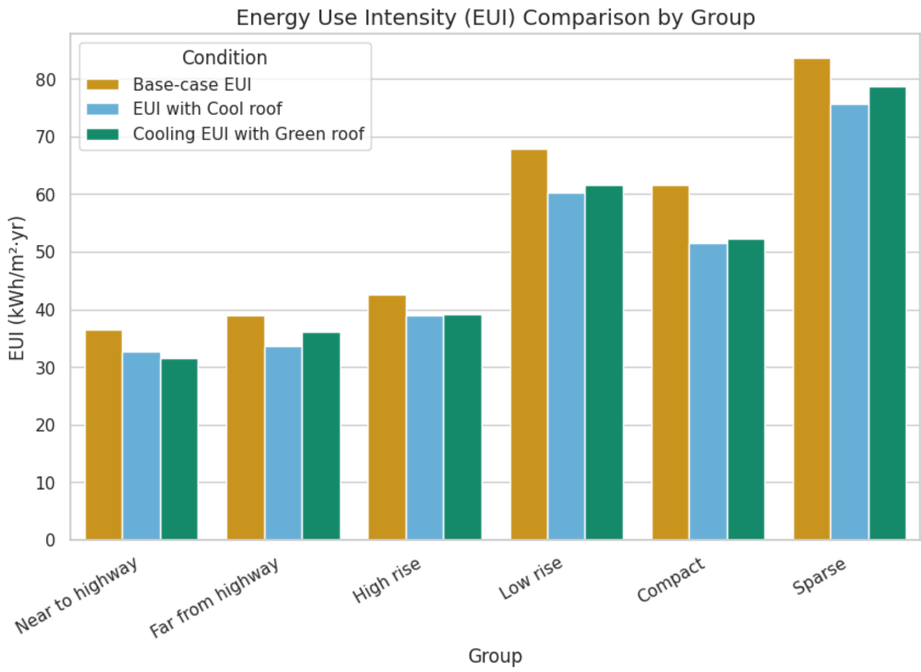

Figure 16 Comparison of EUI for baseline, cool roof, and green roof scenarios across different urban groups in Mumbai, Faridabad, and Udaipur. The chart illustrates reductions in annual cooling energy demand intensity (kWh/m²·yr) achieved through passive roof interventions, highlighting the relative effectiveness of each strategy within varying urban morphologies and climatic contexts.

3.4 Cost-Benefit Analysis

A comprehensive cost-benefit analysis was conducted to evaluate the economic viability of cool and green roof retrofits across Mumbai, Faridabad, and Udaipur. Taking the example of a typical 150 m² building in Mumbai near the highway, the retrofit cost for a cool roof was estimated at ₹120,000 (₹800 per sqm), while the green roof retrofit was higher at ₹180,000 (₹1200 per sqm). Annual energy savings were calculated by first determining the reduction in cooling energy demand intensity (kWh/m²·yr) comparing baseline and retrofit scenarios. For the cool roof case, cooling demand decreased from 36.58 to 32.7 kWh/m²·yr, resulting in annual energy savings of 582 kWh for the building. Multiplying this by the local commercial electricity tariff of ₹12.5/kWh gave an annual savings of ₹7,275. Dividing the retrofit cost by annual savings provided a payback period of approximately 16.5 years, illustrating economic feasibility within typical building lifecycle considerations.

Similar calculations were repeated across scenarios and cities, with tariff rates varying by location [20]. In Mumbai, payback periods for cool roofs ranged roughly from 12 to 17 years, while green roofs, despite higher energy savings in some instances, entailed longer paybacks of 18 to 33 years due to their higher upfront costs. Faridabad exhibited longer paybacks (28 to 63 years) reflecting lower ambient electricity tariffs and higher cooling loads in low-rise typologies. Udaipur's arid climate, higher tariffs, and significant cooling demands enabled the shortest payback periods, with cool roofs demonstrating paybacks around 10 years.

Overall, cool roofs emerge as a cost-effective retrofit strategy offering rapid returns in energy cost savings and UHI mitigation, particularly in Indian urban environments characterized by high cooling loads. Green roofs, while offering additional environmental and biodiversity benefits, demand higher capital investments and incur slower financial paybacks. Policymakers and urban planners should weigh these trade-offs carefully to design effective, context-specific urban heat mitigation programs.

Table 6 Calculations for Cost-Benefit (for single 150 m² building)

City	Context Variable	Measures Applied	Retrofit Cost (INR)	Annual Energy Saving (kWh)	Annual Savings (INR)	Payback Period (years)	Comments
Mumbai	Near to highway	Cool Roof	120,000	582	7,275	16.49	Highest reduction near highway
	Near to highway	Green Roof	180,000	765	9,563	18.82	Greater savings, higher cost
	Far from highway	Cool Roof	120,000	810	10,125	11.86	Near highway alternative case
	Far from highway	Green Roof	180,000	438	5,475	32.87	Smaller savings further away
Faridabad	Low rise	Cool Roof	120,000	642	4,173	28.75	Higher energy demand in low-rise

City	Context Variable	Measures Applied	Retrofit Cost (INR)	Annual Energy Saving (kWh)	Annual Savings (INR)	Payback Period (years)	Comments
	Low rise	Green Roof	180,000	438	2,847	63.19	Higher retrofit cost, lower saving
	High rise	Cool Roof	120,000	540	3,510	34.19	Better performance in high-rise
	High rise	Green Roof	180,000	522	3,393	53.04	Moderate retrofit effect
Udaipur	Compact spacing	Cool Roof	120,000	1,515	12,120	9.91	Highest thermal load, best payback
	Compact spacing	Green Roof	180,000	1,095	8,760	20.55	Higher cost but sustained savings
	Sparse spacing	Cool Roof	120,000	1,210	9,680	12.40	Sparse, higher cooling load
	Sparse spacing	Green Roof	180,000	750	6,000	30.00	Less effective in sparse urban form

The cost-benefit analysis indicates that cool roof retrofits generally offer quicker paybacks than green roofs due to lower upfront costs, although green roofs provide additional environmental benefits including biodiversity and long-term insulation. Mumbai's proximity to highways shows significant cooling energy reductions, reflecting higher base demands linked to anthropogenic heat. Faridabad's low-rise buildings have higher cooling loads and longer payback times, highlighting the impact of building typology on retrofit cost-effectiveness. Udaipur, with its high cooling loads, demonstrates the best payback periods, especially in compact building clusters, affirming the strong mitigation potential in such environments. Costs and savings must be considered in the context of local tariff variations and urban form to optimize retrofit strategies.

4 Discussion

4.1 Interpretation of Results

The site-specific retrofitting and optimization of urban form demonstrably reduce both neighbourhood-scale UHI intensity and per-building cooling energy demand across diverse contexts. The differential energy savings observed among Mumbai, Faridabad, and Udaipur validate the context-driven approach—where high-rise corridors in Faridabad, high-density highway-adjacent sectors in Mumbai, and dense clustered old-town arrangements in Udaipur experience the greatest mitigation benefits. Cost-benefit analysis further identifies cool roofs as consistently cost-effective retrofits with payback periods as short as approximately 10 years in high thermal load zones like Udaipur. Green roofs, despite their notable ecological advantages, generally require longer payback periods, partially due to higher installation costs and maintenance demands. This nuanced understanding underscores the imperative to tailor interventions based on local urban typologies, climatic conditions, and economic considerations for maximum impact.

4.2 Policy Implications

These findings reveal that existing state bylaws, while often well-intended, fall short of climate responsiveness—particularly within inner, high-risk heat island cores. In many cases, minimum street widths, setback distances, and green cover mandates in states like Maharashtra, Haryana, and Rajasthan diverge substantially from optimised thresholds derived from thermal and urban morphological analyses. The study strongly advocates for urgent amendments to local codes that incorporate wider streets, enhanced vegetation quotas, stricter setback regulations, and mandatory adoption of passive heat mitigation technologies, including cool and green roofs. Strategically targeting mitigation measures within identified thermal hotspots can amplify efficacy, enable efficient resource allocation, and bolster urban resilience against intensifying heat stress.

4.3 Lessons from Global Best Practices

A comparative analysis between Indian recommendations and leading international UHI policies reveals encouraging alignment, particularly regarding the mandatory and incentivized adoption of climate-responsive urban forms and rooftop retrofits. Jurisdictions such as Toronto, with its comprehensive green roof bylaw mandating coverage on large developments, Paris's white roof legislation emphasizing reflectivity, and Sydney's blend of incentives and regulations, exemplify effective frameworks adaptable to Indian urban settings. New York City's stringent Local Laws 92 and 94 demonstrate the integration of mandatory rooftop measures for new constructions and retrofits, albeit with higher implementation costs. Biodiversity and green infrastructure targets seen in France and Australia underscore the potential for multi-functional urban greening strategies, though Indian contexts may need strengthened NDVI and canopy cover norms to achieve comparable outcomes. Successful Indian adoption will hinge on policy contextualization, enforcement mechanisms, and stakeholder engagement to translate global best practices into tangible heat mitigation benefits locally as summarised in Table 7.

Table 7 Comparative analysis of international UHI mitigation policies and regulations alongside corresponding Indian recommendations. This table highlights global best practices involving green and reflective roofing mandates, incentive programs, and biodiversity integration. The Indian context reveals varying degrees of regulatory alignment and implementation challenges, emphasizing the need for localized policy innovation and enforcement to effectively mitigate urban thermal stress and enhance climate resilience.

Jurisdiction	UHI / Green Roof Regulation	Key Specifications	Indian Recommendations	Notes on Implementation and Adaptation
Toronto	Green Roof Bylaw	Applies to large developments > 2000 sqm, mandates 50-100% roof coverage	Mandate comprehensive green/reflective roofs on new and retrofitted buildings	Strong alignment; feasible for Indian metro areas with adaptation for cost and enforcement
Paris	Cool Roof / White Roof Regulation	Mandatory reflective roofs on new builds and large renovations	Enforce high-albedo materials; encourage retrofits	Matches well with Indian need to drive reflectance-based solutions
Sydney	Incentive-based Programs	Vary by district; mix of mandates and incentives	Develop incentive schemes complementing evolving urban bylaws	High convergence; incentives critical to adoption feasibility
New York City	Local Law 92 and 94	Requires solar and/or green roofs on new public and large rooftops	Recommend phased mandate for public buildings and commercial structures	Highly effective but cost-intensive, requiring tailored local adaptation
France / Australia	Biodiversity and Green Infrastructure Targets	Integrate biodiversity, vegetation targets across rooftops, façades, parks	Invest in urban green infrastructure; enhance urban canopy coverage	Partial alignment; India's NDVI norms lag; scaling bio-diverse urban solutions needed

4.4 Limitations

This study acknowledges three primary limitations. First, the reliance on satellite-derived LST data introduces constraints in spatial and temporal resolution, potentially limiting fine-scale detection of microclimatic variations within heterogeneous urban fabrics. Second, the energy simulations apply standardized occupancy and operational assumptions, which may not fully capture contextual behavioural and usage variability, impacting the precision of cooling demand estimates. Third, enforcement and compliance with local building bylaws remain inconsistent across study sites, thereby challenging the translation of optimized urban parameters into practice. These factors, collectively, suggest that while findings are robust at macro and meso scales, localized and socio-economic nuances warrant further exploration.

5 Conclusions

This study presents a comprehensive and multi-scalar approach to understanding and mitigating UHI effects in Indian cities, integrating satellite remote sensing, urban morphological analytics, machine learning, and detailed energy simulation. The application to three exemplar cities—Mumbai, Faridabad, and Udaipur—demonstrates significant spatial variability in UHI intensity and corresponding energy penalties, underscoring the critical need for context-aware interventions.

Our findings highlight that strategic retrofitting, particularly the adoption of cool and green roofs, offers measurable reductions in cooling energy demand, with potential decreases in EUI ranging from approximately 8% to 16% depending on urban morphology and climate. The cost-benefit analysis suggests that cool roofs provide the most economically viable retrofit option, with payback periods as short as nine years in arid contexts, while green roofs contribute broader ecological benefits at higher upfront costs.

Optimization of urban design parameters—such as minimum street widths, building density (FAR), vegetation indices (NDVI), and highway distances—reveals discrepancies with extant building codes, indicating substantial scope for policy reform. Aligning regulatory frameworks with empirically derived optimization benchmarks promises to enhance urban thermal resilience and reduce energy burdens.

Furthermore, comparative analysis with international best practices—ranging from Toronto's green roof mandates to Paris's cool roof laws—confirms the relevance and adaptability of these strategies to Indian urban contexts, with appropriate calibration for economic and cultural conditions. The study advocates for targeted, enforceable policies complemented by public awareness and capacity-building to ensure effective implementation.

Ultimately, advancing climate-responsive urban planning and building regulations—supported by robust data-driven methodologies—can significantly mitigate UHI impacts, enhance occupant comfort, and contribute to sustainable energy usage in rapidly urbanizing Indian cities. Future research should focus on integrating socio-economic variables, expanding model validation, and exploring synergistic effects of combined mitigation strategies to further optimize urban climate resilience.

6 References

[1] Sangiorgio V, Fiorito F, Santamouris M. Development of a holistic urban heat island evaluation methodology. Sci Rep 2020;10:1–13. https://doi.org/10.1038/s41598-020-75018-4.

[2] Mohan M, Bhati S, Sati AP. Chapter 11 - Urban heat island effect in India: assessment, impacts, and mitigation. In: Khan A, Akbari H, Fiorito F, Mithun S, Niyogi D, editors. Glob. Urban Heat Isl. Mitig., Elsevier; 2022, p. 199–250. https://doi.org/https://doi.org/10.1016/B978-0-323-85539-6.00007-X.

[3] Rahmani N, Sharifi A. Urban heat dynamics in Local Climate Zones (LCZs): A systematic review. Build Environ 2025;267:112225. https://doi.org/10.1016/j.buildenv.2024.112225.

[4] Schwaab J, Meier R, Mussetti G, Seneviratne S, Bürgi C, Davin EL. The role of urban trees in reducing land surface temperatures in European cities. Nat Commun 2021;12:1–11. https://doi.org/10.1038/s41467-021-26768-w.

[5] Fuladlu K, Riza M, Ilkan M. THE EFFECT OF RAPID URBANIZATION ON THE PHYSICAL MODIFICATION OF URBAN AREA. 2018.

[6] Na N, Xu D, Fang W, Pu Y, Liu Y, Wang H. Automatic Detection and Dynamic Analysis of Urban Heat Islands Based on Landsat Images. Remote Sens 2023;15. https://doi.org/10.3390/rs15164006.

[7] Wang J, Bretz M, Dewan MAA, Delavar MA. Machine learning in modelling land-use and land cover-change (LULCC): Current status, challenges and prospects. Sci Total Environ 2022;822:153559. https://doi.org/10.1016/j.scitotenv.2022.153559.

[8] Santamouris M. Cooling the cities - A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Sol Energy 2014;103:682–703. https://doi.org/10.1016/j.solener.2012.07.003.

[9] Vinayak B, Lee HS, Gedam S, Latha R. Impacts of future urbanization on urban microclimate and thermal comfort over the Mumbai metropolitan region, India. Sustain Cities Soc 2022;79:103703. https://doi.org/10.1016/j.scs.2022.103703.

[10] Kotharkar R, Bagade A, Ramesh A. Assessing urban drivers of canopy layer urban heat island: A numerical modeling approach. Landsc Urban Plan 2019;190:103586. https://doi.org/10.1016/j.landurbplan.2019.05.017.

[11] Li Y, Schubert S, Kropp JP, Rybski D. On the influence of density and morphology on the Urban Heat Island intensity. Nat Commun 2020;11:1–9. https://doi.org/10.1038/s41467-020-16461-9.

[12] Khan A, Akbari H, Fiorito F, Mithun S. Global Urban Heat Island Mitigation 2022.

[13] Mirabi E, Davies PJ. Urban Climate Mitigating urban heat along roadways ; systematic review of impact and practicability. Urban Clim 2024;58:102207. https://doi.org/10.1016/j.uclim.2024.102207.

[14] Wang Z. Reconceptualizing urban heat island : Beyond the urban-rural dichotomy. Sustain Cities Soc 2022;77:103581. https://doi.org/10.1016/j.scs.2021.103581.

[15] Akbari H, Pomerantz M, Taha H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Sol Energy 2001;70:295–310.

https://doi.org/10.1016/S0038-092X(00)00089-X.

[16] MA&UD and GHMC. Telengana-Cool-Roof-Policy-Booklet.Pdf 2017:30.

[17] Diem PK, Nguyen CT, Diem NK, Diep NTH, Thao PTB, Hong TG, et al. Remote sensing for urban heat island research: Progress, current issues, and perspectives. Remote Sens Appl Soc Environ 2024;33:101081. https://doi.org/https://doi.org/10.1016/j.rsase.2023.101081.

[18] Ma YX, Yu AC. Impact of urban heat island on high-rise residential building cooling energy demand in Hong Kong. Energy Build 2024;311:114127. https://doi.org/10.1016/j.enbuild.2024.114127.

[19] Santamouris M. On the energy impact of urban heat island and global warming on buildings. Energy Build 2014;82:100–13. https://doi.org/10.1016/j.enbuild.2014.07.022.

[20] Electricity Rate per Unit in India: State Wise Rate List (2025) n.d.