Urban Heat Island Analysis: Green Roof Identification for Bengaluru's Hotspots

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DOI: https://doi.org/10.51584/IJRIAS.2025.100500087

Received: 11 May 2025; Accepted: 15 May 2025; Published: 16 June 2025

ABSTRACT

Urban Heat Island (UHI) is a pressing environmental challenge in rapidly urbanizing cities like Bengaluru, where dense built-up areas experience elevated surface temperatures, adversely impacting urban living conditions and public health. The widespread increase in hard surfaces, coupled with the reduction of green spaces, intensifies the Urban Heat Island (UHI) effect by elevating surface temperatures, degrading air quality, and increasing energy demands for cooling. Green roofs, which leverage vegetation to reduce rooftop temperatures and promote urban cooling, offer a sustainable solution to mitigate these effects. This study aims to identify UHI hotspots in Bengaluru and evaluate rooftops suitable for green roof implementation. The methodology employs remote sensing, utilizing Land Surface Temperature (LST) derived from Landsat 8 thermal satellite imagery to pinpoint high-temperature zones. Building footprint data from sources like OpenStreetMap and Google Open Buildings are integrated with thermal data using Geographic Information System (GIS) tools to assess rooftop suitability. Key criteria include roof size (minimum 50 m^2), mean temperature, and urban density, ensuring optimal site selection. The analysis identifies 179,587 suitable rooftops spanning 27.25 km^2, primarily in low- to medium-density areas. These findings provide actionable insights for urban planners and policymakers to strategically deploy green roofs, fostering urban cooling, enhancing air quality, and improving public health. By promoting sustainable urban design, this approach strengthens Bengaluru's resilience to climate change and supports the creation of liveable, eco-friendly urban landscapes, aligning with global trends toward green infrastructure.

Keywords: Urban Heat Island (UHI), Green Roofs, Thermal Satellite Data, Land Surface Temperature (LST), Rooftop Suitability Analysis, Geographic Information System (GIS), Bengaluru Urban Planning, Sustainable Urban Design, Building Footprint Data**.**

INTRODUCTION

Urban Heat Island (UHI) refers to elevated temperatures in urban areas compared to surrounding rural regions, primarily caused by increased impervious surfaces, reduced vegetation, and human activities [1], [4]. This phenomenon intensifies surface heat retention, degrades air quality, increases cooling energy demands, and exacerbates public health risks such as heat stress and respiratory ailments [7], [8].

In Indian metropolitan regions like Bengaluru, rapid urbanization has resulted in significant land-use changes, replacing natural green cover with concrete infrastructure, thereby accelerating the UHI effect [3], [6]. Current studies on UHI in India are largely confined to coarse land use or LULC-scale analyses, with limited attention to building-level or rooftop-scale mitigation strategies [6]. This gap restricts effective micro-level urban planning and implementation of climate-resilient infrastructure.

Green roofs—vegetated systems applied to rooftops—have been shown to mitigate UHI through increased evapotranspiration, surface shading, and improved thermal insulation [1], [2]. They also support biodiversity, reduce energy consumption, and enhance urban aesthetics. However, their implementation requires careful rooftop suitability assessment considering surface temperature, size, and urban density.

This study aims to bridge the research gap by integrating Landsat 8-derived Land Surface Temperature (LST) data with high-resolution building footprint datasets from Google Open Buildings and OpenStreetMap. Through GIS-based spatial analysis, we identify UHI hotspots in Bengaluru and evaluate rooftops larger than 50 m² for green roof feasibility. By adopting a building-level geospatial methodology, this research contributes a replicable, data-driven framework for UHI mitigation and green infrastructure planning in rapidly growing urban centers like Bengaluru

LITERATURE REVIEW

Studies such as *Mitigating Urban Heat Island Through Green Roofs* [1] highlight the cooling effects of green roofs, achieved through the albedo effect and evapotranspiration. These systems not only reduce surface temperatures but also enhance urban aesthetics and energy efficiency. Similarly, *Green Roofs and Urban Heat Island Effect – Cities in the 21st Century* [2] explains how green roofs reduce energy consumption during peak heat periods, offering environmental and economic benefits.

In the Indian context, the Urban Heat Island (UHI) effect in cities like Bengaluru is primarily driven by rapid urbanization, declining green cover, and increasing built-up density. *The Urban Heat Island of Bengaluru, India: Characteristics, Trends, and Mechanisms* [3] provides localized insights into the city's surface temperature variation. These findings align with broader perspectives, such as the review *On the Linkage Between Urban Heat Island and Urban Pollution Island* [4], which highlights the combined impacts of heat accumulation and air pollution due to dense urban forms.

Advancements in GIS and remote sensing have revolutionized urban climate research. For instance, *Evaluation of the Potential of Green Roofs Applied to an Urban Fabric Using GIS and Remote Sensing Data: Case of the Nador City, Morocco* [5] demonstrates how high-resolution spatial data—including LiDAR-derived building models—can effectively identify rooftops for green roof implementation. By integrating thermal imagery with detailed building geometries, such approaches allow for precise targeting of UHI-prone zones. Similarly, the present study adopts a polygon-based analysis, utilizing accurate building footprints from *Google Open Buildings* and *OpenStreetMap*, along with *Landsat 8* thermal imagery, to assess rooftop suitability across Bengaluru. Unlike earlier Indian studies that rely on coarse land-use overlays, this method delivers building-level, spatially explicit insights, offering a scalable and cost-effective framework for green infrastructure planning in dense urban settings.

Comparative reviews such as *Urban Heat Island Studies: Current Status in India and a Comparison with International Studies* [6] emphasize the urgent need for context-specific UHI mitigation strategies tailored to India's diverse climate zones and rapid urbanization. However, much of the existing literature remains confined to city-wide or LULC-scale assessments, with limited integration of thermal satellite data and high-resolution rooftop geometries. This gap is especially evident in Indian cities like Bengaluru, where localized, building-scale evaluations for green infrastructure remain rare. The present study addresses this research void by combining *Landsat 8 LST*, *building footprint data*, and *GIS-based analysis* to propose a data-driven, site-specific approach to UHI mitigation.

Further, studies like *Mitigating Urban Heat Island and Enhancing Indoor Thermal Comfort Using Terrace Garden* [7] reinforce the dual benefits of green roofs in improving both outdoor urban microclimates and indoor thermal comfort. *Optimized Greenery Configuration to Mitigate Urban Heat* [8] supports the use of multi-criteria GIS-based planning, aligning with this study's geospatial methodology for scalable urban heat interventions.

However, most existing Indian studies focus on land use-scale analyses, and there is a lack of high-resolution, building-level assessments integrating rooftop data with satellite-derived thermal imagery. This study addresses that gap

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue V May 2025

Description of the Study Area

Bengaluru is a city situated in the southern part of India ,possesses an area of approximately 741 km² and lies at an average elevation of 900 meters above sea level. It is the capital city of the Indian state of Karnataka.

Bengaluru is located between the latitudes of 12°50′N and 13°05′N and longitudes of 77°30′E and 77°40′E geographically. The city is a part of the Deccan Plateau, which contributes to its unique elevation and climate. It's a significant hub for commerce, technology, and education in India because of its strategic location. Bengaluru had an estimated 8.4 million residents in 2011 according to the Census of India, and by 2025, the number is expected to rise to 12.5 million. The metropolitan region has been one of India's fastest-growing urban areas. Bengaluru offers a diverse mix of residential types, including modern apartments, independent houses, and traditional homes in older neighbourhoods. With regard to its geographical position, the city enjoys a tropical savanna climate with distinct wet and dry seasons .The climate is characterized by occasional rainfall ,moderate temperatures and dry winters. The city benefits from the southwest and northeast monsoons, although rainfall patterns have become increasingly erratic in recent years due to climate change.

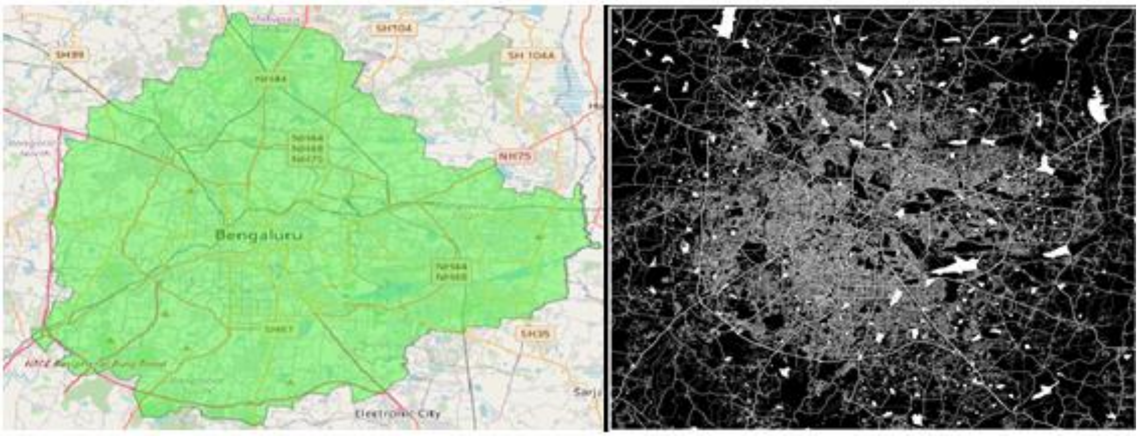

Figure 1. Location of the study area (Bengaluru city)

Data Used

This study uses a combination of satellite imagery, building footprint data, and geospatial tools to analyse urban heat islands (UHIs) in Bengaluru and recommends suitable rooftops for the implementation of green roofs. The core basis of the analysis involves the integration of thermal satellite data (Landsat 8) and spatial building footprint data (QGIS).

Table 1. Data Sources and Components for UHI

Category	Details
Satellite Imagery	Landsat 8
Satellite Data Source	United States Geological Survey (USGS) via Earth Explorer
Data Components	Surface Reflectance Bands: SR_B1 to SR_B7 (Land cover and vegetation analysis)
	Surface Temperature Bands: ST_B10, ST_ATRAN, ST_EMIS (Land Surface Temperature analysis)
	Quality Assurance Files: QA_PIXEL, QA_RADSAT (Cloud masking and quality assurance)
	Metadata Files: MTL.txt, MTL.xml (Georeferencing and alignment)
Building Footprint Data	Google Open Buildings Dataset
Boundary Data	OpenStreetMap (OSM) boundary file in GeoJSON format (Bengaluru)
Coordinate Reference System (CRS)	EPSG:4326 - WGS 84 (Global applicability with the World Geodetic System 1984)

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue V May 2025

METHODOLOGY

This section explains the methodological framework adopted for the identification of optimal rooftops for green roof implementation in Bengaluru by integrating geospatial analysis, remote sensing, and computational tools. QGIS and Python were used for spatial data processing, visualization, and automation throughout the study.

Data Acquisition

The study first involved acquiring high-quality satellite data from the Landsat 8 OLI/TIRS platform, sourced from the United States Geological Survey (USGS). The datasets included surface reflectance, thermal bands , quality assurance files and metadata files as mentioned in Table 1. These data, obtained via the USGS Earth Explorer platform, were indispensable for radiometric correction and land surface temperature (LST) calculations.

Building footprint data was sourced from OpenStreetMap and the Google Open Buildings Dataset. The dataset from Google, weighing 4.8 GB of building data for South India, needed pre-processing to extract the data specifically for Bengaluru. The administrative boundary of Bengaluru was used in QGIS to clip the dataset, resulting in a subset which ensured that only the buildings within the city were considered.

Data Pre-processing

QGIS was used in some of the initial steps for pre-processing: reprojection of all datasets to a common coordinate reference system, EPSG:4326 (WGS 84), ensuring spatial alignment. Cloud masking was performed in QGIS using QA_PIXEL files to remove those pixels affected by clouds, hence improving the accuracy of the thermal analysis. The datasets were resampled and clipped to match the spatial resolution of the area of interest.

The datasets were resampled and clipped to match the spatial resolution of the area of interest. QGIS was used for visual inspections, overlays, and ensuring the spatial integrity of the datasets. Python complemented these efforts by automating repetitive tasks such as band extraction, dataset normalization, and filtering specific regions of interest.

Land Surface Temperature (LST) Analysis

LST was estimated from thermal infrared Band 10 (ST_B10) of Landsat 8 imagery. QGIS was used to display and process the satellite images, and Python was used for the computational processing, such as converting raw digital numbers (DN) to radiance and then to temperature values in degrees Celsius. The calibration parameters required for converting raw DN from the satellite imagery into radiance and subsequently into temperature values were extracted from the metadata files (MTL.txt). (Figure 2) shows the LST of the city. These parameters include the radiance multiplicative scaling factor (M_L), radiance additive scaling factor (A_L), and thermal constants (K1 and K2), which are specific to the Landsat 8 thermal sensor

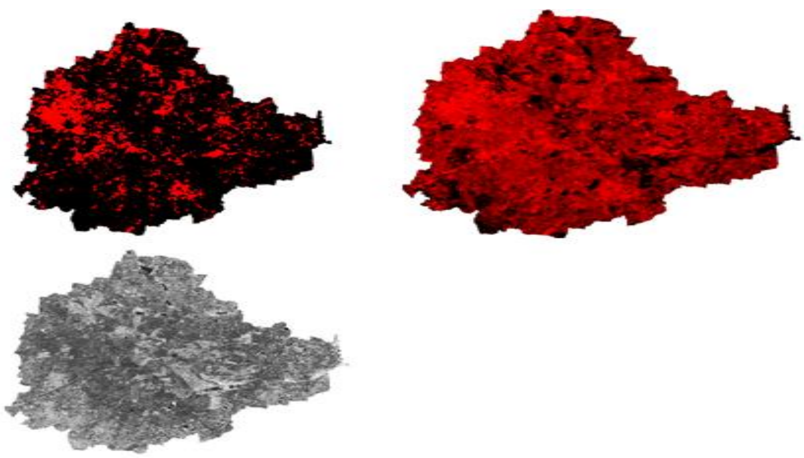

Figure 2. NDVI, LST, urban heat islands

Radiance Conversion

The first step involves converting the raw DN values into top-of-atmosphere (TOA) spectral radiance (L_λ) using the equation: $L_\lambda = M_L \times DN + A_L$

L_λ : Spectral radiance in Watts/(m²·sr·µm)

M_L : Radiance multiplicative scaling factor (from metadata)

A_L : Radiance additive scaling factor (from metadata)

DN: Raw digital number of the pixel

Python's libraries, Rasterio and NumPy, were used to read the DN values and apply this formula across all raster pixels.

Brightness Temperature Calculation

Once the radiance values are obtained, the brightness temperature (T) of each pixel is calculated using the following formula:

$$T = \frac{K2}{\ln\left(\frac{K1}{L_\lambda} + 1\right)} - 273.15$$

Where:

T: Brightness temperature in degrees Celsius

K1: Calibration constant 1 (specific to Landsat 8 TIRS, from metadata)

K2: Calibration constant 2 (specific to Landsat TIRS, from metadata) L_λ: Spectral radiance (calculated in the previous step)

The subtraction of 273.15 converts the temperature from Kelvin to Celsius. The constants K1 and K2 are also provided in the metadata file.

Spatial Processing and Visualization

The metadata-derived parameters ensured accurate radiometric calibration for LST estimation. Python was used to automate these computations across all pixels in the satellite image. The resulting temperature data was then visualized in QGIS, where spatial patterns of temperature variation were mapped to identify urban heat islands.

This computational workflow, leveraging Python for processing and QGIS for visualization, provided a robust method for estimating land surface temperatures and defining UHI zones in Bengaluru

Building and Rooftop Analysis

After identifying UHI zones, they were overlaid on the building footprint data in QGIS to determine the buildings located within high-temperature areas. This integration in QGIS allowed for precise spatial analysis of urban heat impacts. Python was used to automate the filtering and attribute queries, leveraging libraries such as GeoPandas, which combines the Pandas data structure with GeoPy's spatial functionalities. The buildings falling within UHI zones along with their respective rooftop areas were extracted.

Buildings with rooftop areas smaller than 50 m² were excluded from the analysis, as they were considered unsuitable for green roof implementation. This threshold is supported by prior research and industry guidelines, which suggest that rooftops below this size often lack the structural capacity, vegetation viability, and cost-effectiveness required for meaningful environmental impact. Studies such as Lambarki et al. (2022) and Zinzi & Agnoli (2012) applied similar thresholds in urban rooftop suitability assessments. Additionally, the FLL (2018) Green Roof Guidelines[9] recommend a minimum rooftop size of 50 m² for extensive green roof installations to ensure proper drainage, maintenance access, and uniform vegetative growth. Spatial filtering was conducted using QGIS's "Select by Feature," while Python automated data extraction and processing.

The finalized dataset, was visualized in QGIS. The visualization included UHI zones overlaid with filtered building footprints, providing clear insights into the spatial patterns and distribution of suitable rooftops across Bengaluru.

QGIS and Python Integration

The combination of QGIS and Python is invaluable throughout the study. Where QGIS is used for data visualization, manual checks, and management of spatial layers, Python automated intensive tasks of data extraction, normalization, and thermal calculations. The integration of both tools ensures a balance between accuracy and efficiency, enabling large datasets to be handled while maintaining high precision.

Final Outputs and Analysis

The processed data layers, including UHI zones and suitable rooftops, were visualized in QGIS to generate thematic maps. These maps gave us actionable insights into areas most affected by urban heat and the distribution of potential green roof sites. Python was used further to validate the results, normalize NDVI values, and create statistical summaries. (Figure 2) showcases the urban heat islands in Bengaluru.This methodology shows the effective use of geospatial tools and computational methods in urban heat mitigation and provides a robust framework for green roof planning in Bengaluru.

RESULTS AND DISCUSSIONS

The outcomes of the study are showcased and evaluated thoroughly. The results are analysed in relation to the research goals and are compared with current literature to comprehend their importance in tackling the Urban Heat Island (UHI) phenomenon in Bengaluru. Possible avenues for further research include addressing obstacles encountered during this study process.

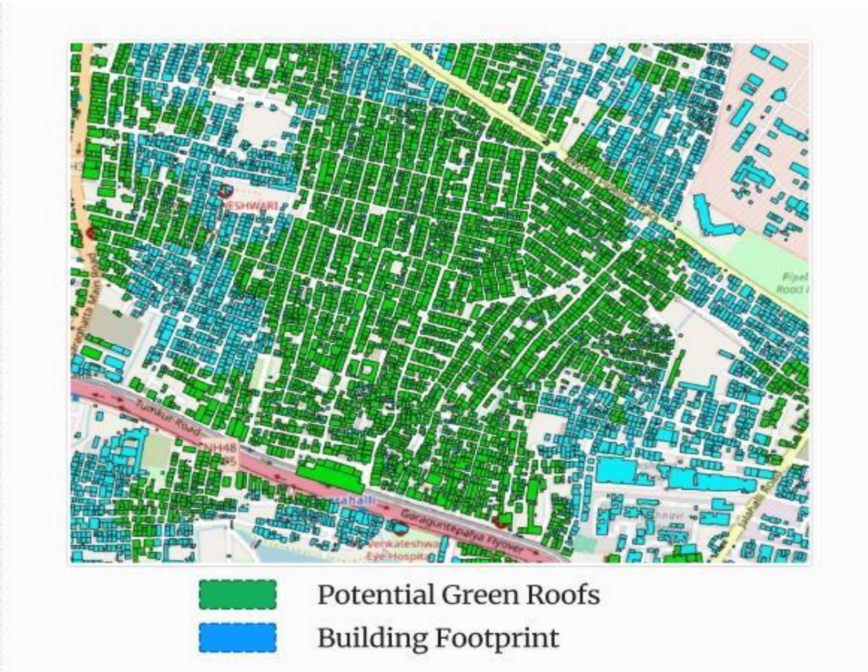

Figure 3. Distribution of Green Roof Suitability in Nagasandra, Bengaluru

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue V May 2025

Figure 4. Distribution of Green Roof Suitability in Outer ring road, Bengaluru

Figure 3 highlights the Green roof suitability and building footprints for Nagasandra, Bengaluru. Dense clusters are shown for suitable rooftops in residential areas, whereas Figure 4 focusses on the Outer Ring Road suitability concentrated in larger commercial and industrial rooftops reflecting differences in urban topology

Identified UHI Hotspots in Bengaluru

Thermal Mapping identified severe Urban Heat Island (UHI) areas within Bengaluru from the thermal infrared data obtained from Landsat 8. The results show high surface temperatures for highly populated urban areas, commercial centres industrial areas.

Rooftop Suitability Evaluation

In UHI-affected areas, a total of 272,518 buildings were identified across Bengaluru. Among these, 179,587 rooftops exceeded 50 m², marking them as highly suitable for green roof implementation. Suitability analysis indicated that about 65.9% of rooftops in UHI zones are viable for green roof adoption, offering significant potential for mitigating urban heat. Geospatial analysis integrated thermal and rooftop data to identify optimal locations for green roofs, particularly in low to medium-density urban areas on the city outskirts. The total area of rooftops suitable for green roof adoption in these UHI zones is approximately 27.25 square kilometres.

Implications for Urban Heat Island Mitigation

Green roofs can significantly lower localized temperatures by absorbing heat and promoting evapotranspiration, enhancing urban liveability in UHI hotspots. Regions with minimal green cover and intense urbanization would gain maximum cooling benefits from green roof adoption. By reducing rooftop temperatures, green roof helps in mitigating heat stress thus improving thermal comfort for building occupants

Comparison with Machine Learning and Deep Learning models.

While machine learning (ML) and deep learning (DL) models provide excellent predictive accuracy for UHI analysis, they require extensive data and computational resources. In contrast, this geospatial analysis leverages publicly accessible data, making it more cost-effective and user-friendly. Additionally, geospatial methods offer better interpretability for urban planners compared to ML/DL models, which require domain-specific expertise. However, ML/DL can complement geospatial approaches by refining vegetation selection for green roofs and predicting their long-term benefits.

Limitations and improvements.

The study faced limitations in the resolution of thermal and rooftop data, restricting accuracy. Advanced datasets like LiDAR or hyperspectral imagery could enhance precision. Furthermore, the suitability criteria were simplified, excluding factors such as rooftop orientation, shading, and structural integrity. While this methodology is specific to Bengaluru, it can be adapted to other urban contexts with necessary local adjustments.

Scope for Improvement

Future studies should consider the integration of ML/DL techniques to improve hotspot identification and rooftop suitability mapping. Advanced algorithms such as Convolutional Neural Networks (CNNs) could process satellite imagery with higher precision, enabling more accurate identification of UHI hotspots. ML models can also incorporate complex parameters such as shading patterns, vegetation indices, and rooftop material properties to refine suitability assessments Temporal analyses should also be conducted to cover seasonal variations of UHI and their effects on green roof performance.

RECOMMENDATIONS FOR URBAN PLANNERS AND POLICYMAKERS

Prioritization: Focus should initially be directed toward 179,587 rooftops identified as highly suitable for green roof implementation, particularly in areas with high surface temperatures and significant roof areas.

Incentivization: Providing tax benefits or subsidies for property owners can encourage the widespread adoption of green roofs.

Long-Term Monitoring: Establish a monitoring mechanism to track the performance of green roofs over time. This data will help evaluate their impact on urban microclimates and inform future policies for sustainable urban development.

CONCLUSION

This study aims to identify Urban Heat Island (UHI) hotspots in Bengaluru and evaluate rooftops suitable for green roof implementation using Landsat 8 thermal imagery, Google Open Buildings data, and GIS-based spatial analysis.The identification and implementation of green roofs in Bengaluru is a promising solution to mitigate the urban heat island effect (UHI) and the increasing environmental stress caused by rapid urbanization. Green roofs provide substantial benefits, including improved air quality, reduced building energy consumption, and enhanced public health through the creation of green spaces in concrete-heavy urban environments. These benefits would tackle the rising temperatures in Bengaluru which poses significant challenges to urban sustainability

This research, based on satellite imaging and GIS analysis, has identified **272,518 buildings** within UHI zones, out of which **179,587 rooftops** exceed 50 m².

The study approximately identified **27.25 square kilometres** of rooftops in UHI zones, marking a substantial area suitable for green roof implementation Considering the rooftop area, sun exposure, and other building characteristics, the analysis made is focused on identifying the urban heat hotspots where installing green roofs would have the most considerable effect. The results indicate that green roofs in these identified areas would significantly cool the urban atmosphere, reduce the impact of the urban heat island, and therefore enhance the resilience of the city to climate change.

This research highlights the importance of nature-based solutions for sustainable urban planning. Apart from providing a cooling effect green roof helps in stormwater management, enhancing biodiversity, and providing residents with access to much-needed green spaces. Findings from this research will be an important resource for urban planners, policy makers, and decision-makers in Bengaluru to support the development and implementation of green roof projects that maximize environmental and socio-economic benefits.

By identifying **179,587 suitable rooftops**, this research highlights the significant potential for green roof adoption in Bengaluru. It also underscores the need for integrated, data-driven strategies in city planning, with a focus on green infrastructure. The output of this study feeds into the emerging global momentum toward eco-friendly and climate-resilient cities, providing recommendations on how Bengaluru can be made more liveable, environmentally healthy, and sustainable through the strategic implementation of green roofs.

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