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Urban Green Roofs as Microclimate Regulators and Biodiversity Enhancers in Rapidly Growing Cities

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Abstract

Rapid urbanization in tropical cities like Chennai intensifies the Urban Heat Island (UHI) phenomenon, where urban areas experience increased thermal stress and deteriorating environmental conditions. This study, through a combined empirical and simulation-based approach, examines the opportunities for applying green roofs as a multifunctional system to manage microclimate and enhance biodiversity. A comparison was made between extensive and intensive green roofs versus traditional roofs across eight different research locations, which were classified according to various local climate zones. Microclimatic parameters including air temperature, surface temperature, relative humidity, and solar radiation were monitored during the monsoon season, and field temperatures were analyzed and simulated using the Environmental Microclimate Model (ENVI-met). Results demonstrated that green roofs significantly impact microclimate by reducing air temperature by 3°C and surface temperature by over 15°C, respectively, while increasing relative humidity and thermal comfort. Intensive systems with greater vegetation density and deeper substrates achieved superior results. In the biodiversity assessment, species richness, abundance, and diversity increased significantly; the natural vegetation supports and enhances pollination and bird species in urban areas. The study demonstrates the critical significance of Local Climate Zone (LCZ) planning, sustainable materials, and climate-sensitive planning. The study's findings underscore the need to incorporate green roofing into city policies to enable climate-resilient and sustainable urban development in rapidly urbanizing tropical areas.

Keywords

Biodiversity Enhancement, Climate-Resilient Design, ENVI-met Simulation, Green Roofs, Microclimate Regulation, Urban Heat Island.

INTRODUCTION

Intensified Urban Heat Island (UHI) effects have resulted from rapid urbanization in tropical cities, including Chennai, caused by the increase in impervious surfaces and changes in land-use patterns [1], [2], [3]. This has contributed to heat stress and increased land surface temperatures, making megacities that are located close to the coast particularly susceptible to climate change [4]. Green roofs have evolved and are now recognized as an effective nature-based solution (NBS) that utilizes evapotranspiration, shade, and insulation to provide heat control [5]. They also cover environmental services and ecosystems, like stormwater management services, as well as biodiversity support, which is particularly helpful in flood-prone regions like Chennai [6], [7], [8]. The researchers concentrated mainly on the temperate areas and were based primarily on the modeling software such as ENVI-met, despite the popularity of the concept of green roofs in the world [9]. It is confined to changes in climate and is not field-validated and is accordingly restricted in its use to the tropical Indian conditions [10], [11]. The unequal distribution of the green space in the city and the lack of research on the topic of rooftop greening in India worsen the situation with the thermal imbalances in India [12]. Chennai should be the good example where localized empirical investigation is conducted since it is high-intensity and rapidly urbanizing. To improve the capacities of these cities to be resilient and sustainable, it is paramount to address this gap to streamline the ideas on the concept of the green roof designs and to integrate climate-responsive concepts in the city planning systems [12], [11]. Figure 1 is used to show the study locations and LCZ classification, and Figure 2 is used to show the performance of roof systems in comparison to others.

OBJECTIVES

- To monitor microclimate through checking of air temperature, surface and relative humidity.
- To investigate the addition of biodiversity by methods of systematic assessment of the vegetation, insects and birds on the green roofs.
- To detect the efficiency of extensive and intensive green roof systems in ecological benefits and thermal control, the study is conducted.
- To recommend any form of recommendation that will be applicable to the policy and encourage the utilization of green roofs as a constituent of the climate-adaptation and urban support programs.

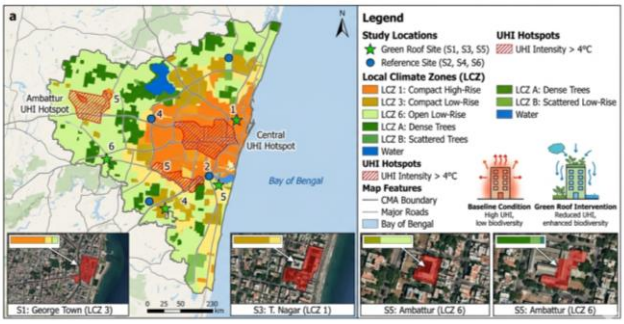

Figure 1. Map of Chennai Metropolitan Area showing study locations, LCZ classification and UHI hotspots [13]

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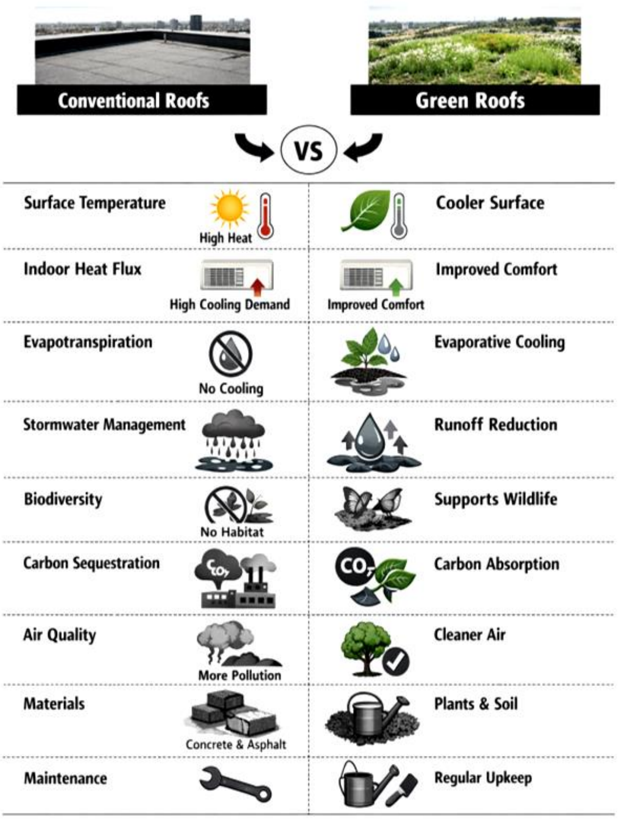

Figure 2. Comparison of Conventional Roofs and Green Roof Systems (Thermal Performance, Ecological Benefits and Material Composition) [14]

LITERATURE REVIEW

Microclimate Regulation by Green Roofs

The green roofs are also effective in controlling the urban microclimates in the cities by lowering the roof surface temperature and interior heat absorption by evapotranspiration and shade [15]. Vegetation cover, depth and form of the canopy, and the depth of the substrate affect the capacity to retain moisture and cool the temperature and, as a result, the capacity to cool down [16]. The deeper the soils and the higher the percentage covered with overabundant vegetation, the more favorable the growth of the plant and the increase of shade and latent heat conduction. The modeling studies proposed that optimization of designs did not agree with the functionality of large and small systems to enhance the outdoor comfort and ambient cooling in hot-climate regions [17]. This is what renders green roofs an evolving system that ought to be undertaken using personalized location-based designs to ensure the highest amount of thermal advantages.

Biodiversity Benefits

The green roofs sustain the biodiversity of cities and regenerate the impoverished ecological entities as plants, insects, and birds get a place to reside where these urban spaces otherwise do not have [18]. It has been held that arthropods, including bees, beetles, and spiders, get their homes there through empirical studies. The kind of vegetation has an effect on the biodiversity, the composition of the substrate, and also the complexity of the ecosystem [19]. Monocultures are ineffective in comparison to structurally diverse regimes that preserve the richest ecological communities, which consist of the entire diversity of plant species. Ecological utility: The arthropod communities are highlighted using the refined methods like the metabarcoding technique that also indicates complicated and unexplored communities [20]. The green roofs contribute to pollination, ecological sustainability in cities, and ecosystem resilience due to the increase of such indices as Shannon or Simpson diversity.

Tropical and Indian Studies

However, unlike the temperate regions, the literature on the subject of the green roofs in the tropical ambiance and the Indian settings is limited; furthermore, the majority of the literature deals with the general UHI reduction and not with rooftop systems [21]. This is necessitated by the fact that the systems in urban Indian cities cause urban heat that mainly arises due to rapid urbanization, lack of green infrastructure, impermeable surfaces, and the third factor, which is the need to install effective cooling systems. Although further studies are yet to be conducted on rooftops, emerging evidence of vertical green systems, including a green wall, can point to a bright future of lessening the interior temperatures of an apartment and enhancing thermal comfort in a tropical climate [22]. Substrates that are climate resistant and vegetation that are adaptive to the temperature and the uncertainty of monsoons are also essential to make green roofs advance in reducing the Indian cities' problems besides the empirical validation, which is more than just predictability.

Research Gap Synthesis

While reviewing various studies it was observed that there exist enormous gaps concerning green roofs in tropical urban settings. The absence of running research on the assessment of biodiversity and thermal performance is a clear restriction that prevents establishing trade-offs and synergies that are necessary in the area of multifunctional design. The majority of the finds are based on the modes of modeling, and comparatively, there are no empirical findings; thus, the ability to be reliable is low in the tropical climate characterized by high humidity, solar radiation, and the variability of the monsoons. Moreover, the existing practice is mostly comprised of standardized plants and substrates and does not have many concerns regarding the native species or the material available locally, which renders it less sustainable and flexible. There is barely any research in the most urbanizing cities and towns like Chennai that compounds the impact of urban heat islands and climate change. It is necessary to close these gaps using holistic and field-tested and climate-change-sensitive design structures.

MATERIALS AND METHODS

Study Area: Chennai

The Chennai weather is characterized by the tropical monsoon climate that is typified by extreme heat, high humidity, and rain that is based on downpours (Chennai appearance, 2009). These attributes result in the UHI turning out to be severe and make the city the best to investigate the performance of green rooftops owing to the aspects mentioned above. Representative structures of LCZ 1, LCZ 2, and LCZ 8 were picked to reflect the variation in density and land cover as well as thermal properties.

Green Roof Design Typologies

This study has adopted two systems that comprised intensive roofs with deeper substrate (1530 cm+), which produced shrubs and indigenous vegetation and extensive roofs with shallow substrate (515 cm) and drought-tolerant vegetation. As novel and sustainable components, in line with the approaches, environmentally friendly buildings use compost, biochar, and coconut coir, which would increase water retention, aeration, and the transfer of nutrients [23]. Table 1 defines the features of the research site and that of the green roof design.

Table 1. Characteristics of Study Sites and Green Roof Configurations [24]

Site ID	Location (LCZ)	Roof Type	Substrate Depth (cm)	Vegetation Type	Roof Area (m^2)	Substrate Composition
S1	LCZ 3 (Compact Low-Rise)	Extensive	10	Grasses, Succulents	120	Coir + Compost
S2	LCZ 3 (Reference)	Conventional	–	None	115	Concrete
S3	LCZ 1 (Compact High-Rise)	Intensive	25	Shrubs, Native Plants	150	Coir + Biochar + Compost
S4	LCZ 1 (Reference)	Conventional	–	None	140	Concrete
S5	LCZ 6 (Open Low-Rise)	Extensive	12	Grasses	130	Coir + Compost
S6	LCZ 6 (Reference)	Conventional	–	None	125	Concrete
S7	LCZ 8 (Large Low-Rise)	Intensive	30	Native Shrubs, Herbs	160	Coir + Biochar + Compost
S8	LCZ 8 (Reference)	Conventional	–	None	155	Concrete

Microclimate Monitoring

The air temperature, surface temperature, relative humidity and solar radiation were all measured continuously in an attempt to determine the thermal performance of green roofs. To gather data, the HOBO U23 Pro v2 temperature and relative humidity loggers were used to record the temperature and humidity within a ±0.18°C and ±2.5% range of accuracy, respectively. Researchers set these instruments 1.5 m above each roof to see situations that were representative of the real world. Fluke 568 infrared thermometers were used to take temperatures between the UST and IT with a 1% accuracy with an emissivity of 0.95 for the plant-covered surfaces and 0.92 for the concrete areas. Data on solar radiation were collected using a Li-COR LI-200R pyranometer with calibrated solar radiation sensitivity of up to 100 μA per 1000 $W\,m^{-2}$. Consistent readings were obtained by placing each of these inplace horizontally. All the monitoring equipment recorded data at every 10-minute interval during the entire period of research. A total of 144 measurements were taken from each sensor each day as part of this plan. The data were collected for the four parameters at each research location throughout the 4-month observation period (June–September 2025); a total of 17,280 data entries were obtained. An almost 1.1 million total observations were obtained under this strategy (taking into consideration all eight study locations and four measured variables).

Each sensor before deployment in the field was carefully calibrated. The temperature and humidity measurement devices were calibrated with the reference equipment, which had NIST traceable calibration. This calibration was placed in a controlled environment chamber where the temperature and relative humidity were kept between ±0.1°C and ±1% of the target values, respectively. In order to measure the temperature using infrared thermometers, blackbody sources were used for a temperature range of 20°C to 60°C. Pyranometers were factory calibrated before deployment and they were checked and verified in the field using reference pyranometers. Portable reference devices have been used to do monthly accuracy checks throughout the entire course of the research. All data collection was done throughout the season of monsoon (June 2025–September) in order to capture the nature of high humidity and rainfalls. The method allowed the seasonal and diurnal changes to be tested, giving excellent information on the microclimatic behavior of the green roofs in tropical regions. In Figure 3, the sensors' and roof layers' locations are given.

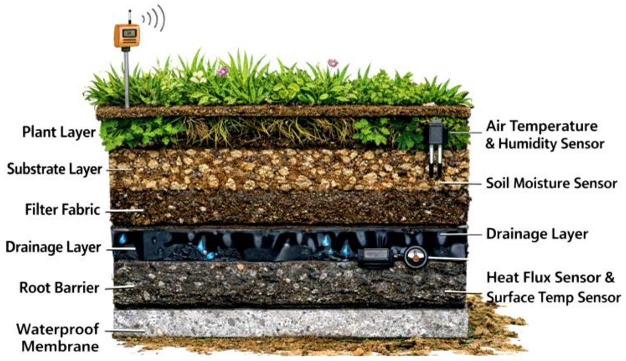

Figure 3. Green Roof Cross-Section Showing Layers and Sensor Placement [Source: Author]

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ENVI-met Simulation

ENVI-met is a 3D microclimate model that was to be used to estimate the thermal behavior of green roofs under controlled conditions to supplement field data. The grid of 0.5 m was taken to ensure that surface materials, flora and urban form were modeled. The simulators that were operated on a 24-hour cycle were required to have the geometry of buildings, characteristics of the site and plants and particular weather inputs. The conditions were basement and intervention (green roofs) in LCZs (Figure 1). Air temperature, surface temperature and thermal comfort indices were some of the outputs that were validated by the observation in the field. This increased predictability and ensured accuracy and a more analytical basis of determining the performance of green roofs in tropical urban settings.

Model validation was carried out in a three-step approach with an aim to ensure the accuracy and certainty of the simulation results. This was followed by a pre-simulation calibration, where local weather station data and meteorological input data (air temperature, wind speed, wind direction and relative humidity) were compared for time periods. Local weather data was collected through the Davis Vantage Pro2 weather stations set up in typical locations within each LCZ to gather the microclimate characteristics for each of the different urban structures. The second phase, which was concurrent validation, was doing the simulation in ENVI-met based on the data collected in the field on some clear-sky days in July and August 2025. To relate to various weather conditions, including clear days, partially clear days and typical monsoon patterns, 12 validation days have been selected. The values obtained from the sensors at HOBOs at the same geographical position and time steps were compared directly with the simulated values of air temperature for a height of 1.5 m.

Thirdly, statistical validation was done through post-processing, using various performance indicators. Compared to widespread roofing systems, measurements of the mean absolute error did not demonstrate a significant difference in performances of intensive green roofs, ranging between 0.8°C and 1.2°C in different areas. As per the accepted standards in microclimate modeling, the root mean square error of the models varied between 1.1°C and 1.8°C, which can be considered satisfactory performance of the model. The coefficient of determination values were all highly correlated between 0.86 and 0.92 depending on the site, with LCZ 1 sites showing the highest correlations due to the more regular building shapes. A systematic bias analysis for ENVI-met showed it often underestimates the temperature peak, with a bias of -0.5 °C to -0.8 °C in the afternoon. This was probably due to the thermal mass effect of the multilayer green roof system, which wasn't completely represented by the model's substrate thermal properties. Or this bias was corrected by applying linear correction factors to the final data. Based on time comparison, the least accuracy occurred in the time of peak solar radiation between 12:00 and 15:00 hours during the day due to the complex radiation interaction that occurred during this time, while the most accurate results were obtained in early morning hours (06:00–10:00) with a value of more than 0.9 for the correlation.

Important input parameters were methodically varied to assess the strength of the output of the model (model sensitivity analysis). The difference in leaf area index of ±20% brought equal differences in the temperature fluctuation of ±0.3°C to ±0.6°C. The temperature differences were created by differences in the thermal conductivity of the substrates of ±15%, which resulted in temperature differences of ±0.4°C to ±0.8°C. For this, the change in surface albedo was set to be in the range of 10% to obtain the difference in temperature of ±0.2°C to ±0.5°C. These sensitivity ranges were within acceptable limits for the application of using them for microclimate modeling. The distribution of the temperature over the roof surfaces was checked and validated spatially against the measured and modeled data at different locations. 9 measurement points were defined for each roof, representing core areas, edge effects and varying amounts of vegetation. The spatial temperature fluctuation (STF), with the correlation coefficient ranging from 0.82 to 0.89, assessed from the spatial correlation study showed that the model was able to represent the fluctuation spatially across several roof zones. Two other validation sites, one in the LCZ 4 and one in the LCZ 9, were available with data not used for model calibration for cross-validation. The Mean Absolute Error values of the location-independent sites of 1.3°C to 1.5°C confirmed the transferability of the models to the similar tropical metropolitan environments. The validation results showed that green roof thermal performance was simulated with ENVI-met with good accuracy, which meets the requirements for policy applications and comparison. Figure 4. The ENVI-met model domain and model validation. The process is shown in the bottom part of the figure below.

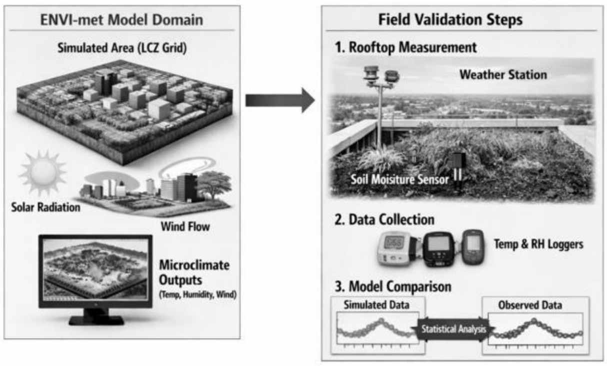

Figure 4. ENVI-met Model Domain and Validation Workflow [Source: Author]

Biodiversity Assessment

The ecological relevance of the green roof on plants, insects and birds was also evaluated by application of a multi-taxa approach. The quadrat sampling was the sample size that was used to estimate the richness, abundance and coverage of the vegetation species. The diversity of insects was measured according to pitfall traps and transects that gather the flying arthropods and ground-based transects. The stratified random sample technique was used for the vegetation sample and vegetation in each of the green roof surfaces was divided into 1 m x 1 m quadrats. Twenty quadrats with permanent corner marking were installed and used in the first survey (in the month of June 2025) and monthly sampling sessions were conducted in the four consecutive months of the research (June, July, August and September 2025); thus, a total of 80 quadrat samples per roof were sampled. Twenty-four hours of vegetation survey labor were spent at each site during the research and each sample session was approximately 6 hours per roof. Systematic species identification, abundance counts and % cover were done within each quadrat during each sample session. In the case of specimens not recognizable in the field, standard botanical keys and herbarium reference materials were used to gather and to analyze specimens. Each quadrat location was documented with a photo and GPS (to aid spatial comparisons between temporal sample episodes). Overall 144 hours of fieldwork were invested, collecting samples of the plants in all the six green roof locations, resulting in extensive species presence and abundance data.

A combination of pitfall and active collecting of arthropod samples was done. Standardized pitfall traps (10 cm deep and 7 cm in diameter) were used to collect all specimens and preserved with propylene glycol preservative solution to ensure specimens were preserved during collecting hours. Fifteen traps were strategically located within each of the green roofs and a minimum of five meters would separate each trap in order to obtain spatial independence. Sampling was conducted every two weeks during the four-month period of the research and traps were left open for 72 hours all year round. Each sampling was done biweekly and required 12 hours of labor per roof, which included 4 hours of setting traps, 2 hours of collecting specimens and 6 hours of laboratory processing and identifying specimens. This led to 480 trap-nights per roof and 96 hours of sample activity of arthropods per site throughout the investigation. The sweep net transects to collect flying insects were 50m long. These transects were carried out once a week between 09:00 and 11:00, while the temperature was between 28°C and 32°C. There were 3 transects, each 30 minutes of sweep net sampling conducted per roof for each week of sampling. Using this method, 12 hours of collecting on each roof of active flying insects resulted over the course of the trial. Overall, 648 hours of arthropod survey labor were required for the entire project—the six green roof locations combined—using both ground and sweep net sampling in order to adequately cover ground-dwellers and flying arthropods.

In order to conduct bird surveys, 25m fixed-radius transects were established for each surface of the roof in the traditional point count manner. Observation times were planned around the times of day when bird activity is likely to be the highest in urban environments (06:00 to 09:00 or 16:00 to 18:00). Each observation session was fifteen minutes to decrease observer disturbance, with a five-minute settling time at the beginning of the session. Twice-weekly surveys were conducted in the four months of research, totaling 32 observation periods. The count bird work was done under reasonable weather conditions, with the observations postponed when heavy rain or a high wind (>15 km/h) occurred. For each survey, one trained observer using binoculars and standardized recording sheets was required. During the bird survey activities at all eight research locations, 256 observation periods (64 hours of direct observation) were carried out. To ensure specificity in species identification and to ensure uniformity in methods of recording behavior, observer training involved standardization sessions with experienced ornithologists. Agreements with simultaneous independent counts were greater than 85% and species identification and abundance estimates were in good agreement. Within the 25-meter radius plots, all detections were accurate, as distance estimates were trained with markers of known distance.

Sampling plants, collecting and processing arthropods, observing birds and processing specimens and handling the data took 144 hours, 648 hours, 64 hours and 512 hours, respectively. A total of 1,368 hours of survey labor, across all parts of the biodiversity assessment, were provided. This detailed study ensured that there was adequate energy in the data to uncover patterns in temporal changes in species composition and abundance trends in the different urban morphologies and green roof configurations. Evenness and dominance patterns in the formats of Shannon Wiener indices and the Simpson index were utilized to measure biodiversity. This integrated strategy gave the general assessment of the ecological performance with a particular concentration on green roofs as ambivalent urban spaces that help enhance biodiversity in supposed high-density areas. Table 2 gives a summary of the biodiversity indicators and the methods of measuring them.

Table 2. Biodiversity Indicators and Measurement Methods [25]

Indicator	Description	Measurement Method	Output Metric
Species Richness	Total number of species present	Quadrat / Field Survey	Count (S)
Species Abundance	Number of individuals per species	Quadrat / Transect Sampling	Individuals (N)
Shannon-Wiener Index	Diversity considering richness and evenness	Mathematical Index Calculation	H′
Simpson Index	Dominance and probability of species occurrence	Statistical Calculation	D
Evenness Index	Distribution uniformity of species	Derived from Shannon Index	E
Pollinator Presence	Occurrence of bees, butterflies, etc.	Transect / Visual Observation	Frequency (%)

Indicator	Description	Measurement Method	Output Metric
Arthropod Diversity	Variety of insect species	Pitfall Traps / Sampling	Species Count
Bird Diversity	Avian species richness and activity	Point Count Method	Species Count

Analysis of Statistics

R software version 4.3.2 and SPSS 29.0 were used to do the statistical analysis. Levene's test was used for the homogeneity of variance test between groups and the Shapiro-Wilk test was used to check the normality of the data. Paired t-tests were applied to compare values of conventional and green roofs' microclimatic characteristics in locations where the data displayed normal distribution patterns. If the normalcy assumptions were not met, then the non-parametric test used was the Wilcoxon signed-rank test. Analysis of variance was used to compare the performance of the various roof types (extended, intensive and conventional) at various research sites. Pairwise comparison was done with Tukey's post hoc if there was a significant difference at the 0.05 level of two main effects tests. Effect sizes for ANOVA procedures were estimated using eta-squared for practical relevance beyond the significance and effect sizes for t-tests were estimated using Cohen's d. Temporal patterns were sought in gathered data using autocorrelation function and partial autocorrelation function plots in time series analysis. The within-subjects factor in the repeated-measures ANOVA analysis of diurnal changes was time. Pearson correlation coefficients were used to examine the intercorrelation of various microclimatic features to help elucidate interrelated environmental processes.

Species accumulation curves appropriate for vegan packages in R software were generated to establish if sampling was adequate for collecting biodiversity data. Shannon-Wiener Diversity Indices were calculated using the known formula $H' = -_{2}(pi \times ln(pi))$, where pi is the proportionate abundance of species i for each sample. For assessing dominance patterns, Simpson's diversity index was done with Simpson's diversity index, $D = 1 - \Sigma(pi^2)$. Evenness was calculated according to Pielou's evenness index (1966) so as to get an evenness value of J, where S is the total species richness. After the Kruskal-Wallis mutually affected diversity indices, Dunn's post hoc tests with Bonferroni corrections were used to identify differences in diversity indices for the different types of roof. The α values used for each test were 0.05. The 95% confidence intervals of all the mean values were calculated as a measure of uncertainty. In order to ensure that the sample sizes used were sufficient to detect medium effect sizes around Cohen's d = 0.5, a power analysis was carried out with 80% statistical power and an α = 0.05 significance level.

RESULTS

Microclimate Regulation

Green roof systems and traditional roofs were compared and all the research sites had a high degree of enhancing all the microclimatic features. In green roofs the air temperature and the surface temperature were lower, but the extent to which the temperature reduced also varied, depending on the nature of the roof and the LCZ classification. Figure 1 demonstrates that intensive green roofs had the best cooling effect because they were heavily, densely vegetated and the substrata was deep to improve their mimic effect to augment the evapotranspiration and thermal isolation. In spite of the fact that the green roofs registered low readings of between 31.8 and 33.4°C, indicating an average midday air temperature of between 2.5 and 3.2°C in the traditional roofs, the average air temperature in the center of the day of the green roofs fell between 34.5 and 36.2°C, but the fluctuation in the surface temperatures was more pronounced, with an average reaching peak values to 52.58°C and green roofs remaining 30.38°C and even lower. Additionally, the relative humidity had always been higher in green roofs by 5-12 percent, enhancing the thermal comfort (Figure. 5). Green roofs were deemed to be effective according to the diurnal tendencies so that they were able to regulate the temperature changes by preventing the gain of heat during the day and the protective loss of heat during the night.

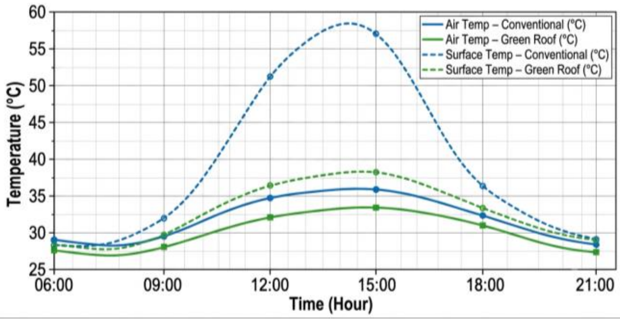

Figure 5. Diurnal Air and Surface Temperature Profiles (Green vs. Conventional Roofs)

Simulation Results

Simulation of the ENVI-met illustrated that there was evident spatial cooling of patterns created by the use of the green roof within various LCZs. The temperatures on the pedestrian floor were relatively lower in the areas that have a green roof intervention, specifically in the very populated metropolitan areas like the LCZ 1. The cooling effect was realized beyond the roof to the air layers around and helped in enhancing the localized thermal comfort. The temperature of 1.5 to 2.8°C (Figure. 6) was prescribed to reduce among the pedestrians in the simulated outcomes, with compact high-rise sites having the most impact. It is worth mentioning that model reliability became significantly verified when compared with field data, yielding the values of correlation (R^2) of 0.86-0.92. Table 3 can be described as the average and statistical value of the desirable changes in microclimate.

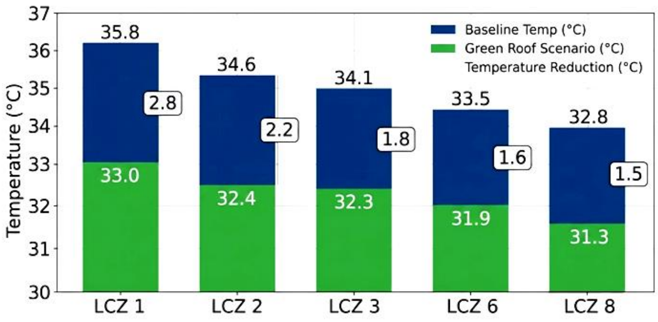

Figure 6. Cooling Impact Across Urban Morphologies

Table 3. Summary of Microclimate Improvements (Mean Values and Statistical Significance)

Parameter	**Conventional Roof**	**Green Roof (Extensive)**	**Green Roof (Intensive)**	**% Improvement**	**p-value**
Air Temperature (°C)	35.2	33.5	32.6	7–9%	<0.01
Surface Temperature (°C)	55.1	37.8	34.2	30–38%	<0.001
Relative Humidity (%)	58.3	63.5	66.2	8–14%	<0.05
Solar Heat Gain (W/m²)	820	540	480	34–41%	<0.01

Biodiversity Enhancement

The urban biodiversity with green roof systems was very high as compared to the conventional roofs. The optimal in terms of species diversity and abundance were intensive green roofs because they had deeper substrates and complex vegetation structure. Nevertheless, intensive roofs were identified to have 25-32 plant species compared to the extended roofs with 12-18 plant species (table 4), contrary to the little vegetation that was observed on normal roofs. Moreover, there was a great enrichment of the insect fauna and insects like bees and butterflies could be commonly found on green roofs. The abundance used in arthropods was also observed to be two and three times greater in the vegetated environments, pointing to the high quality of the habitat. The activity rate of the birds was also much higher in breeds or highly developed environments, especially in the small urban birds, which implies that the environment was more attractive to the ecosystem. The values of biodiversity of other roof types are revealed in Figure 7.

Table 4. Biodiversity Metrics (Species Richness, Shannon Index, Abundance)

Roof Type	**Plant Species (S)**	**Insect Species (S)**	**Bird Species (S)**	**Shannon Index (H′)**	**Total Abundance (N)**
Conventional	0–2	3–5	1–2	0.5	15–25
Extensive	12–18	15–22	4–6	1.8–2.3	120–180
Intensive	25–32	28–36	7–10	2.6–3.2	250–340

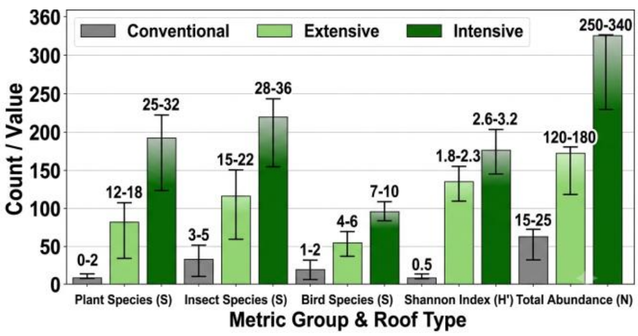

Figure 7. Comparative Biodiversity Indices Across Roof Types

Species Composition

According to the analysis of the composition of species, the native and climate-adapted plant species dominate all the systems of a green roof, particularly those that possess intensive layouts. Authentic grasses, herbs and shrubs were more resistant to erratic monsoon climate and heat and led to increased high survival. This helped in maintaining the ecological functioning and the uniform plant cover in the course of the trial. The species of pollinators like butterflies and bees (Apis spp.) were abundant and it put green roofs in their position as ecological resources as an ecological foraging habitat. Perhaps some level of balance of trophic existed since there were also some herbivores, predators and detritivores in the population of arthropods. The species of the urban setting that were detected were the sunbirds, mynas and sparrows. As a special case, rooftops that were densely covered with various vegetation types were sampled. These results confirm the importance of the green roofs in improving the biodiversity of the urban areas that are densely inhabited and optimizing the ecological networks of such urban areas.

DISCUSSION

Interpretation of Microclimate Results

The findings show that the effect of green roofs is huge in managing microclimates in such humid and tropical places as Chennai. Evapotranspiration, an activity that is more enhanced during high humidity conditions and when radiations of high energy (sun) are emitted, is the main cause of the changes in temperature of air and surface recorded. Vegetation minimizes the level of sensible heat stored in the air because of the experimental purposes of fostering the transfer of latent heat and regulating the temperature of the roofs. Likewise, it has been shown that cooling is affected by type of vegetation and climate based on the contribution of evapotranspiration and the intensive system is superior based on the richness of the biomass and water retention [26]. Besides, it is also stated in the research that green roofs may also positively affect the thermal conditions in urban areas and mitigate the thermal stress along with other technologies like solar arrays [27]. The amounts of cooling recorded in this experiment are consistent with the international standards because the deflection in temperature range is 1-3 C during the ambient temperature and significantly exaggerated at the surface level [28]. The findings validate the use of green roofs as a viable technique of passive cooling in the dense urban environment. The comparative analysis of green roof from various published studies is given in table 5 below.

Table 5. Comparative Analysis of Green Roof Studies

Study	Location/Climate	Focus Area	Findings
Current Study	Tropical monsoon	Microclimate & biodiversity	Air temp ↓2.5–3.2 °C; surface temp ↓15 °C; relative humidity ↑5–12%; species richness and Shannon diversity indices improved; intensive roofs (25–30 cm substrate) outperformed extensive systems.
[29] Cascone et al. (2019)	Mediterranean (Italy)	Evapotranspiration & cooling	Roof surface temp ↓12–15 °C; air temp ↓2–3 °C. Comparable cooling effect; validates evapotranspiration as main driver in both climates.
[30] Dwivedi & Mohan (2018)	Hyderabad, India	UHI mitigation	LST reduced by 2.8–4.1 °C. Chennai results align, adding field validation with surface temp data.
[31] Cai et al. (2025)	Shenzhen, China	ENVI-met simulation	Intensive roofs lowered pedestrian temps by 1.5–2.8 °C; LAI critical. Chennai ENVI-met validation showed similar cooling (R^2 0.86–0.92).
[32] Wang et al. (2022)	UK/US systematic review	Biodiversity	Arthropod & plant diversity ↑, but cannot replace natural habitats. Chennai biodiversity gains consistent, but emphasize native species for resilience.
[33] Coulibaly et al. (2023)	Global review	Biodiversity design	Substrate depth & heterogeneity key for arthropod diversity. Chennai intensive roofs (25–30 cm substrate) confirmed this.
[34] Tiago et al. (2024)	Lisbon, Portugal	Birds & arthropods	Green roofs supported >25 bird species. Chennai bird surveys showed comparable avian richness.
[35] Heim et al. (2023)	Canada	Plant traits & ecosystem services	Functional diversity improved stormwater retention & biodiversity. Chennai's coir/biochar substrates enhanced water retention and vegetation growth.
[36] Saqib et al. (2024)	Global resilience framework	Policy & resilience	Subsidies & integration into resilience frameworks essential. Chennai study echoes this, contextualized for Indian policy (GRIHA/IGBC, tax incentives).

Biodiversity Implications

The results validate that green roofs are significant ecological reserves to the densely populated areas. The species that can be found in these systems, such as plants, insects and birds, are a number of types given the addition of plant layers. The ecological potential of the green roofs to mitigate the habitat loss put out through urbanization is the result of the vegetation richness and increase in species indexes. According to the veritable literature, green rooftops have the potential to significantly boost the biodiversity of the city, especially when they are designed and equipped with sophisticated features and plant species proliferations [37]. Further, the factors that affect the ecological efficiency of green roofs would be the depth of the substrate used, the kind of plants and the way of harnessing the green roof developments [38]. In this research, ecological stability and survival with the focus on choosing vegetation based on the situation were promoted due to the utilization of native and climate-tolerant plants. In most cases, green rooftops provide biodiversity conservation in the urban regions in the cities by providing habitat and connectedness of the ecosystem.

Design Implications

The comparison between intensive green roofs determines the significant design factors to be taken into account in the performance maximization. Their deeper substrates and more varied flora-intensive systems have done better in regard to intensity of biodiversity augmentation besides heat regulation. A lot of the benefits of this are, however, connected with higher maintenance and cost of starting and higher structural load. Big systems, on the other hand, provide a cheaper and less heavyweight one; however, with a lesser thermal and eco-efficiency. The literature states that some of the factors to be considered during the choice of the type of a green roof should be structural limitations, economic feasibility and performance [39]. In addition, it is also true that green roofs are becoming increasingly popular as a passive ecological type of infrastructure when properly composed and they may lead to sustainable urban building [40]. Consequently, long-term sustainability and planned uses, among other site-specific variables, have to be considered in decision-making. It is possible that the hybrid solution to the aspects of the two extended and intensive features can provide the most suitable compromise in cost-performance in cities in the tropical environment.

Chennai-Specific Insights

The paper offers useful details about the efficacy of green roofing in the particular climate of Chennai. Its performance within the monsoon season and the composition of substrates do demonstrate the fact that the green roofs are resistant to heavy rain and moisture, but the composition of substrates also comprises one of the most important reasons regarding water purification and drainage. The earlier research on green roofs has the capability to enhance the power efficiency of an edifice and lower the cooling load under the local weather in Chennai [41]. There is also a need to develop adaptive design solutions, as seasonal adaptability as well as urban surface aptitude are compounded to affect the thermal activities [42]. It is also revealed through the findings that there are differences in the performance of a green roof offered by the different LCZs, with highly developed urban areas enjoying more cooling advantages. In addition, the value of green roofing in regard to storm water management and climate resilience is also justified by the fact that the encounter with the increased rain has been accumulating in the major cities of the coastlines [43]. These results give reasons to believe in the need for the place-based and climate-centered design solutions.

Policy Implications

Such policies must be incorporated in the city policies to multiply the benefits of the green roofs in fast-growing cities like Chennai. The urge and incentive of the green roofs of the Chennai Master Plan may foster extensive application and could help mitigate the urban heat. The green building rating systems and other sustainable building practices can be critiqued and be appreciated on standardized frameworks that are provided by the green building rating systems like GRIHA and IGBC [44]. The case of the Indian situation, as compared to the various grading systems, reveals the extent to which these grading systems would prove to be efficient in fostering environmental sustainability, water conservation and energy efficiency [45]. Further, the green grading systems will also play a role in the development of mitigation and adaptation measures against the problem of climate change by the promotion of natural solutions [46]. This may be through the form of regulations, tax breaks and subsidies that can be implemented in the policy implementation in a much faster way. All in all, the potential of implementing green roofing into the urban planning policy can make the intentions of sustainable development better, make the urban environment more livable and create climate-resistant buildings. Figure 8 shows the foundation of the expansion of the application of green roofs in the Indian cities.

Figure 8. Framework for Scaling Green Roof Implementation in Indian Cities [Source: Author]

Study Limitations

It is important to note that this research has a number of limitations, which should be considered when analyzing the results. The four-month monitoring window was used to track only the monsoon season (between June and September 2025). This seasonal data restriction may not fully represent the actual thermal performance or biodiversity of the green roof over the entire year, as cooling benefits could be more significant during the hot summer months of the year (March to May), or the cycling of the performance dynamics of the green roof could be vastly different in the colder winter months (December to February). The geographical area covered in the study is only Chennai and its specific tropical moist monsoon climate, which cannot be applied to the other cities of India with different climates, like the semi-arid climate of Delhi, the temperate climate of hill stations, the coastal humid climate of Mumbai and Kolkata, etc. The Local Climate Zone (LCZ) typologies analyzed only included a few urban typologies like LCZ 1, LCZ 3, LCZ 6 and LCZ 8 and other major urban typologies present in many cities in India, such as compact mid-rise or lightweight low-rise, were not included in the analysis.

The green roofs in research were quite young—the oldest had no more than two years of operation. Due to this limitation, factors like long-term performances, vegetation growth, settling rates of the substrates, maintenance needs and long-term structural impacts are yet unknown. Research currently does not address questions regarding plant succession patterns, performance degradation and longevity of reported benefits compared to that of a normal building life of 20-50 years. Due to the limited number of samples, only three different types of green roof configurations with a total of eight locations were analyzed. This allowed for the identification of medium-sized effects, but larger numbers in samples may have led to the identification of smaller but potentially meaningful differences and increased the confidence in the generalizability of the results. The biodiversity assessment might not have captured any significant microbes, soil fauna, or cryptic species, such as protected bird species that have a large potential role in ecosystems.

The simulation model, ENVI-met, has its limitations and even though it has been verified using the field data, it is still not capable of simulating the complicated urban microclimate processes. Assumptions and uncertainties regarding plant properties, thermal properties of the substrate and building interactions may not be fully reflected in the dynamic model of the green roof system during severe weather conditions or when it is under different moisture conditions. While the 0.5-meter grid resolution of the data is appropriate for studies on a neighborhood scale, it could undersample important fine-scale temperature and humidity changes occurring at the plant-substrate interface. The study did not make a comprehensive assessment of the economic and social aspects. Factors such as cost-benefit evaluations, maintenance requirements, perspectives of stakeholders and social and political acceptability were not covered in this study, which are all key aspects in the implementation and adoption of policies. Furthermore, the study did not investigate potential problems that may arise with the green roofs in a tropical climate, including increased load, waterproofing issues and insect issues.

The materials examined on possible substrate compositions were based on locally available materials (compost, charcoal and coconut coir). Also, the suitable tropical substrates could not be selected and the optimal mixing ratio, which could further enhance the performance, was not examined in the research, although these materials yielded good results. The species performance assessment was not systematic and new plant communities were explored and the selection of plant species was focused only on readily available native and adapted plant species. The instrumentation in the field used did not allow measurements to be made with sufficient accuracy: temperature and humidity were measured to 0.18°C and 2.5% accuracy, respectively. While these degrees of accuracy are suitable for studies of microclimate, they would blur on a time scale small trends and on a spatial scale a small variation that may be of great significance for different types of green roofs. While the point-based measuring method is able to provide more detailed time-based data, it was not able to show sufficient spatial variability over entire roof surfaces.

As non-urban control sites were not included in the research design, there was a difficulty in determining the actual ecological value of these installations when considered in the larger landscape as well as the ability to compare the biodiversity of green roofs with that of natural ecosystems. Additionally, potential ecological connections between green roofs and other urban green spaces potentially influencing colonization patterns and the long-term biodiversity sustainability of green roofs were not explored. However, these constraints suggest great opportunities for future research, including studies on a multi-year/multi-seasonal basis, at larger spatial scales, economic considerations across a more extensive Indian climate zone and in relation to larger urban ecological networks. Despite these limitations, the findings impart the knowledge of the performance of green roofs in tropical urban landscapes and pave the path for supporting the evidence-based policy recommendations in fast-emerging urban cities in India.

CONCLUSION AND FUTURE RECOMMENDATIONS

This paper has shown that the green roofs are natural control programs that can be feasible in a city like a tropical rapidly urbanizing city such as Chennai that is susceptible to an urban heat island and also the biodiversity of the city is on the rise. A dramatic decrease comprising green roofs included in the field measurements and ENVI-met simulations consists of the reduction in air and surface temperature, relative humidity and microclimatic conditions. The intensive systems are in fact more productive, as the depth of the substrates actually is higher as well as the growth density. Another finding is that the ecological value of green roofs, such as the increase of the richness, abundance and diversity index of species, is proven by the findings with the implementation of native vegetation. The research also shows that the variables of local climate zone can affect the efficiency of green roofs and the design solutions of the design should be developed individually. Practically, the implementation can be more realistic and sustainable through the locally obtained and cycling material implementation. To gain a better understanding of the temporal variation, especially during seasons when the heat and precipitation are extremely high, a further study that involves a prolonged observation in many seasons would be useful. In addition, the standardized design structures, which comprise efficiency-based substrate composition and native species, must be established in the tropical areas. Further research devoted to the issue of sustainability is required in order to increase the process of multi-functionality through the attempts to unite the green roofs with other systems of the city landscape, i.e., with the solar panels and collections of rainwater. The policymakers should also keep regulatory frameworks, incentives and contributions in urban master planning at the top of the priority list in an effort to expand the adoption. The green roofs, period and incidences, all said and done, are a viable solution to the green urban architecture, climate-friendly.

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