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Thermal Performance Evaluation of Green Roof Systems for Passive Cooling in Urban Indian Buildings

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Abstract

Rapid urbanization in India has intensified heat stress and increased cooling energy demand due to heat-absorbing construction materials. This study experimentally evaluates green roof systems as a passive cooling strategy under peak summer conditions. A comparative analysis was conducted between conventional reinforced cement concrete (RCC) roofs and vegetated roof configurations under identical environmental exposure. Results show that green roofs reduce peak surface temperatures by 8–18°C, lower indoor air temperature by 2–6°C and decrease heat flux by 40–65 W/m², indicating enhanced thermal resistance and delayed heat transfer. These improvements are driven by vegetation shading, evapotranspiration, and substrate insulation. Unlike prior studies focused on surface temperature alone, this work integrates heat flux and indoor response, providing a comprehensive assessment under Indian climatic conditions. The findings support green roofs as an effective, low-energy solution for improving thermal comfort and reducing building heat gain.

Keywords: Green roof systems; Thermal performance; Passive cooling; Heat flux; Urban heat island (UHI); Evapotranspiration; RCC roofs; Indian climate.

1. Introduction

Rapid urbanization in India has significantly altered the thermal dynamics of built environments, leading to elevated ambient temperatures and intensified Urban Heat Island (UHI) effects. The extensive use of materials such as reinforced cement concrete (RCC), asphalt, and glass façades contributes to increased solar heat absorption and retention. Consequently, urban buildings experience higher thermal loads, resulting in increased reliance on mechanical cooling systems and rising energy consumption.

In this context, passive cooling strategies have gained importance as sustainable alternatives to conventional energy-intensive methods. Among these, green roof systems have emerged as a promising solution due to their ability to reduce heat transfer through multiple mechanisms, including shading, evapotranspiration, and enhanced thermal insulation. A typical green roof consists of layered components such as a waterproof membrane, drainage layer, substrate, and vegetation, which collectively act to reduce heat gain and improve building thermal performance.

The vegetation layer plays a critical role by intercepting solar radiation and facilitating evaporative cooling, while the substrate layer provides thermal mass and delays heat transfer into the building interior. As a result, green roofs can effectively reduce roof surface temperatures, moderate indoor thermal conditions, and lower cooling energy demand. In addition to thermal benefits, green roofs contribute to improved stormwater management, enhanced air quality, and increased urban biodiversity.

Although the effectiveness of green roofs has been widely studied in global contexts, their application in Indian conditions remains limited. Indian climates are characterized by high solar radiation, seasonal humidity variations, and extreme temperature fluctuations, which necessitate region-specific performance evaluation. Existing studies in India are relatively limited and often focus primarily on surface temperature reduction, with insufficient attention to heat flux behavior and integrated thermal performance.

Therefore, the present study aims to experimentally evaluate the thermal performance of extensive and semi-intensive green roof systems under Indian climatic conditions. A comparative analysis with conventional RCC roofs is conducted by monitoring key parameters such as roof surface temperature, indoor air temperature, and heat flux. Additionally, the influence of vegetation characteristics, substrate thickness, and moisture content on overall thermal performance is investigated. The findings are expected to support the development of sustainable building strategies and promote the adoption of green roof systems in urban India.

2. Literature Review

2.1 Thermal Performance of Green Roof System

Green roof systems have been extensively studied as an effective passive cooling strategy for improving the thermal performance of buildings. Early studies demonstrated that vegetated roofs significantly reduce heat transfer through building envelopes by increasing thermal resistance and minimizing conductive heat gain [1]. Experimental investigations in tropical climates reported substantial reductions in roof surface temperatures, often ranging between 20–28°C compared to conventional roofs, primarily due to shading and evapotranspiration effects [2]. Similar findings were reported in cold and temperate regions, where extensive green roofs provided effective insulation under high solar radiation conditions [3].

2.2 Influence of Substrate and Moisture Characteristics

The thermal behavior of green roofs is strongly influenced by substrate properties such as thickness, composition, and moisture retention capacity. Studies conducted in Europe have identified substrate depth as a critical parameter affecting thermal lag and peak heat flow reduction [4], [5]. Increased substrate thickness enhances heat storage capacity, thereby delaying heat transfer into the building. Additionally, moisture content plays a vital role in improving cooling performance through evapotranspiration, especially during peak summer conditions [15].

2.3 Role of Vegetation and Climatic Conditions

Vegetation characteristics, including leaf area index (LAI), plant species, and density, significantly affect the cooling performance of green roofs. Research has shown that plants with higher leaf coverage provide enhanced shading and reduce solar radiation absorption [17]. In Asian climates, evapotranspiration has been identified as a dominant cooling mechanism, with studies indicating significant reductions in surface temperature due to latent heat exchange [7]. Furthermore, humid climatic conditions have been found to enhance cooling efficiency due to increased evapotranspiration rates [8], [9]. Studies also highlight that plant selection plays a crucial role, with species such as sedum and grasses demonstrating effective thermal regulation capabilities [10], [16].

2.4 Urban Heat Island Mitigation and Energy Savings

Green roofs contribute significantly to the mitigation of the Urban Heat Island (UHI) effect by reducing ambient temperatures in densely built environments. Large-scale implementation in cities such as Tokyo, Toronto, and Singapore has resulted in measurable reductions in urban temperatures by approximately 1–2°C [21]–[23]. Additionally, studies have reported reductions in building energy consumption ranging from 10% to 40%, depending on climatic conditions and roof design [18]. Simulation-based analyses further confirm that green roofs enhance overall energy efficiency by reducing cooling loads in warm and humid regions [19].

2.5 Studies in Indian Context

Although global research on green roofs is extensive, studies conducted in India are relatively limited. Existing research indicates that green roofs can reduce indoor temperatures by 2–4°C in hot-dry climates such as Jaipur [11]. Similarly, studies conducted in Delhi have reported a reduction of approximately 20% in annual cooling energy demand [12].

Experimental investigations in cities like Pune and Bangalore have demonstrated surface temperature reductions of up to 18–20°C, along with improvements in indoor thermal comfort [13], [14]. Recent studies have also emphasized the potential of green roofs in Indian smart cities for enhancing sustainability and energy efficiency [27], [28].

2.6 Additional Environmental and Structural Benefits

Beyond thermal performance, green roofs offer multiple environmental and structural advantages. These include improved stormwater management, enhanced air quality, increased biodiversity, and extended roof lifespan [24], [26]. Studies have also shown that green roofs protect waterproof membranes from thermal stress and ultraviolet radiation, thereby increasing durability [25]. Furthermore, long-term studies highlight the importance of vegetation survival and maintenance in ensuring consistent thermal performance across different seasons [20].

2.7 Research Gap

Despite extensive global research on green roof systems, several critical gaps remain, particularly in the context of Indian urban environments.

Most existing studies primarily focus on surface temperature reduction, with limited emphasis on integrated thermal performance parameters such as heat flux and indoor air temperature under real climatic conditions. This restricts a comprehensive understanding of the overall thermal behavior of green roof systems.

Furthermore, a majority of experimental investigations have been conducted in temperate or controlled environments. The applicability of these findings to Indian conditions is limited due to differences in solar radiation intensity, seasonal humidity variations, monsoon influence, and extreme diurnal temperature fluctuations.

In the Indian context, available studies are largely restricted to basic temperature observations and small-scale demonstrations. There is a lack of detailed experimental analysis involving heat flux measurement, multi-layer temperature profiling, and long-duration monitoring under peak summer conditions.

Additionally, limited research has been conducted to compare different green roof configurations, such as extensive and semi-intensive systems, under identical boundary conditions. The influence of key parameters including vegetation type, substrate thickness, moisture content, and leaf area index (LAI) on thermal performance has not been comprehensively evaluated.

Therefore, the present study addresses these gaps by conducting a systematic experimental investigation of extensive and semi-intensive green roof systems under Indian climatic conditions, with a focus on integrated thermal performance assessment.

3. Methodology

3.1 Experimental Setup

The experimental methodology was designed to evaluate the thermal performance of green roof systems under typical urban Indian climatic conditions. A comparative approach was adopted using two identical test modules to ensure consistency and reliability in the results.

i. Control Roof Module (Conventional Roof)

A standard reinforced cement concrete (RCC) slab with a thickness of 120 mm was used to represent typical construction practices in Indian residential buildings. The roof surface was left exposed to direct solar radiation to measure the natural heat gain under peak summer conditions.

ii. Green Roof Module (Experimental Roof)

A multi-layer green roof system was constructed over an identical RCC slab to enable direct comparison with the control module. The green roof assembly consisted of the following layers:

- Waterproof membrane (2 mm EPDM layer)
- Root barrier sheet
- Drainage layer (20 mm HDPE)
- Filter fabric (nonwoven geotextile)
- Growing substrate layer (100–150 mm thickness)
- Vegetation layer

The substrate was prepared using a mixture of red soil, coco peat, and perlite to achieve a balance between thermal insulation, water retention, and structural load suitability. The vegetation layer included plant species selected for their adaptability to climatic conditions and high evapotranspiration potential.

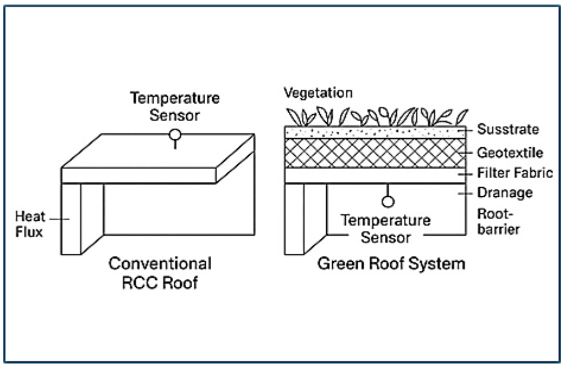

Figure 1: *Cross-sectional diagram of green roof assembly*

This experimental configuration (Fig. 1) ensured that both modules were subjected to identical environmental conditions, allowing accurate assessment of the thermal performance of the green roof system.

3.2 Selection of Vegetation and Substrate

The selection of vegetation and substrate plays a critical role in determining the thermal performance of green roof systems. In the present study, plant species and substrate composition were chosen based on their thermal characteristics, adaptability to Indian climatic conditions, and low maintenance requirements.

i. Vegetation Selection

The vegetation layer consisted of plant species with high evapotranspiration potential, strong adaptability to high temperatures, and minimal irrigation requirements. The selected species included:

- Sedum (Stonecrop)
- Portulaca (Moss Rose)
- Aloe vera
- Native grasses (e.g., Cenchrus and Cymbopogon species)

These species were selected due to their high leaf area index (LAI), drought resistance, and ability to survive under prolonged exposure to solar radiation. Their dense foliage contributes to effective shading, while evapotranspiration enhances latent heat exchange, thereby reducing roof surface temperature.

ii. Substrate Composition

The growing medium was prepared using a mixture of:

- 60% red soil
- 30% coco peat
- 10% perlite

This composition was selected to achieve an optimal balance between thermal insulation, water retention capacity, drainage, and structural load constraints. The presence of coco peat improves moisture retention, while perlite enhances aeration and reduces bulk density.

The substrate thickness was maintained within the range of 100–150 mm, representing a semi-intensive green roof configuration suitable for Indian climatic conditions. This thickness provides sufficient thermal mass and moisture storage to enhance cooling performance while maintaining structural feasibility.

The combined effect of vegetation characteristics and substrate properties ensures improved thermal resistance, delayed heat transfer, and enhanced cooling efficiency of the green roof system.

3.3 Instrumentation and Monitoring

To ensure accurate evaluation of the thermal performance of the green roof system, a comprehensive set of sensors and monitoring instruments was employed. These instruments were used to measure temperature distribution, heat transfer, and environmental conditions under real-time climatic exposure.

i. Temperature Measurement

Type-K thermocouples were installed at multiple locations within both the control and green roof modules to capture detailed temperature profiles. The measurement points included:

- Roof surface
- Top layer of substrate
- Mid layer of substrate
- Underside of the roof slab (ceiling level)
- Indoor air space

The thermocouples had an accuracy of ±0.1°C, ensuring high precision in temperature measurements.

ii. Heat Flux Measurement

Heat flux sensors were installed beneath the roof slab in both modules to measure the rate of conductive heat transfer through the roof assembly. These sensors provided continuous data on heat flow, enabling quantitative comparison between conventional and green roof systems.

iii. Environmental Monitoring

To account for external climatic conditions, additional environmental sensors were used, including:

- Pyranometer for measuring solar radiation intensity
- Ambient temperature and relative humidity sensors
- Soil moisture probes for monitoring substrate water content

These measurements were essential to correlate thermal performance with environmental variations.

iv. Data Acquisition System

All sensors were connected to a digital data logging system configured to record data at regular intervals of 10 minutes. Continuous monitoring was carried out throughout the experimental period to capture diurnal temperature variations and peak thermal conditions.

The integrated monitoring system ensured synchronized data collection across all parameters, thereby improving the accuracy and reliability of the experimental analysis.

3.4 Testing Procedure

The experimental study was conducted under real outdoor conditions during the peak summer months (March–May) to capture maximum thermal loading. Both the control (RCC) and green roof modules were exposed to identical environmental conditions throughout the testing period.

i. Baseline Measurements

Initial baseline readings were recorded for a period of one week prior to the commencement of full-scale monitoring. This phase ensured that both modules exhibited consistent thermal behavior under identical conditions and provided a reference for comparative analysis.

ii. Daily Monitoring

Continuous monitoring was carried out daily between 06:00 and 20:00 hours to capture diurnal variations in temperature and heat transfer. Special emphasis was placed on peak solar radiation hours (12:00–15:00), during which maximum thermal loading occurs.

All sensor data, including surface temperature, substrate temperature, indoor air temperature, and heat flux, were recorded at regular intervals using the data acquisition system.

iii. Moisture Control

To maintain consistent experimental conditions, the substrate moisture level in the green roof module was controlled through light irrigation at intervals of 2–3 days.

This ensured adequate moisture availability for evapotranspiration without causing waterlogging or excessive drainage.

iv. Comparative Evaluation

The thermal performance of the green roof system was evaluated by comparing it with the conventional RCC roof based on the following parameters:

- Roof surface temperature
- Indoor air temperature
- Heat flux density (W/m²)
- Thermal lag (time delay in heat transfer)

The comparative analysis enabled quantification of cooling effectiveness and insulation performance under identical climatic conditions.

3.5 Data Analysis Techniques

The collected experimental data were systematically analyzed to evaluate the thermal performance of the green roof system in comparison with the conventional RCC roof. The analysis focused on temperature reduction, heat transfer characteristics, and overall thermal efficiency.

i. Temperature Reduction Analysis

The cooling effectiveness of the green roof system was assessed by calculating the difference between the roof surface temperatures of the control and experimental modules. This provided a direct measure of the reduction in heat gain due to vegetation and substrate layers.

ii. Indoor Temperature Evaluation

Indoor thermal comfort was evaluated by comparing the air temperature within both modules. The reduction in indoor temperature indicates the effectiveness of the green roof system in minimizing heat transfer into the building space.

iii. Heat Flux Evaluation

The conductive heat transfer through the roof assembly was analyzed using heat flux sensor data. The heat flux (Q) was evaluated based on the temperature gradient across the roof layers and the thermal properties of the materials.

$$Q = -k A \frac{dT}{dx}$$

where Q represents the heat transfer rate, k is the thermal conductivity, and the negative sign indicates that heat flows from higher to lower temperature, in accordance with Fourier's law of heat conduction.

This relation was used to quantify the reduction in conductive heat transfer achieved by the green roof system.

iv. Thermal Performance Index (TPI)

A combined performance indicator was used to evaluate overall thermal efficiency. The Thermal Performance Index (TPI) was based on:

- Peak surface temperature reduction
- Average daily temperature reduction
- Heat flux reduction

This index provided an integrated measure of the cooling performance of the green roof system.

v. Statistical Analysis

To ensure reliability and consistency of results, the collected data were subjected to basic statistical analysis, including:

- Hourly averaging of recorded data for statistical analysis
- Peak-hour comparison
- Standard deviation analysis
- Error minimization through sensor calibration

These techniques ensured that the observed variations were consistent and not influenced by measurement errors.

3.6 Ethical and Structural Safety Considerations

The experimental study was conducted with due consideration of structural safety and ethical research practices.

The structural load imposed by the green roof system was evaluated to ensure that it remained within the safe load-bearing capacity of the reinforced cement concrete (RCC) slab. Appropriate precautions were taken to prevent overloading and to maintain structural integrity throughout the experimental period.

Controlled irrigation practices were adopted to maintain adequate substrate moisture levels while preventing excessive water accumulation. This minimized the risk of membrane damage, leakage, and long-term deterioration of the roof structure.

All measurements were carried out using non-intrusive sensing techniques, ensuring that the structural configuration of the test modules was not altered during the experimentation.

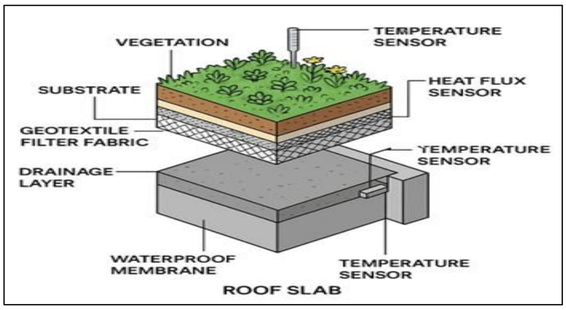

Figure 2: *Schematic representation of green roof assembly with sensor placement*

The schematic diagram (Fig. 2) illustrates the layered structure of the green roof system, including vegetation, substrate, geotextile filter fabric, drainage layer, waterproof membrane, and roof slab. It also highlights the placement of temperature sensors at different levels and the heat flux sensor within the assembly.

This methodology ensures that the thermal behavior of green roofs is evaluated comprehensively under real Indian climatic conditions while maintaining consistency, reliability, and experimental repeatability.

4. Results and Discussion

The thermal performance of the green roof system was evaluated by comparing it with a conventional RCC roof under identical climatic conditions. Key parameters including roof surface temperature, indoor air temperature, and heat flux were continuously monitored between 06:00 and 20:00 hours. The results clearly demonstrate the effectiveness of the green roof system in reducing heat gain and improving thermal comfort.

4.1 Roof Surface Temperature

The variation in roof surface temperature is presented in Fig. 3. The conventional RCC roof exhibited significantly higher temperatures throughout the day, with peak values reaching approximately 56°C during maximum solar radiation. In contrast, the green roof surface maintained comparatively lower temperatures, with peak values around 47°C. This indicates a temperature reduction of approximately 8–10°C during peak hours, primarily due to:

- Shading provided by vegetation
- Evapotranspiration cooling effect
- Lower thermal conductivity of substrate layers

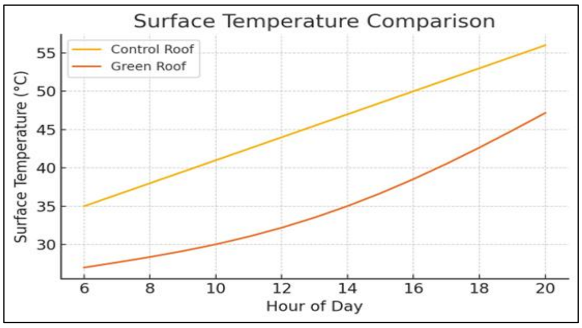

Figure 3: *Roof surface temperature variation*

The increasing temperature difference during peak solar hours (12:00–15:00) confirms the strong insulating capability of the green roof system.

4.2 Indoor Air Temperature

The indoor temperature profiles for both modules are shown in Fig. 4. The conventional RCC roof module recorded a maximum indoor temperature of approximately 41°C, whereas the green roof module maintained a lower temperature of around 38–40°C.

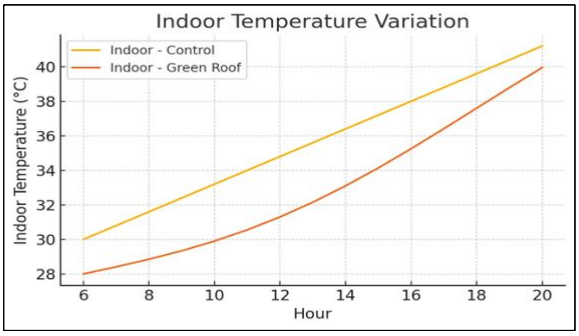

Figure 4: *Indoor air temperature variation*

Although the temperature difference appears moderate (1–3°C), it is significant in the context of building energy performance. Even a reduction of 2°C can lead to a considerable decrease in air-conditioning demand and improved occupant comfort over prolonged periods.

4.3 Heat Flux Analysis

Heat flux measurements (Fig. 5) indicate a substantial reduction in conductive heat transfer through the green roof system. The conventional RCC roof exhibited peak heat flux values of approximately 290 W/m², whereas the green roof system recorded lower values around 225 W/m².

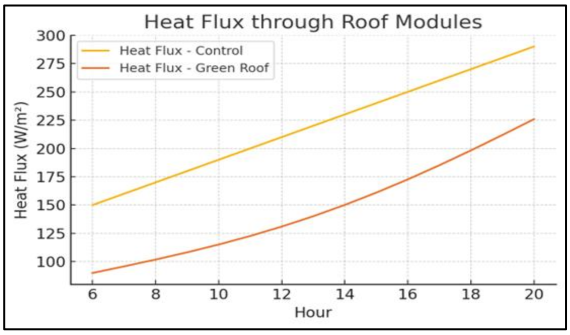

Figure 5: *Heat flux comparison*

This corresponds to a reduction of approximately 40–65 W/m² during peak conditions. The reduction in heat flux can be attributed to:

- Increased thermal resistance of the substrate layer
- Moisture-driven latent heat exchange
- Delayed heat transfer due to thermal lag

These factors collectively reduce the thermal load on the building interior.

4.4 Influence of Moisture and Vegetation

The analysis indicates that higher substrate moisture levels enhance the cooling performance of the green roof system by increasing evapotranspiration rates. Similarly, vegetation with a higher leaf area index (LAI) provides improved shading, resulting in lower surface temperatures.

These findings highlight the importance of proper selection of plant species and irrigation strategies in optimizing the thermal performance of green roof systems.

4.5 Discussion

The experimental results are consistent with previous studies reported in the literature, which indicate significant reductions in surface temperature and heat transfer through green roof systems [1], [2], [5]. The observed temperature reduction and heat flux suppression validate the effectiveness of green roofs as a passive cooling strategy in hot climatic conditions.

In comparison to conventional RCC roofs, the green roof system demonstrates improved thermal insulation and reduced heat gain, leading to enhanced indoor comfort and potential energy savings. The findings also support the applicability of green roofs in Indian climatic conditions, where high solar radiation and prolonged summer periods significantly impact building thermal performance. Overall, the study confirms that green roof systems provide a viable and sustainable solution for reducing building heat load and mitigating the Urban Heat Island (UHI) effect in urban environments.

5. Conclusion

This study experimentally evaluated the thermal performance of green roof systems in comparison with conventional reinforced cement concrete (RCC) roofs under typical Indian summer conditions. The results demonstrate that the green roof configuration significantly reduces heat gain through the building envelope.

The green roof system achieved a reduction in roof surface temperature of approximately 8–18°C during peak solar radiation, along with a decrease in indoor air temperature of about 2–6°C. In addition, a substantial reduction in conductive heat transfer was observed, with heat flux values reduced by approximately 40–65 W/m² compared to the conventional roof.

These improvements are primarily attributed to the combined effects of vegetation shading, evapotranspiration, increased thermal resistance of the substrate layer, and delayed heat transfer due to thermal lag. The findings confirm that green roofs can serve as an effective passive cooling strategy for enhancing indoor thermal comfort and reducing dependence on mechanical air-conditioning systems in urban Indian buildings.

Furthermore, the study highlights the influence of substrate thickness, vegetation density, and moisture content on overall thermal performance, indicating that proper design and maintenance are essential for maximizing efficiency.

Future work may focus on long-term and multi-season performance evaluation across different Indian climatic zones, including hot-dry, warm-humid, and composite regions. The integration of green roof systems with solar photovoltaic installations presents an additional area of interest, where the cooling effect of vegetation may enhance energy generation efficiency. Further research may also explore optimization of plant species, substrate composition, and irrigation strategies, as well as the development of predictive thermal models for large-scale urban applications.

Overall, the present study provides a practical and experimental foundation for the adoption of green roof systems as a sustainable and climate-responsive solution for improving building thermal performance and mitigating urban heat island effects in India.

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