

GREEN ROOF: IMPACT ON INDOOR TEMPERATURE AND THERMAL COMFORT – A CASE STUDY

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ABSTRACT

Urban expansion is replacing the forests and suburban regions with non-permeable surfaces, leading to increased temperatures. Thus, sustainable building and construction strategies are required to decrease urban heat and enhance indoor thermal comfort. Green roofs implementation Strategy comes as a viable option which Places greenery on rooftops and can reduce temperatures and improve thermal comfort, particularly in hot, humid environments. This study aims to analyze the variations in temperature and thermal efficiency between green roofs and traditional roofs. Essential factors, including surrounding temperature, fluctuations in indoor temperature, and relative humidity (%), roof surface temperature and CO₂ concentration were assessed using digital thermometers, hygrometers and NDIR sensors. The measurements were conducted on identical top floors during both day and night to ensure consistency and accuracy. The results show significant variations in temperature, humidity and CO₂ concentrations between green and conventional roofs. These findings highlight green roofs as a sustainable approach for enhancing the indoor environment, promoting occupant well-being, and reduced energy demands. The findings showcased that implementation of green roofs is a sustainable and effective solution to improve indoor thermal conditions, support environmentally responsive building design and reduce energy consumptions in rapidly growing urban centers. The findings also demonstrate the potential of green roofs as an integrative solution that addresses environmental, social, and economic challenges associated with urban heat and resource consumption, thereby encouraging their wider adoption in sustainable building practices.

Keywords: *Green roof; Indoor thermal comfort; Temperature variance; One-to-one interview; Energy efficiency in buildings.*

1. INTRODUCTION

1.1 Background

Global warming, a topic of current interest, is a serious concern for many people worldwide. Urbanization, industrialization, and deforestation significantly contribute to global warming, which hurts the indoor environment and the comfort levels of occupants. Urbanization in developed countries is predicted to reach approximately 83% by the end of 2030 (Mohammad et al.,2018). Buildings account for one-third of global greenhouse gas emissions (Uri et al., 2014). Due to the growth of large cities and urban areas, the problem is becoming increasingly severe as artificial surfaces replace natural surfaces. As a result, this causes a significant disturbance to the function of trees that shade the sun's rays throughout the day and retain heat at night. This results in more temperature fluctuations throughout the planet (Zaron et al., 2016). To alleviate the negative impacts of urbanization, expanding green spaces, particularly by installing rooftop gardens, emerges as a highly effective solution.

1.2 Green Roof

Green roofs are also named “eco-roofs”, “living roofs”, “cool roofs”, or “rooftop gardens”, which involve the installation of vegetation and plants on rooftops (Mohammad et al.,2018; Uri et al., 2014). These roof systems vary from simple plant cover to complex parks. A typical green roof is composed of various components, including vegetation, a filter layer, insulation, substrate, a root barrier, waterproofing membranes, and drainage materials (Mohammad et al., 2018). Green roofs offer numerous environmental and socio-economic benefits, including managing stormwater, promoting urban vegetation and extending roof life, providing habitats for wildlife, enhancing air quality, improving quality of life, reducing building energy consumption and Carbon footprints, creating recreational opportunities, and enhancing roof aesthetics (Chow et al., 2013).

Despite the known benefits of green roofing systems, detailed data and analyses on their thermal performance and impact on occupant satisfaction in subtropical climates are notably scarce. Understanding the efficacy of green roofing in warm, humid climates is essential for developing sustainable urban cooling strategies. This study seeks to fill the gaps by investigating the differences in the living experiences of the occupants. It also aims to qualitatively measure the thermal comfort of the occupants through well-conducted interviews. Additionally, the focus is on providing empirical data to demonstrate the differences in air temperature and humidity between two buildings with traditional and green roofing systems. This dual approach thoroughly explains how green roofs affect indoor climate and resident well-being. Ultimately, the aim is to demonstrate the superior aspects of green roofing systems compared with traditional roofing systems in terms of indoor air quality, thermal comfort, and other environmental and socio-economic benefits.

1.3 Global Perceptions, Local Practices and Challenges

Past studies have shown the effectiveness of implementing green roof strategies in reducing indoor temperatures, enhancing thermal comfort and reducing energy consumptions particularly in Europe, North America and East Asia (Chow et al., 2013). Even in some developed regions of the world, green roof strategy is supported by urban policies and incentive programs. However, in south-asia like Bangladesh, many other countries have limited adoption of this strategy and mostly are small scaled. In Bangladesh, cities like Rajshahi has limited Green roofing implementation as widespread use of this strategy is hindered by high initial costs, lack of favourable incentives and policies, lack of technical knowledge and public awareness.

2. METHODOLOGY

This investigation focused on experimental buildings located in Rajshahi, a mid-sized city located in the northern part of Bangladesh. It has a latitude of 24°22'26" N and a longitude of 88°36'04" E. It was chosen as the ideal location for this study due to its distinctive humid, subtropical climate, which represents many urban centers facing significant heat challenges. The city has a humid subtropical climate, classified as such. The city experiences a typical temperature that falls between 16-21°C during the winter and 32-36°C during the summer. The mean annual air temperature is 26°C, with a maximum of 43°C and a minimum of 7.5°C (as of 2024). The average relative humidity in the city's air is around 75% (Mahmud et al., 2012). During the day, solar radiation levels remain elevated, with a normal value of 4.5-4.8 kW/m², an air temperature of 33°C, and a relative humidity of 85% (mean values). The daily wind speed averages about 3.55 km/h (Source: BMD). The analysis focused on a specific week in June 2024 (June 22–28, 2024), which exemplifies the typical summer period in Rajshahi. Understanding the climate conditions is crucial for analyzing how different roofing systems affect indoor temperature regulation in various geographical locations and seasons.

Given Rajshahi's humid subtropical climate, it serves as an ideal locale for evaluating the efficacy of green versus traditional roofing systems in managing indoor air temperatures. This study focuses on two experimental buildings within the city. The first (with a green roof) experimental building was a 5-story residential building. For this experiment, only the top floor was considered. The top-floor carpet area was approximately 1,100 sq.ft. It had bare masonry walls with plastered surfaces covered by enamel paint. The building featured Aluminum sliding glass windows. The roof of the experimental building was divided into two parts: one part consisted solely of a cement-concrete layer, and the other part of the roof was covered with plants. The green roof covered approximately 1,040 sq.ft of the total roof area, and the rest consisted of flat cement-concrete layers with no vegetation or plants that can be seen in Figure 1. The second (with a traditional roof) experimental building was a 5-story residential building, too. For this experiment, only the top floor was considered.



Figure 1: Experimental Building with green roofing system

This time, the top-floor carpet area was approximately 950 sq ft. It had bare masonry walls with plastered surfaces covered by oil paints. Steel sliding glass windows were noticed in

this case. Over the floor, there were no green roofs or vegetated plants this time which can be seen in Figure 2.



Figure 2: Experimental Building with a traditional roofing system

The experiment was divided into two main phases. A mixed-method approach combining quantitative measurements of temperature and relative humidity with qualitative assessments of occupant satisfaction was employed. In the first segment, the indoor air temperature, CO₂ concentration, relative humidity and roof surface temperature were measured simultaneously in the experimental building, which was covered by both a green and traditional roofing system, for quantitative measurement. The measurements were taken for three different sections (morning, noon, and evening) each day for a week. For this experiment, two thermometers and two hygrometers were used to measure temperature and relative humidity, respectively. 2 NDIR sensors were used to measure CO₂ concentration. These instruments are shown in Figure 3. Following the quantitative measurements, the study progressed to the second phase. In this phase, the focus was on a qualitative approach through a series of semi-structured, direct interviews with the occupants of the respective experimental buildings. This approach helped to delve deeper into the occupants perceived comfort levels. The purpose was to validate the computational results and determine whether the changes in temperature and relative humidity significantly improved occupants thermal comfort levels. Although the interview was unscripted, a set of predetermined topics was discussed. An unscripted interview allowed the participants to discuss their experiences openly, providing a clearer understanding of the scenario. To capture a diverse range of experiences, interviews were conducted with two occupants from the building with conventional roofing and four from the building with green roofing. The NVIVO software was used to code the interview transcript.

Characteristics of the Experimental Buildings

To ensure transparency of the experimental setup, the detailed characteristics of the selected study buildings are summarized in Table-1. The buildings were selected to maintain similarity in height, construction type, while differing in roofing systems. This controlled selection allowed for a direct comparison of thermal performance between green and conventional roofs under the same climate.

Orientation and Openings of Study Buildings

Both experimental buildings were oriented along a north–south axis. The main window openings were facing the east and west directions. The top-floor units had comparable window sizes and opening configurations to reduce biasness caused by ventilation. Similar floor layouts were maintained to ensure consistent exposure to solar radiation and air.

Qualitative Analysis Using NVIVO

Occupants were analyzed using NVIVO software and Qualitative interview data was collected from there. The coding process revealed primary themes such as perceived temperature reduction, reduced dependence on air conditioning, *and* overall comfort satisfaction among occupants of the green-roof buildings. On the other hand, occupants of the conventional roof buildings often expressed worries regarding high cooling costs, excessive heat, and discomfort during peak hours at day. These

qualitative findings correlate with the quantitative results, and support that green roofing systems largely enhance indoor thermal comfort and occupant well-being.

Table 1: Characteristics of the Experimental Buildings

Parameter	Building with Green Roof	Building with Conventional Roof
Building type	Residential	Residential
Number of stories	5	5
Floor considered	Top floor	Top floor
Carpet area	~1,100 sq ft	~950 sq ft
Roofing type	Extensive green roof + concrete	Concrete flat roof
Green roof coverage	~1,040 sq ft	Not applicable
Wall construction	Plastered masonry	Plastered masonry
Window type	Aluminum sliding glass	Steel sliding glass
Occupancy	Residential	Residential
Cooling system	Intermittent AC use	Frequent AC use



Figure 3: Thermometers, hygrometers and NDIR Sensors used

3. RESULTS

Understanding the cooling process requires examination of various factors, with temperature and relative humidity being paramount. Our initial assessment compared the internal room temperatures of the two experimental buildings. The initial observation regarding the green roof's performance was a substantial reduction in temperature and its daily variation as seen in Figure 4.

Indoor temperatures for green and traditional roofing systems were recorded at different times. The different times can be seen in the Figure 4. The data show that the indoor temperatures for green roofing systems are lower than those for traditional roofing systems. To accommodate variations in sunlight, clouds, wind, and other environmental factors, readings were taken at various times of the day. Throughout the day, during maximum sunlight exposure, the air temperature for the green roofing system remained significantly lower than that of the traditional roofing system. While the maximum indoor temperature was measured at 34°C for the green roofing system, it was recorded at 38°C for the conventional roof. Additionally, the mean indoor temperature for the green roof model was subtracted from the traditional roof model for each monitoring time. This demonstrated the effectiveness of the roof models across various hours of the day and their differences in performance. The average temperature contrast between the two roof models was compared. As sunlight and temperatures decreased, the difference in indoor temperatures between the two roofing systems diminished as seen in Table 1. Analysis showed that at noon, when sunlight exposure is at its peak, green roofs demonstrate their maximum cooling effect. This is likely because the plants and soil layer act to protect the roof from direct sunlight at that time.

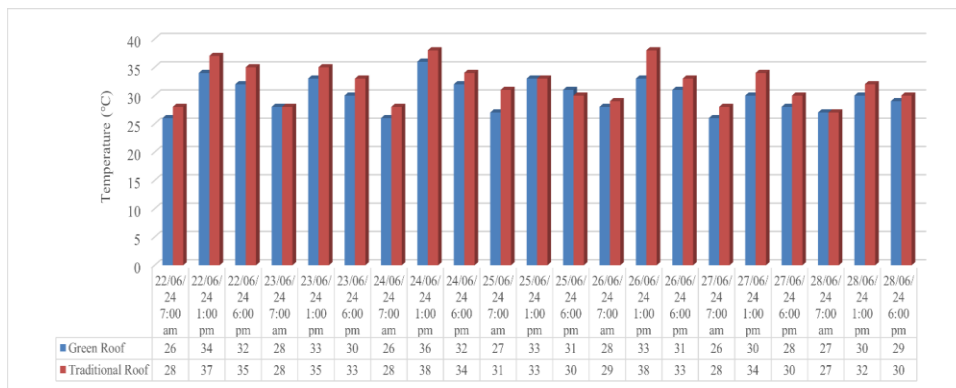


Figure 4: Air Temperatures at various times for green and traditional roofing systems

For both traditional and green roofing systems, the highest relative humidity was recorded at 6:00 PM, with humidity ranging from 80% to 89%. In contrast, the minimum level was documented at 7:00 AM for most days, ranging from 64% to 88% as seen in Figure 5.

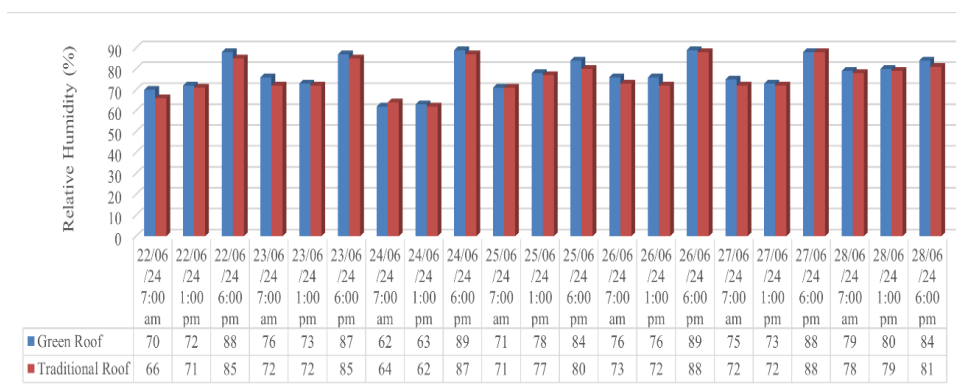


Figure 5: Relative humidity at different times for green and traditional roofing systems

According to the data, the green roof model reported higher indoor humidity levels than the traditional roof model. The highest humidity recorded was at 6:00 PM with a value of 89% under a green roof. The mean values of relative humidity for the green roof were subtracted from the traditional roof model for the selected period. This showed the effect of adopting green roof technology on the average relative humidity. At 6:00 PM as shown in Table 3, the green roof model exhibited the most significant variation in relative humidity, showing a 2% difference compared to the standard roofing system which can be seen in Table 3.

From Table 2, it can be seen that buildings with green roof had lower indoor temperature (about 1.57°C) than the conventional buildings at morning. The biggest drop shows at noon, around 1 PM which is about 2.57°C. So, at midday, the biggest cooling difference is observed. At the evening, the drop is moderate as 1.71°C.

From Table 3, It is observed that, indoor relative humidity is higher at all the selected times. The increment is modest but steady which ranges from 1.43% from 2.14%. At the evening, the disparity in relative humidity was found to be a maximum of 2.14% while it was the lowest at noon. In the morning, the relative humidity difference was moderate (1.86%) between the conventional and green roof buildings.

Table 2: The difference between average indoor temperatures

Time	Difference in average indoor temperature (°C)
7:00 AM	-1.57
1:00 PM	-2.57
6:00 PM	-1.71

Table 3: The difference between average relative humidities

Time	Difference in average indoor relative humidity (%)
7:00 AM	+1.86
1:00 PM	+1.43
6:00 PM	+2.14

Table 4: The difference between average roof surface temperatures

Time	Difference in average roof surface temperature (°C)
7:00 AM	-3.01
1:00 PM	-4.34
6:00 PM	-3.23

Table 5: The difference between average indoor CO₂ Concentration

Time	Difference in average indoor CO₂ Concentration (PPM)
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7:00 AM	-41.86
1:00 PM	-62.43
6:00 PM	-42.14

From Table 4, it is noteworthy that, the average difference of roof surface temperature is highest (4.34°C) at Noon and lowest (3.01°C) in the morning. The average roof surface temperature difference between conventional and green roof buildings is about 3.23°C in the evening.

Furthermore, from Table 5, it is noteworthy that, CO₂ concentration difference is found highest (62.43 PPM) at noon and lowest (41.86 PPM) in the morning. The concentration difference is found to be 42.14 PPM in the evening.

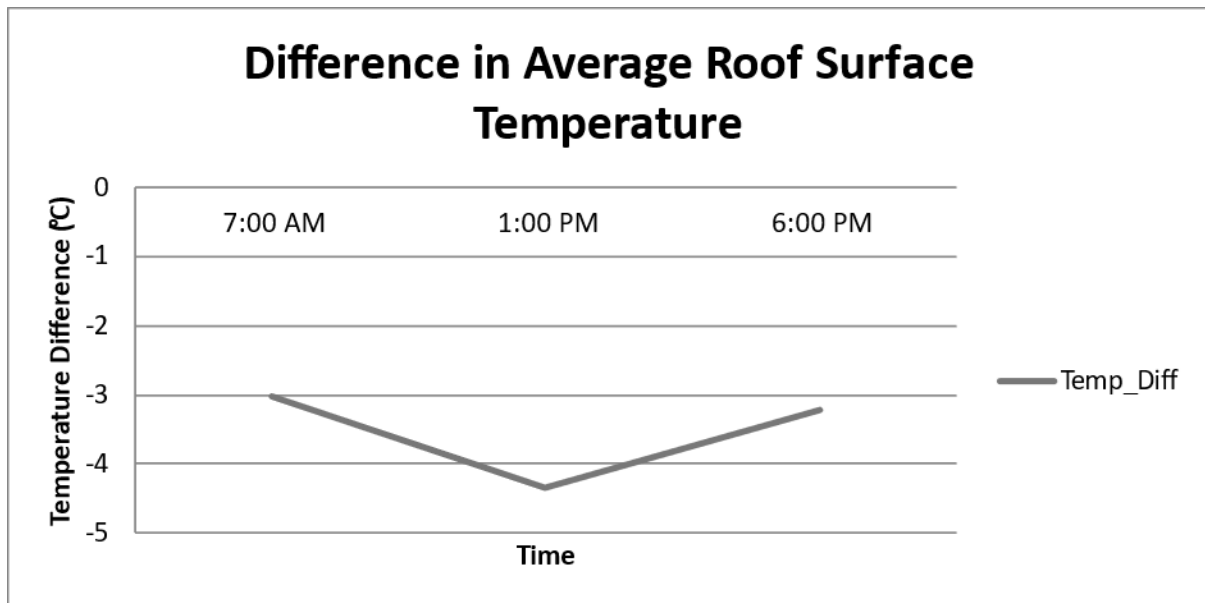


Figure 6: Time vs Temperature Difference graph

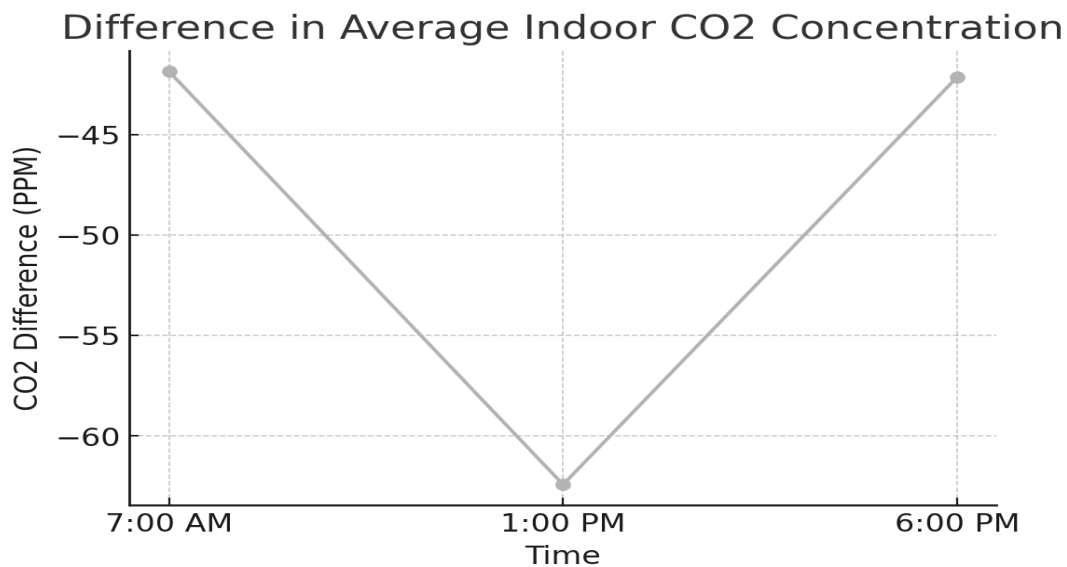


Figure 7: Time vs CO₂ Concentration Difference graph

4. DISCUSSION

4.1 First experimental building (With green roofing system):

The results indicated that the indoor temperature, roof surface temperature and CO₂ concentration was lower with the green roofing system than with the traditional roofing system. However, the humidity levels were higher in buildings with green roofs. The top floor is typically warmer than the other floors of the building. This is due to the higher amount of heat transferred to the adjacent floor, as it faces direct sunlight. A green roofing system was installed to mitigate excessive heat. The occupants found that the room under the green roof was generally cooler than other rooms and was more comfortable. It is noteworthy that air conditioners were used less to cool the rooms. Another occupant stated that they preferred the room under a green roof on days when the temperature was higher than usual. The interviewees also noted that the air quality was better. The occupants experienced a slight increase in humidity compared with the other parts of the building, which was negligible.

4.2 Second experimental building (Without green roofing system):

The traditional roofing system does not provide a barrier between the roof and the adjacent floor, preventing direct sunlight. As a result, it gradually heats the room more than the floors beneath. The occupants felt that the apartments were warmer, even more so than the outdoor temperature. The residents noticed that the temperature inside the building was significantly warmer than outside. Consequently, they became more dependent on air conditioners. Residents also mentioned that the temperature remained relatively stable at night without dropping significantly. This is because the heat trapped in the roof was slowly transferred to the lower floor. Occupants mentioned that the humidity inside was almost the same as outside.

The results helped to justify that the green roofing system significantly influenced the thermal comfort of the occupants. It decreased the indoor air temperature and enhanced the indoor air quality. Furthermore, the findings also suggest that the green roof cooling performance has the highest correlation with solar emissions. A portion of the solar radiation absorbed by the plant tops facilitates diffuse heat exchange with the surrounding air. The remainder is dissipated through evapotranspiration. According to a study by Leo et al. (2013) and Jason et al. (2013) in China, evapotranspiration is responsible for 58.15% of scattered heat, highlighting the broader environmental benefits of green roofs. A total of 30.9% of the long-wave gleaming exchange between the canopy and air was attributed to sensible heat. Another 9.5% accounted for the total photosynthesis of trees. Just 1.2% was retained by plants and soil or moved within the room space below (Mohammad et al., 2021; Young et al., 2016; Seri et al., 2019). Green roofs also help reduce the building's energy expenditure and absorb carbon dioxide from the atmosphere. So, it is environmentally sustainable.

While existing studies emphasize the role of green roofing systems in reducing outdoor urban temperatures, a substantial gap remains in quantitative studies focused on the indoor environmental benefits. Detailed analysis of temperature variation, relative humidity, and occupant thermal comfort in buildings with green roofs compared to conventional ones is scarce. It is intended that these findings will influence policy, design, or construction practices to better address the challenges posed by urbanization. Notably, the study had some gaps, including the long-term performance of extensive green roofing systems, which were not investigated. The performance of green roofs in comparatively cooler periods and the impact of seasonal variation on their performance have not been investigated. Additionally, the experiment was not conducted on other types of buildings, such as commercial and industrial buildings, beyond residential buildings. For this study, the homogeneity of roofing models was used. However, varying designs and materials could influence the results, which were not investigated.

Though detailed architectural floor plans are not graphically presented, but the internal layouts, opening characteristics, and orientations of the study buildings were carefully examined before data collection. Both buildings have comparable floor layouts, ceiling heights, room functions, and top-floor exposure, with primary window openings oriented in same directions and they are comparable in material and size. Moreover, other Controlling factors such as construction materials, occupancy pattern, floor level, and ventilation behavior were considered during site selection to reduce thermal biasness which is unrelated to the roofing system.

From an expert in energy and environmental field, it came to light that the effectiveness of green roofing systems primarily depends on the correct and necessary structural design such as substrate thickness, vegetation selection, drainage configuration, and load-bearing capacity of the roof slab. In warm and humid climates, inappropriate consideration of these technical aspects may decrease long-term performance or create challenges in maintenance. On the other hand, properly engineered extensive green roofs can give good outputs including consistent thermal benefits without compromising structural safety.

5. CONCLUSION

This study evaluated the performance of green roofing systems compared to conventional flat roofing system. Results showed a clear disparity between indoor and outdoor thermal conditions. Buildings under extensive green roofing systems maintained consistently lower indoor temperatures than those with conventional roofs. The cooling effect was most significant at noon between 12:00 PM and 3:00 PM. It peaked around midday when solar radiation was the highest. Green roofs reduced roof surface temperatures significantly, with a maximum difference of approximately 4.34°C at noon, showcasing strong heat mitigation capability. Indoor relative humidity in green-roof buildings was slightly higher due to moisture retention because of vegetation. But, still it was within favorable limits. Lower indoor CO₂ concentrations were also observed. It demonstrated improved indoor air quality and thermal comfort. Moreover, net energy consumption by occupants was significantly lower in buildings with green roofs compared to conventional roofing systems.

The findings match the results obtained from previous studies in subtropical regions which confirmed the effectiveness of extensive green roofs in reducing indoor and roof surface temperatures. Technically, the results section highlighted the importance of vegetation coverage, substrate depth, and moisture retention in increasing evapotranspiration-driven cooling system. From a Structural perspective, lightweight extensive green roof systems were found appropriate for mid-rise residential buildings.

Overall, the study showed that green roofs can effectively mitigate urban heat, support energy-efficient, climate-resilient building design, and improve microclimates. These findings offer valuable insights for urban planners, policymakers, and architects promoting sustainable urban development in rapidly urbanizing regions.

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DECLARATION OF USE OF AI

AI was used primarily for initial phase literature review and to get a specific workflow or workplan for this specific study. As for the manuscript writing, AI was used to get a concept or sample of the “Introduction” part and was later Rewritten as per authors own understanding of the topic.

REFERENCES

- Mohammad Shafique, R. Kim, & M. Rafiq (2018). "Green roof benefits, opportunities and challenges – A review," *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 757–773.
- Uri Berardi, A. H. GhaffarianHoseini, & A. GhaffarianHoseini (2014). "State-of-the-art analysis of the environmental benefits of green roofs," *Appl Energy*, vol. 115, pp. 411–428.
- Zaron S. M. Odli, I. A. Zakarya, F. N. Mohd, T. N. T. Izhar, N. M. Ibrahim, and N. Mohamad (2016). "Green Roof Technology-Mitigate Urban Heat Island (UHI) Effect," in *MATEC Web of Conferences*, EDP Sciences.
- Chow F. Chen (2013). "Performance evaluation and development strategies for green roofs in Taiwan: A review," *Ecol Eng*, vol. 52, pp. 51–58.
- Leo Chin & Mio. Myoen (2013). "Directions in green roof research: A bibliometric study," *Build Environ*, vol. 66, pp. 23–28.
- Jason K. W. Wong & L. S. K. Lau (2013). "From the 'urban heat island' to the 'green island'? A preliminary investigation into the potential of retrofitting green roofs in Mongkok district of Hong Kong," *Habitat Int*, vol. 39, pp. 25–35.
- Mahmud Shakil, A. Salan, S. Reza, A. Salan, & M. S. Reza (2012). "climate change and seasonal behavioral disruption of climate parameters: a study of rajshahi city."
- Mohammad R. A. Bhuiyan, H. Mamur, & J. Begum (2021). "A brief review on renewable and sustainable energy resources in Bangladesh," *Clean Eng Technol*, vol. 4, p. 100208.
<https://live6.bmd.gov.bd/p/Normal-Wind-Speed>
- Young He, H. Yu, N. Dong, & H. Ye (2016). "Thermal and energy performance assessment of extensive green roof in summer: A case study of a lightweight building in Shanghai," *Energy Build*, vol. 127, pp. 762–773.
- Seri Cascone, J. Coma, A. Gagliano, & G. Pérez (2019). "The evapotranspiration process in green roofs: A review," *Build Environ*, vol. 147, pp. 337–355.