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Assessment of green roofs in comparison to concrete roofs to mitigate heat on the urban surfaces of Kathmandu

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Abstract

This study examines how well green roofs perform thermally in comparison to concrete roofs and how they affect indoor room temperatures in urban settings. ICIMOD's Kailash Bhawan in Kathmandu valley is the site of the study, which uses temperature and relative humidity data gathered from both green and concrete roofs to reduce the effects of Urban Heat Island (UHI) and increase energy efficiency. The findings show that green roofs greatly reduce the impacts of UHI by lowering surface temperatures compared to concrete roofs by 32%. According to correlation studies, green roofs account for 45.9% of the fluctuation in interior room temperature, whilst concrete roofs' surface temperature accounts for 54%. In addition, the concrete roof accounts for 71% of the variance in the interior temperature in the absence of air conditioning, whereas the green roof accounts for 24.01%. According to these results, green roofs may help reduce energy use and improve thermal comfort. According to the study, installing green roofs in densely populated areas like Kathmandu is a sustainable way to reduce the effects of UHI and control internal temperatures, which will increase energy efficiency.

1. Introduction

Vegetated roofs are ancient technology mainly installed in the past for aesthetic purposes, with the most famous example of the Babylonian gardens in Mesopotamia. They have proved historically to be a reliable solution for building roofing, especially in Northern European countries where they provided valid protection against adverse meteorological conditions and improved the insulation effect and durability of the building envelopes in such cold climates. A rediscovery of such technology took place mostly in Europe during the 1960s and 1970s, mainly for the recreational and aesthetic value provided by the installation of vegetated surfaces in buildings[1].

The roof of a building can be fully or partially covered with a layer of vegetation known as a green roof. A green roof is a layered system comprising a waterproofing membrane, a growing medium, and the vegetation layer itself. Green roofs often also include a root barrier layer, drainage layer, and, where the climate necessitates, an irrigation system[2].

Green roofs are an interesting technology that has attracted worldwide attention because of the multidisciplinary benefits, involving the improvement of stormwater management, the mitigation of the urban heat island effect, the prolonged lifespan of the roof membrane, the enhancement of urban aesthetics, the creation of recreational spaces, and the possibility to generate energy savings for building heating and cooling[1].

Green roofs are complex technological systems that adopt vegetation as an integral part of the building shell. A proper design implies energy and environmental benefits, regarding microclimate inside the building; reduction of urban heat islands, improvement of outdoor air quality, supporting of wastewater disposal system. Leaving out aspects that are not strictly "energy-related, green roofs are aimed at reducing roof temperature and thus the summer solar gains, without worsening the

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winter energy performance[3].

There are several advantages of green roofs which reduce urban temperature, provide a clean environment, and save energy. It develops the resilient power of the communities[4].

The Urban Heat Island (UHI) effect is a phenomenon of heat accumulation within urban areas, primarily driven by urban development and human activities. It is widely regarded as one of the most prominent features of urban climates. The rise in land surface temperatures caused by the UHI effect significantly impacts material and energy flows within urban ecosystems, altering their structure and functionality. This leads to various ecological and environmental consequences, affecting urban climates, hydrological conditions, soil characteristics, air quality, biological patterns, material cycles, energy dynamics, and the health of urban residents[5][6][7][8].

Urban heat island refers to the warmth of both the atmosphere and surface in cities compared to their surroundings. It is an undesired climatic modification by changing surface and atmospheric characteristics with urbanization growth. The UHI form in the city comprises the materials used in construction, the surface characteristics like building dimensions and spacing, thermal properties, and the amount of green space. Besides, human activities can also increase the heat island temperature. In general, the intensity and magnitude of the surface heat islands depend on urban characteristics and seasons. It is more in the summer. The urban heat island effect was first observed in London in the 18th century that was observed when industrial revolutions began. London is possibly the longest-studied UHI of any city. Luck Howard was the first scientist to suggest that the temperature recorded in a city was likely to be higher than that in the surrounding countryside[4]. In the United States, 71-95% of the area is occupied by industrial areas and shopping centers almost two-thirds of all impervious area is in the form of parking lots, driveways, roads, and highways [9] and the remaining one-third consists of homes, buildings, and other non-vegetated and open soil areas[4].

With rapid urbanization, population growth, and anthropogenic activities, an increasing number of major cities across the globe are facing severe urban heat islands (UHI). UHI can cause complex impacts on the urban environment and human health, and it may bring more severe effects under heatwave (HW) conditions. Most studies show that urban areas are more vulnerable than rural areas during HWs, but the opposite is also observed in some studies. Recent studies also indicate that increasing albedo, vegetation fraction and irrigation can lower the urban temperature during HWs. HWs are expected to occur more and more frequently. Exploring the synergies between UHI and HW is necessary as it helps to identify the key drivers that may intensify urban overheating and thus may be helpful for the development of adequate mitigation strategies. HWs usually result in higher temperatures in both urban and rural areas. The intensity of UHI depends on the background climate and the different responses to HWs between urban and rural sites. Most studies note intensified UHII during HWs, while other studies find no apparent synergies between them or even a reduced UHII in HWs. The synergies between UHI and HW are influenced by various factors, such as morphology, population, climate background, and many more. For the daytime, the main changes in the energy budgets identified in most studies are the differences in latent heat flux and net all-wave radiation between urban and rural areas, and the relevant drivers include vegetation fraction, evapotranspiration, soil moisture (precipitation), and albedo, etc. For the nighttime, the main changes lie in the differences in the heat storage fluxes (to be released at night) between urban and rural areas, and the relevant drivers include city size and albedo, etc. Increased anthropogenic heat flux due to greater usage of air-conditioning systems and changes in wind conditions can also significantly amplify both daytime and nighttime UHI. Increasing vegetation coverage in urban areas may be effective, but city planners should consider irrigation availability[10].

Green roofs are an increasingly important component of water-sensitive urban design systems that can potentially improve the quality of urban runoff, reduce the energy consumption of buildings, and add esthetic value to the environment[11]. Buildings account for around half of primary energy consumption, hence CO_2 emissions, in the UK and other developed countries. A large proportion of this energy is used to maintain internal building temperatures through heating and cooling systems. This section of the report will therefore address the potential building energy reduction benefits arising from the enhanced thermal properties of a green roof[2].

Radiative heat from the sun dominates the energy balance of a green roof. The solar radiation is balanced by sensible (convection) and latent (evaporative) heat flux from soil and plant surfaces, combined with conduction of heat into the soil substrate and long-wave (thermal) radiation to and from the soil and leaf surfaces. phenomena occur in green roofs:

- Soil works as an inertial mass with a high heat thermal capacity, high time lag effect, and low dynamic thermal transmittance.

- Foliage behaves as a shading device under which convection provokes heat thermal exchange, but foliage absorbs part of the thermal energy for its vital process of photosynthesis.
- Soil and vegetative layers induce evaporative and evapotranspiration cooling.

Green roofs reflect between 20% and 30% of solar radiation and absorb up to 60% of it through photosynthesis. This means that a percentage below 20% of the heat is transmitted to the growing medium. A determinant aspect for assessing the thermal performance of a green roof is the thermal resistance of the roof below the vegetation layer: if the green roof is above a well-insulated roof, then the green roof energy balance would be decoupled from that of the building, and the green roof will have an impact mainly on the urban environment. Contrarily, if the green roof is above a less-insulated roof, then its energy balance significantly affects the building[12].

It is worldwide accepted that green roofs have a variety of environmental, economic, and social benefits. China, which is experiencing rapid urbanization, has great potential to gain the benefits of green roofs, which are not commonly seen in existing or new buildings. Understanding its root causes is important for promoting the larger-scale implementation of green roofs. The root causes are identified as the increase in maintenance cost, increase in design and construction cost, poor arrangement of the use of green roofs, and lack of incentives toward developers[13].

The Kathmandu valley is the highly populous and urban center of Nepal which includes five major cities: Kathmandu, Patan, Bhaktapur, Kirtipur, and Thimi. Kathmandu Metropolitan city is the largest city in Nepal, and it is the cosmopolitan heart. It encompasses a compact zone of temple squares, narrow streets, and a big urban canyon dating back 2000 years of old Kathmandu that corresponds to the current city core. There are 1.04 million households in the urban area of the Kathmandu Valley which is projected to increase by 1.13 million in 2025. More than 80% of the household of the valley is made of cement mortar or concrete block walls and reinforced concrete or cement roofs. Mostly, built-up areas are dense in the middle of the valley where the average annual temperature is 16.64 degree Celsius to 18.44 degree Celsius. The climate of the Kathmandu Valley is sub-tropical warm temperate with a maximum of 35.6 degree Celsius ambient temperature in summer. The temperature in winter ranges between 2 degree Celsius-20 degree Celsius. The average rainfall is 1400 mm and more than 80% of rainfall occurred from June to August. Kathmandu has experienced rapid land use and land cover change due to rocketed urbanization growth. Unplanned urbanization has introduced various environmental problems in Kathmandu and the UHI effect is one of the emerging issues. The early urban growth of Kathmandu was based on its agricultural surplus. Now, agricultural land in urban areas has been decreasing at an alarming rate. The agricultural area in the Kathmandu Valley is reported to have declined an annual average loss of 0.5% or 400 hectares[4].

Urban temperature has been escalating with less greenery and high built-up areas. More than half of the total population resides in urban areas, so the urban environment is highly vulnerable. Restoration of urban forestry is very expensive and almost not possible as they have already used the massive land for development purposes. Kathmandu, one of the fastest-growing cities in South Asia, faces several catastrophic environmental problems related to urban heat. The air surface temperature has significantly increased at the rate of 0.04 degree Celsius yr with a maximum temperature trend of 0.06 degree Celsius[4]. The rise in land surface temperature is primarily due to increasing roads, vehicles, and built-up areas, along with a decline in open spaces, cultivated land, and forests. Thermal analysis shows inner-city areas are hotter than outer-city areas, which, in turn, are warmer than forested regions. This demonstrates that greater urbanization leads to higher temperatures and a stronger UHI effect. If this trend continues, the ecological condition in Kathmandu Valley may deteriorate further. Unplanned urbanization and insufficient open spaces highlight a critical future, requiring significant time and effort to manage residential areas and urban growth to address UHI effects effectively[14].

Many researchers have investigated the potentiality of green roofs to reduce urban heat islands. It found that green roofs can reduce urban temperature. The temperature measurement at the surface of green roofs is lower than the common roof surface. The relationship between green roofs and temperature is negative whether the green roof area increases the temperature decreases[4].

The primary objective of the study is to evaluate the thermal performance of green roofs compared to modern concrete roofs.

1. Evaluation of Surface temperature between green roof and concrete roof.
2. Assessment of the relationship between roofs and rooms below them.

2. Materials and methods

2.1. Methodology

This study adopts a post-positivist paradigm, acknowledging that while absolute objectivity may not be achievable, scientific methods can provide reliable and reproducible insights. Post-positivism aligns with the study's aim to quantify the impact of green roofs on UHI mitigation.

2.1.1. Ontological stance

The ontological stance of this research is critical realism, which posits that phenomena such as urban heat island (UHI) effects and energy efficiency exist independently of our perceptions. These phenomena are measurable through modeling and simulations, reflecting an underlying reality that can be observed and analyzed.

2.1.2. Epistemological stance

The epistemological foundation is empiricism, emphasizing the collection and interpretation of quantitative data. Knowledge is derived through simulations and analysis of variables such as temperature, energy consumption, and thermal comfort, using validated tools and techniques.

2.2. Method

This section Consists of the method followed by author to achieve results.

2.2.1. Selection of study area

ICIMOD's Kailash Bhawan (Figure 1) was selected for the study of green roofs as well as concrete roofs. Both green roofs and concrete roofs were selected near each other to avoid external variable interruptions.

Figure 1: ICIMOD Kailash Bhawan

2.2.2. Tools and equipments

Data loggers (Figure 2, 3, 4 and 5) were used to measure the temperature and Relative humidity. Hobo external temperature data loggers were used to measure the surface temperature of the green roof and Concrete roof. CO_2 recorder data laggers were used to measure the ambient temperature and Relative humidity of the rooms below each roof respectively just 1.5m above ground.

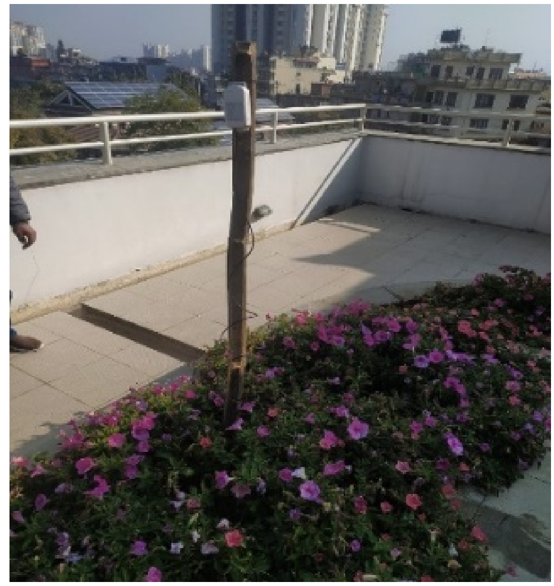

Figure 2: Surface temperature logging of green roof

Figure 3: Surface temperature logging of green roof

2.3. Floor plan of the rooms

Figure 6 and Figure 7 shows the floor plan of rooms.

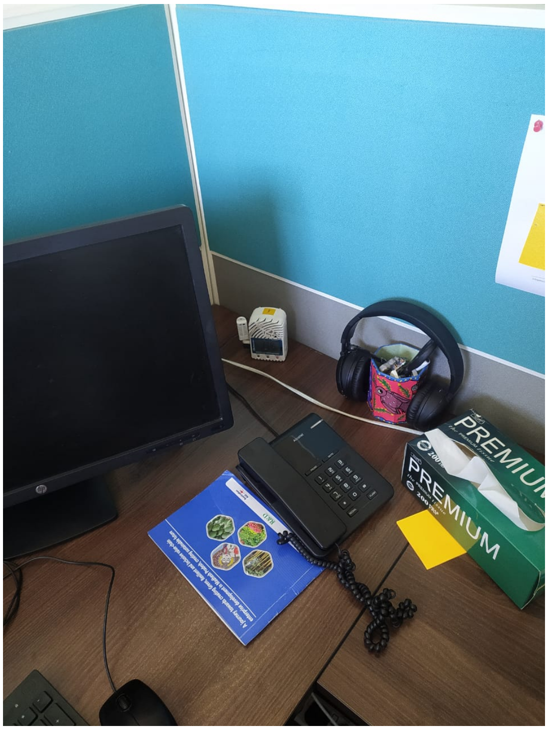

Figure 4: Internal temperature logging below green roof

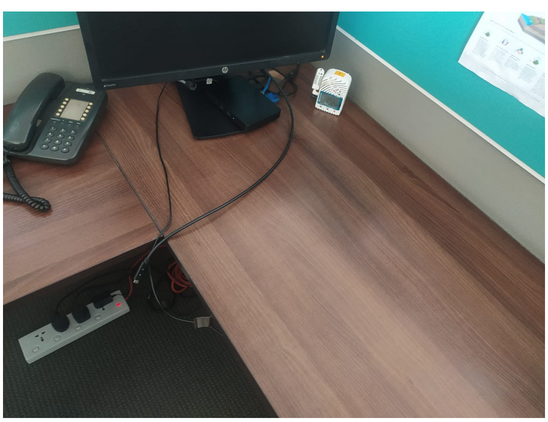

Figure 5: Internal temperature logging below concrete roof

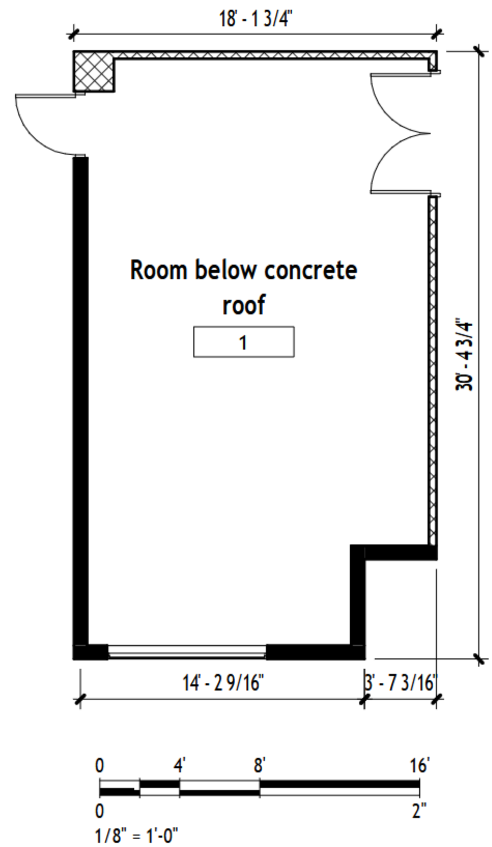

Figure 6: Room below Concrete roof

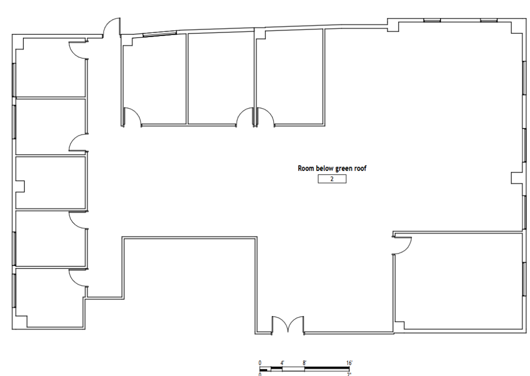

Figure 7: Room below green roof

3. Data analysis

3.1. Surface temperature

The data (Figure 8) from the loggers shows that green roofs are significantly cooler than concrete roofs. The average difference between concrete surface and green surface is found to be about 4.84 degree Celsius, maximum of 9.74 degree Celsius and minimum of -3.43 degree Celsius. Below is the Chart (Figure 8) showing the Surface temperature comparison between Concrete roof and green roof. Green roof has thickness of 1 Foot 6 Inch, well Irrigated with plant height of about 6 Inch-10 Inch.

From the chart above it can be stated that green roofs significantly reduce the surface temperature compared to concrete roofs. Figure 9 and Figure 10 indicates that ST of green roof is significantly cooler compared to that of concrete roof. Even during day and night the ST of green roof is cooler than that of concrete roof to

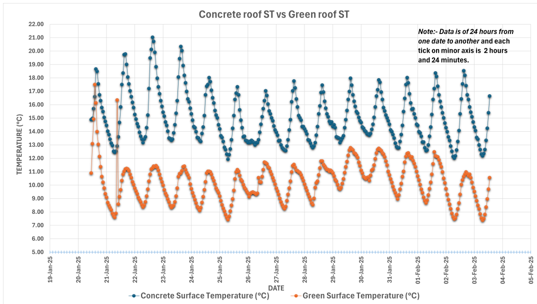

Figure 8: Surface temperature comparison of green roof vs concrete for 2 weeks

green roof can cool the urban microclimate significantly reducing UHI and Heat waves effect.

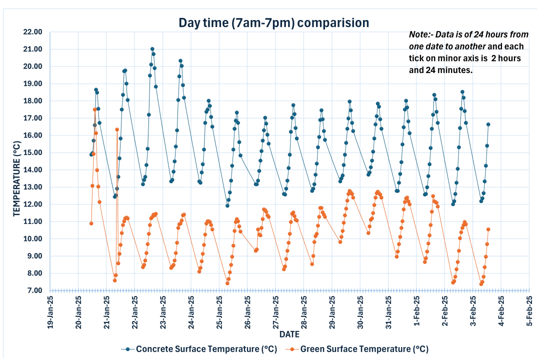

Figure 9: Surface temperature comparison for green roof vs concrete roof at daytime

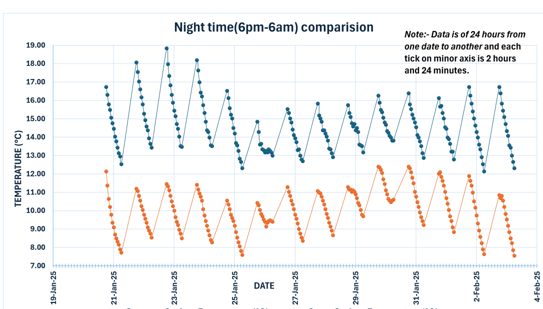

Figure 10: Surface temperature comparison for green roof vs concrete roof at night

The temperature at nighttime shows high heat loss by concrete at night compared to green roof. In daytime high heat gain can be observed by concrete roofs compared to green roofs.

3.2. Room ambient temperature

Rooms below the green roof and concrete rooms were measured respectively with CO_2 Recorder data loggers for 14 days. The rooms have HVAC units which is used mostly during office hours thus for analysis of data it is divided into Temperature with HVAC and Without HVAC.

3.2.1. Without HVAC

The Figure 11 shows the temperature data without HVAC. It can be deduced that the insulation properties of concrete are significantly lower than that of the green roof which is indicated by the sharp rise of temperature during hotter days while reduction during colder days. The temperature of the room below the green roof is comparatively stable compared to the temperature of the room below concrete roof.

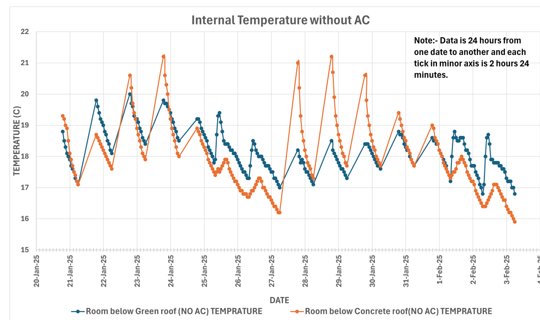

Figure 11: Internal temperature comparison between room below green roof and concrete roof without HVAC

Figure 11, which represents the indoor ambient temperature of rooms just below the green and concrete roof without HVAC reveals the temperature spikes in rooms just below the concrete roof whereas the room below green roof is quite stable all around. This suggests that concrete has poor insulation compared to that of concrete roof which in turn indicates that the high temperature peaks at the peak hours as in the chart above.

3.2.2. With HVAC

The Figure 12 shows the temperature data with HVAC which indicates high temperatures in the room below concrete roof suggesting high energy consumption by HVAC units to maintain stable internal temperatures.

Figure 12, which represents the indoor ambient temperature of rooms just below the green and concrete roof with HVAC shows high temperature spikes in room just below the concrete roof whereas the room below green roof has small temperature spikes compared to that of room below concrete roof. This again solidifies the fact that concrete has poor insulation compared to concrete roofs and it also reveals how rooms below green roofs require less energy to maintain optimal room temperature while rooms below concrete roof require high energy to maintain the same optimal temperature.

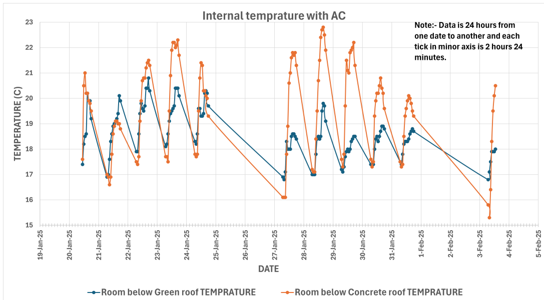

Figure 12: Internal temperature comparison between room below green roof and concrete roof with HVAC

3.2.3. *Correlation between Concrete roof surface temperature and room below internal temperature*

While performing correlation analysis between concrete roof and internal temperature of the roof below, a Pearson correlation coefficient (r) of 0.735 indicates a moderately strong positive relationship between surface temperature (ST) of concrete roof and internal temperature (IT) of room below it. The coefficient of determination (r^2) is 0.54 (Figure 13).

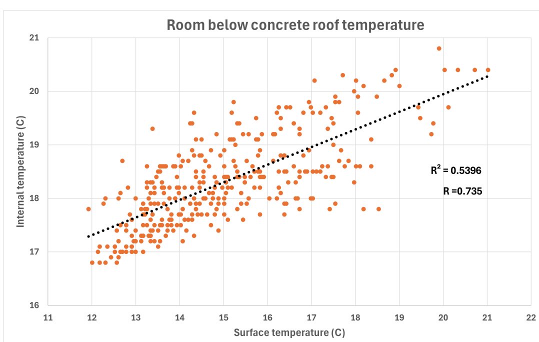

Figure 13: Correlation graph between internal temperature and Surface temperature in concrete roof

3.2.4. *Correlation between Green roof surface temperature and room below internal temperature*

While performing correlation analysis between concrete roof and internal temperature of the roof below, A Pearson correlation coefficient (r) of 0.677 suggests a moderately strong positive relationship between surface temperature (ST) and internal temperature (IT). The coefficient of determination (r^2) is 0.459 (Figure 14).

3.2.5. *Correlation between Green roof surface temperature and room below internal temperature without HVAC*

The correlation between internal room temperature and the green roof, without air conditioning, showed a moderate positive correlation coefficient of 0.49. The coefficient of determination (r^2) is 0.24 (Figure 15).

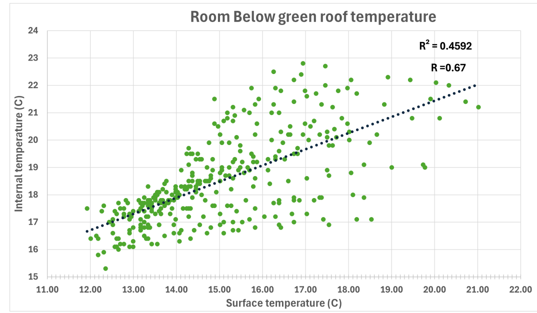

Figure 14: Correlation graph between internal temperature and Surface temperature in green roof

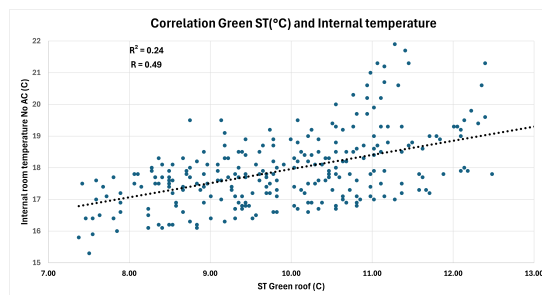

Figure 15: Correlation between green roof ST and Internal room temperature with No AC

3.2.6. *Correlation between Concrete roof surface temperature and room below internal temperature without HVAC*

A Pearson correlation coefficient (r) of 0.506 suggests a moderately positive relationship between surface temperature (ST) of concrete roof and internal temperature (IT). The coefficient of determination (r^2) is 0.71 (Figure 16).

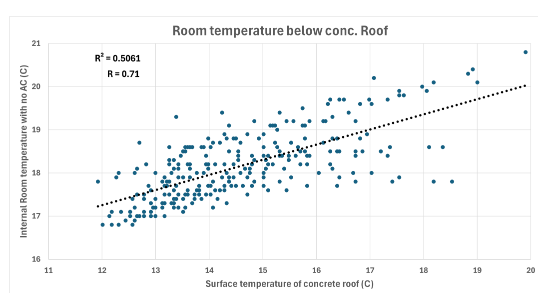

Figure 16: Correlation between green roof ST and Internal room temperature with No AC

3.2.7. Heat Mitigation Efficiency

HME can be calculated using the following formula:

$$\text{Efficiency} = \frac{T_{\text{concrete}} - T_{\text{green}}}{T_{\text{concrete}}} \times 100$$

Where:

- T_{concrete} = Surface temperature of concrete roof
- T_{green} = Surface temperature of green roof

Analyzing the data, the average surface temperature of the concrete roof is 15.03 °C, and the average surface temperature of the green roof is 10.24 °C. Thus, the efficiency is calculated as 31.88%.

This shows that green roofs are around 32% effective in Surface temperature reduction compared to concrete roofs.

4. Result and discussion

4.0.1. Evaluation of surface temperature of green roof and concrete roof

Figure 8 shows that Surface temperature of the green roof is significantly lower than concrete roof. From Figure 9 and 10, it can be deduced that during daytime concrete surface heats up significantly than green surface while during nighttime heat release from concrete surface is higher than green surface. These results highlight the fact that concrete surfaces have poor insulation compared to that of green surfaces. The results also direct to the fact that green surfaces have higher potential in cooling the urban surface thus further solidifying the fact that lack of green surfaces is indeed one of major contributing factors of Urban heat Island (UHI) in the Urban cores. These results suggest that green roofs implemented on policy level can mitigate the effects of urban heat islands in cities like Kathmandu that are highly populated and overused land.

4.1. Relationship between roof surface and internal room temperature

Figure 13's correlation coefficient (r) of 0.735 indicates a moderately strong positive relationship between the concrete roof's surface temperature (ST) and the room's internal temperature (IT). The coefficient of determination (r^2) is 0.54, which means that surface temperature accounts for 54% of the variation in internal temperature. Other elements like insulation, ventilation, HVAC operation, building materials, and outside environmental variables account for the remaining 46% of the difference.

With a correlation coefficient (r) of 0.677 in Figure 14, the association between internal temperature (IT) and surface temperature (ST) of green roof is relatively high. The coefficient of determination, which stands at r^2 is 0.459, shows that surface temperature accounts for 45.9% of the fluctuation.

External environmental conditions, ventilation, relative humidity, and the green roof's insulating qualities account for the remaining 54.1% of the difference. Without air conditioning, the connection between the green roof and the interior room temperature was moderately positive (0.49), as seen in Figure 15. As a result, the green roof accounts for about 24.01% of the variance in internal temperature, with the remaining 75.99% being impacted by external weather, building materials, HVAC, and insulation. Despite this, the moderate correlation indicates that green roofs enhance energy efficiency and help control indoor temperatures without requiring air conditioning.

Without air conditioning, the connection between the green roof and the interior room temperature was moderately positive (0.506), as seen in Figure 16. As a result, the concrete roof accounts for about 71% of the variance in internal temperature, with the remaining 29% being impacted by building materials properties, HVAC, and insulation. This means that a significant portion of the room's temperature changes can be explained by the thermal properties of the concrete roof, such as how much heat it absorbs and releases. The concrete roof likely influences the internal environment quite a bit because of its material characteristics.

5. Conclusion

This study assessed how well both concrete and green roofs performed thermally and how they affected the interior room temperatures in metropolitan settings. In lowering surface temperatures and minimizing the Urban Heat Island (UHI) impact, the results highlight the value of green roofs. Further demonstrating the significance of roofing materials in controlling indoor climate was the examination of relationships between roof surface temperatures and interior room temperatures.

Important findings include:

1. Green roofs are 32% more successful at reducing surface temperatures than concrete roofs, which display far lower surface temperatures.
2. The temperature difference between the inside room and the concrete roof surface was found to be 54% explained by a reasonably strong positive connection.
3. Additionally, a moderately favorable association

between green roofs and internal room temperature was observed, accounting for 45.9% of the variation.

4. In the absence of air conditioning i.e. natural settings, the concrete roof is responsible for 71% of the variation in interior temperature, whereas the green roof is responsible for 24.01%.

5. In highly populated cities like Kathmandu, green roofs can help regulate indoor temperatures and increase energy efficiency, providing a long-term solution to UHI mitigation.

5.1. Recommendations

Given that green roofs have a major effect on lowering surface temperatures and enhancing indoor climate, officials in places like Kathmandu might include green roof projects in urban planning to successfully reduce UHI and improve sustainability in general.

5.2. Broader applications

According to these findings, green roofs may also be a scalable way to reduce urban heat islands in other cities, particularly those with comparable temperatures and environmental problems.

5.3. Limitations

Although the encouraging results, the study is constrained by the brief time frame for gathering data and the unique climatic circumstances of Kathmandu. Future studies should examine the long-term effects of green roofs in diverse climates, investigate how different plant species affect thermal performance, and take biodiversity and improved air quality into account.

5.4. Acknowledgments

The author sincerely appreciates ICIMOD for granting permission to use their building for experimental study. Gratitude is also extended to the Department of Hydrology and Meteorology, Tribhuvan University, for providing data loggers. Special thanks to Prativa Lamsal for her generous support in providing additional data loggers.

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