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Thermal performance analysis of near infra-red reflection and green roof cooling techniques on buildings made of mild steel

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Abstract. This paper investigates the thermal performance of green roofs, cool roofs, and their combined effects in tropical climates. Although each technology has been studied independently for its potential to reduce cooling energy consumption in buildings, their combined effects have not been thoroughly examined in tropical climates. The study employed experimental and numerical methods, demonstrating that combining green and cool roofs can lead to even greater cooling energy savings. The research involved fabricating four identical cubicles made of mild steel sheets and placing them in an open space for testing under two operational conditions: closed window and open window/door. The combined green and cool roof technology achieved a temperature difference reduction of 4.14 °C compared to the original roof under the closed window and door state, with green and cool roofs achieving 0.72 °C and 0.79 °C, respectively. Combining green and cool roofs led to even more significant cooling energy savings, with 53.57 kWh energy savings compared to 20.1 kWh and 3.68 kWh for combined, green, and cool cubicles, respectively. The study found that combining green and cool roofs led to even more significant cooling energy savings, with 53.57 kWh energy savings compared to 20.1 kWh and 3.68 kWh for combined, green, and cool cubicles, respectively. The research suggests that combining these technologies can lead to greater cooling energy savings and highlights the potential benefits of green and cool roofs for tropical climates.

Keywords:: Green roof / cool roof / tropical climate / EnergyPlus

1 Introduction

A roof serves as a crucial element of the building envelope, shielding occupants from direct solar radiation and significantly impacting the overall cooling load [1]. Covering approximately 20–25% of the building's total surface area, the roof's design plays a vital role in maintaining efficient temperature regulation within the structure [2]. An inadequate roof design can cause interior warming, which can cause thermal discomfort and make living spaces uninhabitable.

In recent years, the escalating impact of climate change has led to a surge in energy consumption for space cooling, surpassing all other building end uses and more than tripling between 1990 and 2016 [3]. The International Renewable Energy Agency (IRENA) projects a global energy consumption increase of 56% between 2010 and 2040, primarily driven by non-OECD countries [4]. Additionally, data from the International Energy Agency (2020) reveals a significant rise in global electricity consumption, with an average annual growth rate of 3.2% from 1998 to 2018 [4], there has been a considerable rise in the world's usage of electricity in recent years. The yearly global consumption of electricity increased from 13 181.7 TWh in 1998 to 24 738.9 TWh in 2018, representing an average annual growth rate of almost 3.2% over this time [5]. This surge in energy consumption is particularly concerning as buildings alone contribute to 33% of greenhouse gas emissions worldwide and exhibit an average consumption growth rate of 40% [1,6].

Building cooling, typically achieved through electric-powered fans or air conditioning (AC) systems, not only contributes to the rising global energy demand but also leads to increased emissions, as a significant portion of the electricity mix relies on fossil fuel sources. AC systems

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consume a substantial amount of energy in commercial buildings, ranging between 50% and 60% [7]. Moreover, air conditioning systems release the rejected heat into the atmosphere, contributing to the occurrence of the Urban Heat Island (UHI) phenomenon [6]. The reliance on these systems is not only costly in terms of installation and maintenance but also negatively impacts the aesthetics of the building. Therefore, there is a need to seek alternatives and passive ways of reducing energy consumption in buildings, which must be clean and sustainable.

In response to these challenges, researchers and scientists are actively engaged in research and development (R&D) efforts to explore alternative and sustainable solutions in the field of building cooling. The latest R&D initiatives focus on integrating advanced materials and technologies into roof design, developing "smart roofs" that dynamically respond to environmental conditions. Additionally, the exploration of passive cooling techniques utilizing natural processes and the integration of renewable energy sources into cooling systems are gaining momentum. Furthermore, advancements in building simulation and modeling techniques enhance the understanding of complex interactions, facilitating the optimization of roof designs and cooling strategies [8,9].

Among the various passive cooling techniques, the combination of green roofs and cool roofs has garnered significant attention as an effective solution for reducing energy demand in buildings. Green roofs, characterized by vegetation cover, provide insulation and reduce heat absorption, while cool roofs utilize reflective materials to minimize solar heat gain. By combining these two approaches, the study aims to maximize the benefits of both strategies, further enhancing energy efficiency and sustainability in building cooling [10,11].

The integration of green roofs and cool roofs not only reduce energy consumption but also offers a range of environmental advantages. These combined techniques have been found to mitigate the urban heat island effect, a phenomenon characterized by higher temperatures in urban areas compared to surrounding rural regions [12,13]. Additionally, they contribute to improved air quality, as vegetation filters pollutants and cool roof materials minimize the release of harmful emissions [14].

Despite numerous studies focusing on the individual effects of green roofs or cool roofs, there is a limited body of research investigating the combined impact of these strategies, particularly in tropical climates. Furthermore, there is a significant lack of literature specifically addressing the combined effect of green and cool roofs on buildings constructed with mild steel in such climates. To address this research gap, this study aims to examine the cooling performance of a combination of green roofs and Near-infrared reflective paint roofs as potential alternatives to air conditioning in dwellings constructed with mild steel sheets. The findings of this research will be particularly valuable in the context of Juja, Kenya, where the use of mild steel buildings for residential and commercial purposes has been on the rise.

1.2 Literature review

1.2.1 Green roof overview

A green roof is a roofing system that incorporates vegetation, offering numerous benefits for reducing temperatures in buildings and promoting environmental sustainability. Green roofs can be categorized into two main types: extensive and intensive roofs [15].

Extensive green roofs are recognized for their distinct features, including a thinner substrate layer typically measuring between 5 and 20 cm. This specific design allows for the cultivation of low-growing vegetation like sedum or herbs. Extensive green roofs are known for their lightweight nature, cost-effectiveness, and minimal maintenance requirements [16].

On the other hand, intensive green roofs are characterized by a thicker substrate layer that allows for the growth of larger plant species, such as trees and shrubs [17]. These roofs offer a greater variety and visual appeal in terms of rooftop landscapes. However, it is important to note that intensive green roofs necessitate stronger structural support and more regular maintenance compared to extensive green roofs [18].

Green roofs provide notable cooling benefits through a range of mechanisms. One of these is the natural shading effect created by the vegetation, which helps to reduce the direct impact of solar heat on the surface of the roof [19]. Secondly, the process of evapotranspiration, where plants release moisture into the air through their leaves, helps to cool the surrounding environment [20]. Additionally, green roofs absorb and dissipate solar radiation in different proportions. A substantial portion of solar radiation, approximately 60%, is absorbed and released through evaporation and reflection. Another portion, 27%, is absorbed by the soil layer, while only 13% is absorbed by the vegetation itself [19]. These processes collectively result in lower surface temperatures, reduced longwave radiation emission, and ultimately cooler air temperatures in and around the building [21].

Several recent studies further support the cooling benefits of green roofs. For example, Zhang et al. [22] conducted an experiment to evaluate the thermal performance of green roofs in a hot and arid climate. The study demonstrated that green roofs significantly reduced the peak roof surface temperature and lowered the indoor air temperature of the building. Yang et al. [14] conducted a study that compared green roofs and non-green roofs in China. The findings indicated that green roofs provided significant cooling benefits and resulted in a reduction in energy consumption of 14.7% compared to non-green roofs. The green roof building consumed 7.7 kWh of cooling energy compared to 9.1 kWh for the non-green roof building. Moreover, He et al. [12] compared the roof temperature inside a concrete building equipped with a green roof and a bare roof in the Athen, Greece climate. The results showed that the bare building roof temperature varied from 42 to 48 °C, whereas the green roof varied from 28 to 40 °C, signifying excellent temperature reduction in

green roof buildings. Additionally, Mahsan et al. [20] conducted an experiment in Athens to examine the influence of green roofs on energy savings in buildings with similar insulation characteristics but varying roofing technologies. The study compared two concrete roof buildings, one featuring a green roof and the other without. The results indicated that in the building without a green roof, the internal air temperature exceeded 30 °C for approximately 68% of the analyzed period. In contrast, the building equipped with a green roof experienced internal air temperatures exceeding 30 °C for only about 15% of the studied period.

1.2.2 Cool roof overview

Cool roofs are a type of roofing system designed to reflect sunlight and absorb less heat than traditional roofs [23]. These roofs are typically made of materials that have high solar reflectance and thermal emittance, which allows them to reflect more sunlight and emit more of the absorbed heat [10]. By reflecting more sunlight and absorbing less heat, cool roofs can help reduce the amount of heat absorbed by buildings, leading to lower energy consumption, improved comfort, and reduced urban heat island effects [11].

Recent studies have emphasized the energy-saving potential of cool roofs. For instance, Li et al. [24] conducted a simulation study to evaluate the cooling effect of cool roofs in different climates. The research demonstrated that cool roofs significantly reduced the cooling load and energy consumption of buildings, especially in hot climates.

Furthermore, Gao et al. [25] investigated the economic benefits of cool roofs. The study assessed the cost-effectiveness of cool roof installations in terms of energy savings and reduced cooling demand. The results indicated that cool roofs not only provided energy savings but also resulted in long-term financial benefits for building owners.

Additionally, He et al. [22] explored the impact of cool roofs on urban heat island mitigation. The study demonstrated that widespread implementation of cool roofs in urban areas could effectively reduce the urban heat island effect and improve the thermal comfort of urban dwellers.

1.3 Combining green roofs and cool roofs

While previous studies have explored the cooling benefits of green roofs and cool roofs individually, there is limited research on their combined application. To enhance the cooling effect, passive cooling techniques can be combined. Guo et al. conducted a simulation study on a six-story office building, evaluating the thermal performance, energy saving, and comfort of cool roofs and night ventilation. The findings showed that a combination of cool roofs and night ventilation reduced annual cooling energy consumption by 27%. Jiang et al. experimentally studied the combination of extensive green roofs and night ventilation, reporting reduced indoor temperatures during sunny days.

The present study contributes to the existing research on green roofs and cool roofs by examining the combined effect of these passive cooling techniques in a cubicle setting. While previous studies have individually investigated the energy-saving potential of green roofs and cool roofs, there is limited research on their combined application and its impact on cooling energy consumption.

By integrating both green roof and cool roof strategies in a cubicle, this study offers a novel approach to achieve enhanced energy efficiency and cooling benefits. The novelty lies in the synergistic effects of these techniques, where the green roof reduces heat gain through absorption and evapotranspiration, while the cool roof reflects solar radiation. This combination has the potential to yield greater energy savings and more significant reductions in cooling energy consumption compared to the individual use of either technique.

In comparison to existing research findings, this study builds upon previous studies that have shown the energy-saving benefits of green roofs and cool roofs. However, it extends the knowledge by exploring their combined effect, specifically in a cubicle setting. The findings from this research contribute to a deeper understanding of the combined strategies' effectiveness and their potential for energy savings in indoor environments.

The novelty of this work lies in the comprehensive evaluation of the energy-saving values within each cubicle, including the combined cubicle, green roof, and cool roof. By quantifying the energy savings in terms of kilojoules, the study provides a tangible measure of the cooling energy reduction achieved by implementing these strategies. This quantitative analysis adds value to the existing literature and facilitates a more accurate comparison with other research findings.

Moreover, the inclusion of cost analysis further enhances the novelty of this work. By considering the cost of energy per kilojoule, the study provides insights into the potential monetary savings associated with the energy-saving values. This economic perspective adds a practical dimension to the research, enabling stakeholders to evaluate the financial benefits of implementing green roof and cool roof strategies in a cubicle setting.

2 Methodology and materials

2.1 Experimental site

The present study was undertaken in an open space at Jomo Kenyatta University of Agriculture and Technology (JKUAT), which is situated next to Juja township in Kiambu County in Kenya. The experimental site lies at a latitude of −1.183 and a longitude of 37.117 with a mean annual temperature of 18.9 °C varies varying between 13.6 °C and 26.1 °C [26]. The weather is a tropical climate since Kenya lies on the equator with the hot dry months being the primary time for energy consumption. The weather is sunny and hot during the day with the relative humidity ranging from 15 to 80%. The annual wind speed is 3 m/s and 19.62 $MJ/m^2/day$ global solar radiation.

2.2 Description of the experimental setup

An experimental set-up of the cubicles was installed in an open area where maximum absorption of solar radiation could be obtained. In this study, four identical cubicles

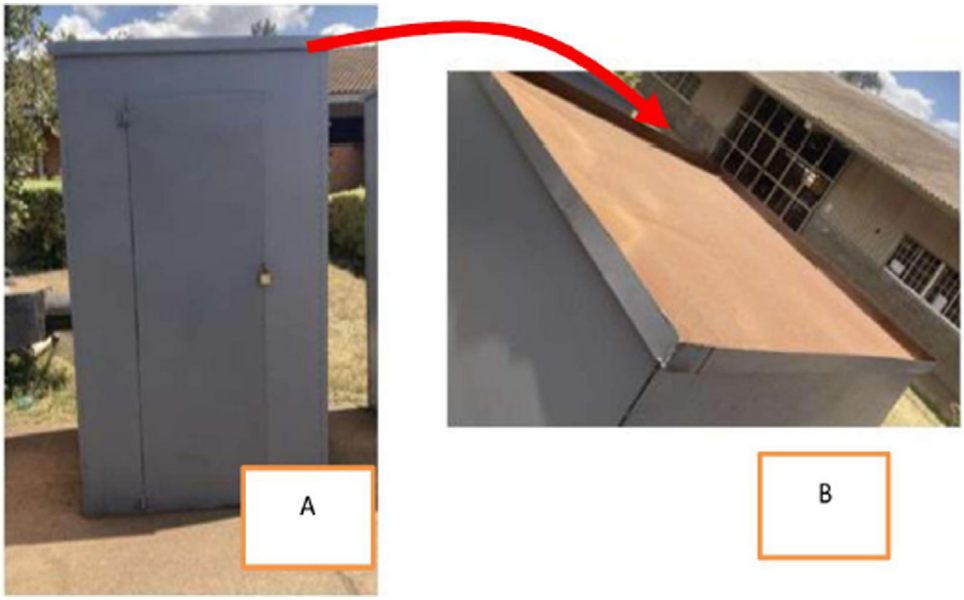

Fig. 1. Bare roof cubicle.

with dimensions of 1.2 m width by 1.2 m length by 2.0 m height were constructed and placed on a concrete floor in an open area with no barriers to solar radiation or shading. To prevent corrosion, the outer surfaces of the cubicles were painted with Jenolite Anti-rust red oxide primer paint which cost. The cubicles were arranged to test different passive cooling techniques, with each cubicle having a unique roof configuration.

The study was conducted from August to November 2022, focusing on both daytime and nighttime performance. For daytime performance, the study focused on the period from 8:00 a.m. to 8:00 p.m., and two operational conditions were applied: closed-window and open-window/door conditions. For the closed-window and door condition, the data from October 21, 2022, was used, and for the open-window and closed-door state, the data from September 21, 2022, was used. These dates were selected because they share the same ambient temperature and they were the hottest in their respective months. The cubicles were arranged as follows.

2.2.1 Case 1: original roof (baseline roof)

The original roof (Case 1) was kept bare without any additional cooling features as shown in Figure 1. Only rust-proof undercoat paint (Jenolite anti-rust red oxide primer paint) was applied on the outer surface walls to prevent corrosion. This cubicle was used as a control group in the study to provide a benchmark for comparison with other cubicles. The purpose of including this cubicle was to evaluate the effectiveness of different passive cooling techniques applied to the other cubicles. Previous research has shown that the roof significantly contributes to the heat load gained inside a building, and most studies cover only the roof with reflective paint [27]. In this study, the original roof was not covered, allowing for a comparison with other cubicles with various cooling techniques.

2.2.2 Case 2: green roof

For Case 2, a similar cubicle as in Case 1 was utilized, but with an additional layer of soil and cowpea plantation on top of the roof, as depicted in Figure 2. An extensive green roof was implemented, comprising a 9 cm soil substrate and a cowpeas plantation with a height of 10 cm which cost KSH 100/kg. The green roof in this case had no filter or drainage layer, as it was constructed with a slope to facilitate smooth water drainage. Cowpeas were selected for the green roof due to their ability to grow rapidly and survive in hot and dry conditions, making them an ideal crop for the local climate [8]. Additionally, cowpeas have been found to provide significant insulation and shading benefits, which can help reduce the amount of heat absorbed by the building.

2.2.3 Case 3: infra-reflective roof

Case 3 involved the examination of the effects of near-infrared (NIR) on temperature and relative humidity inside a steel cubicle. To achieve this, the external smooth surface of the roof was coated with ReduHeat, a paint containing NIR reflective pigments as shown in Figure 3, which cost 10 000 KSH (4 l) in Nairobi. ReduHeat is a shading technique that strikes a balance between light transmission and heat reflection. The paint was mixed with water in a 1:2 ratio and stirred thoroughly to ensure an even mixture. A sprayer was then applied to ensure uniform distribution over the roof surface. Near-infrared (NIR) reflective paint is often used for the passive cooling of buildings because it reflects a significant portion of the solar radiation that hits it. This helps to reduce the amount of heat absorbed by the building, which can lead to a cooler indoor temperature. NIR reflective pigments are designed to reflect radiation in the range of 700–1400 nm, which is the portion of the spectrum that is responsible for most of the heat gain in buildings [27]. By reflecting this radiation,

Fig. 2. Green roof cubicle.

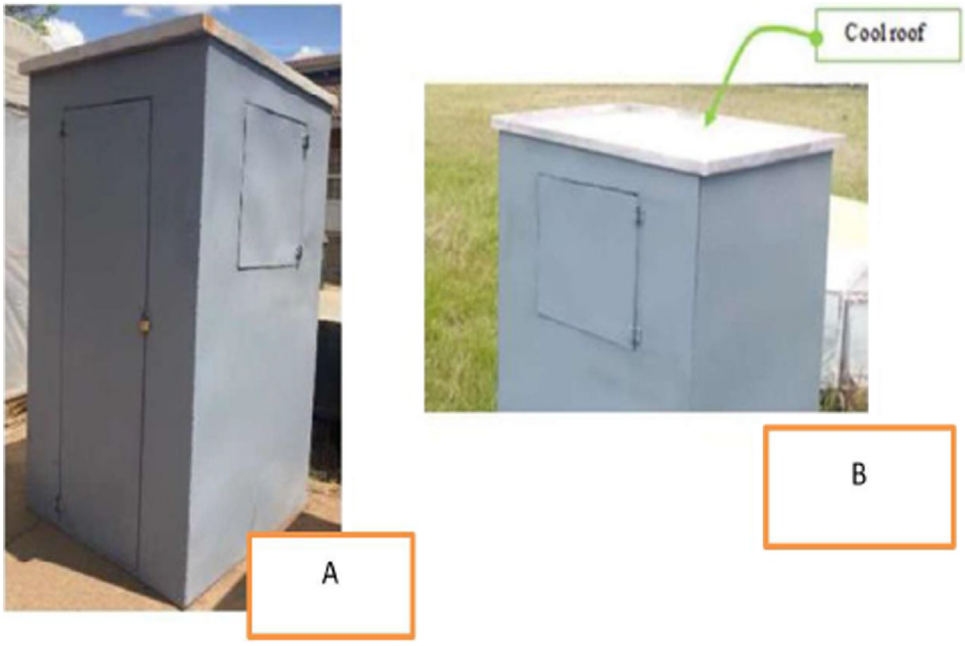

Fig. 3. Cool roof cubicle.

the paint can help to reduce the temperature inside the building and decrease the amount of energy required for cooling [28]. NIR reflective paint has been shown to be an effective passive cooling technique, especially in hot and arid climates where solar radiation is high.

2.2.4 Case 4–cubicle 4: combination of extensive green roof and reflective (cool) roof

This cubicle was designed to assess the combined effect of NIR reflection and transpiration cooling on the temperature and relative humidity within a steel cubicle. Similar to Case 2, an extensive green roof with cowpeas was implemented on the roof, but in addition, the outer surface walls were coated with ReduHeat paint as shown in Figure 4. This paint contains NIR reflective pigments and uniquely balances light transmission and heat reflection [28]. The purpose of combining the green roof and the NIR reflective paint was to evaluate their synergistic effect on reducing the heat load within the cubicle. The use of the green roof and transpiration cooling through cowpeas plantations helps to remove heat through the process of evapotranspiration, while the NIR reflective paint reduces heat gain through solar radiation.

Table 1. Instruments specifications.

Instrument	Type	Variable	Accuracy
HOBO data loggers	MX1101 data Japan	Temperature Relative humidity	±0.21°C from 0°−50°C ±3.5% from 25% −85%

Fig. 4. Combined roof cubicle (equipped with extensive green and cool roof).

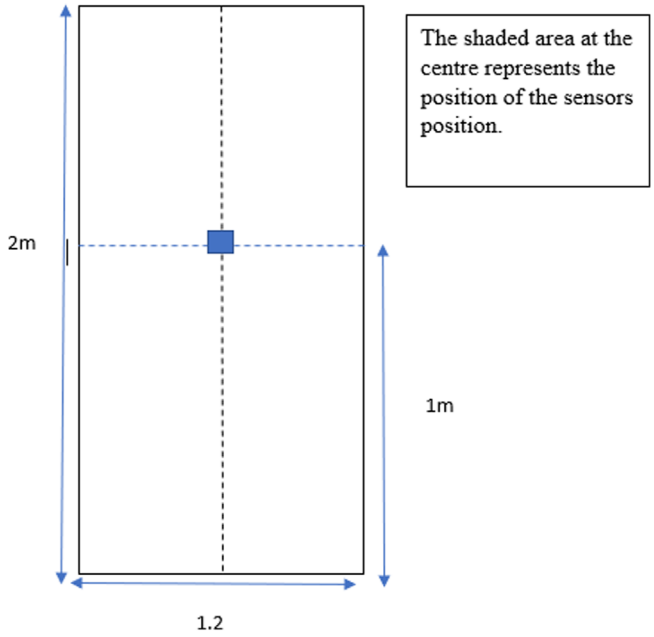

Fig. 5. Cross-sectional view of the cubicle, indicating the placement of the interior sensors.

Table 2. Extensive green roof and reflective roof parameters input for EnergyPlus.

Field	Unit	Object
Subtract thickness	m	0.09
Vegetation LAI	dimensionless	5
Leaf reflectivity	dimensionless	0.9
Plant height	m	0.5
Minimum stomatal resistance	s/m	180
Roughness		Medium smooth
Solar reflectance		0.4
Visible reflecting		0.6

2.3 Equipment used in this experiment for data collection

The equipment used in this experiment is presented in Table 1. To minimize the edge effect, the inside sensors were placed at the center of each cubicle, 1 m from the ground, as illustrated in Figure 5. The temperature and

Table 3. The cubicle geometrical data input into EnergyPlus.

Field	Units	Object 1	Object 2	Object 3	Object 4	Object 5	Object 6
Name		Zone surface East	Zone Surface South	Zone surface west	Zone surface West	Zone Surface north	Zone surface floor
Surface type		Wall	Wall	Wall	Wall	Wall	Floor
Construction name		Ltwall	Ltwall	Ltwall	Ltwall	Ltwall	Ltfloor
Zone name		Zone ONE	Zone ONE	Zone ONE	Zone ONE	Zone ONE	Zone ONE
Outside boundary condition		Outdoor	Outdoor	Outdoor	Outdoor	Outdoor	Adiabatic
Sun exposed		Sun exposed	Sun exposed	Sun exposed	Sun exposed	Sun exposed	No sun exposed
Wind exposed		WindExposed	WindExposed	WindExposed	WindExposed	WindExposed	NoWindExposed
View factor to ground		0.5	0.5	0.5	0.5	0.5	0.5
Number of vertex		4	4	4	4	4	4
Vertex 1X coordinates	m	1.2	1.2	0	0	0	0
Vertex 1Y coordinates	m	1.2	0	0	1.2	0	0
Vertex 1Z coordinates		2	2	2	2	0	2
Vertex 2X coordinates		1.2	1.2	0	0	0	0
Vertex 2Y coordinates		1.2	0	0	1.2	1.2	0
Vertex 2Z coordinates		0	0	0	0	0	2
Vertex 3X coordinates		0	1.2	1.2	0	1.2	1.2
Vertex 3Y coordinates		1.2	1.2	0	0	1.2	1.2
Vertex 3Z coordinates		0	0	0	0	0	2
Vertex 4X coordinates		0	1.2	1.2	0	1.2	1.2
Vertex 4Y coordinates		1.2	1.2	0	0	0	1.2
Vertex 4Z coordinates		2	2	2	2	0	2

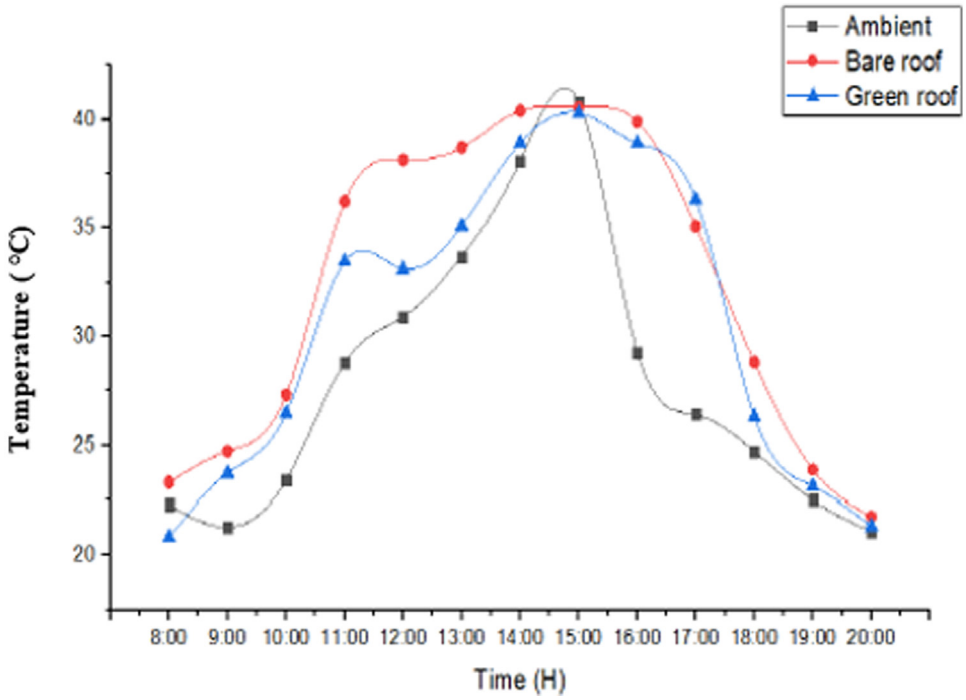

Fig. 6. Comparative analysis of temperature profiles: combined roof, bare roof, and ambient temperature.

relative humidity inside each cubicle were measured every 15 min using the sensors, and the average values were recorded after each hour. The outside sensor was positioned 2 m above the ground to measure the outdoor temperature and relative humidity.

2.4 Green and cool roof model development

Cooling energy demand was determined through computational simulations using an open-source software known as EnergyPlus [29,30]. EnergyPlus is a widely used simulation program for modeling the building's cooling and heating energy required. It was released in 2001, and EnergyPlus replaced BLAST and DOE because of their technical and structural limitations [31]. It simulates 6 to 15 times per hour to show how a typical building would operate when subjected to the yearly weather meteorological [11]. Moreover, it includes a module simulating a vegetated roof's energy balance. EnergyPlus program has been previously verified and validated using experimental data [29,31,32] and it is, therefore acceptable in this study.

In this study, EnergyPlus was used as a secondary means to calculate the energy required and saving inside four fabricated cubicles with different roofing techniques. The green, cool, combined, and bare roofs were modeled in EnergyPlus V8.7. For each of the four cubicles, numerical computations were performed using experimental data measured at the center of each cubicle as an input variable. Green and cool roof input properties are shown in Table 2. Two input files are required to run the EnergyPlus simulation: the input data file (IDF) and the weather file. Input data file (IDF) includes all the building aspects, such as building construction material, geometry, human occupancy, internal load, cooling or heating equipment, glazing, etc. The input data applied in this study are shown in Table 3. This file was generated to reflect the same physical geometry and data used in the experimental setup discussed in Section 2.2. The daily weather file was generated using experimentally measured data obtained from each cubicle. The experimental results included hourly temperature, relative humidity, dew point, and dry point.

3 Results and discussion

This section is divided into four subsections, each highlighting specific aspects of the study. The first two subsections present the experimental results for two different case scenarios: the open-window state and the closed-window state. The third subsection focuses on the energy consumption and savings within each cubicle, using the Energy Plus simulation software. Lastly, the fourth subsection presents the energy-saving values and corresponding monetary savings.

To conduct the analysis, data from two specific days were utilized. The first day, 21 September 2022, represented the open-window state, while the second day, 21 October 2022, represented the closed-window state. These two days were selected due to their status as the hottest days, and they shared identical average ambient temperature and relative humidity conditions of 28 °C and 42%, respectively (presenting outside environmental conditions).

3.1 Temperature distribution in the cubicles-open-window closed door state

3.1.1 Green roof effects on temperature in comparison to bare and ambient temperature

Figure 6 shows the daily temperature of the green roof compared with the bare roof and ambient in the open

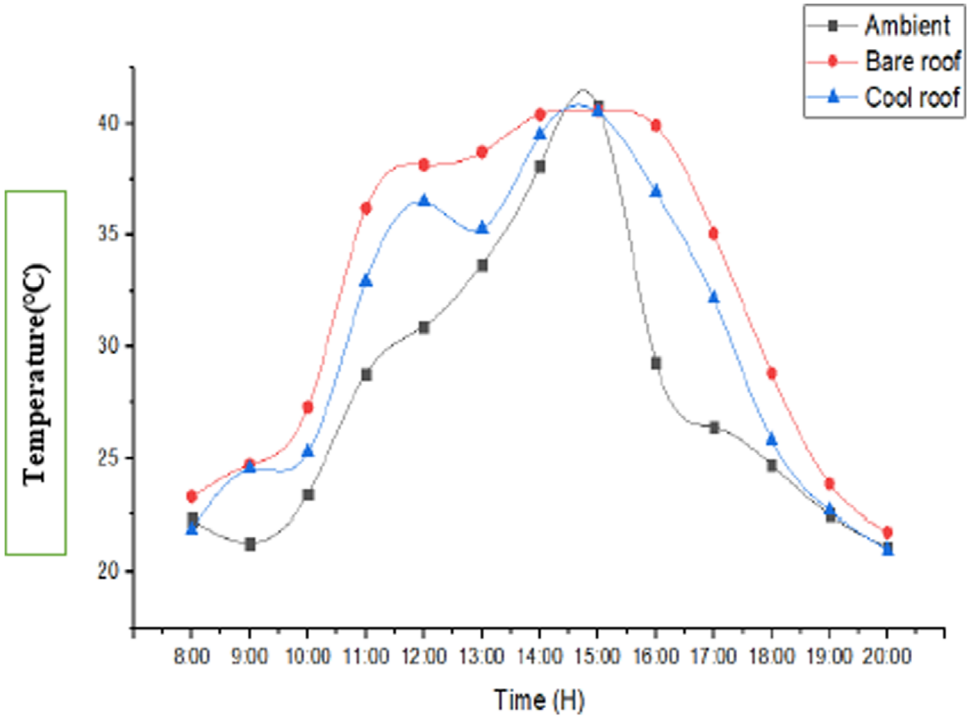

Fig. 7. Comparative analysis of temperature profiles: cool roof, bare roof, and ambient temperature.

window condition, the green roof consistently demonstrated the lowest temperature among all roof types. This is particularly evident during the hottest part of the day, where the green roof temperature remained relatively stable while the bare roof and cool roof temperatures continued to increase. Compared to the bare roof, the green roof had a temperature reduction of 5.04 °C at 12:00 and 1.4 °C at 14:00. This indicates that the green roof was able to effectively insulate the building from the sun's heat, reducing heat transfer to the roof surface and maintaining a cooler temperature. Moreover, several other studies have documented the benefits of green roofs in reducing urban heat island effects and mitigating heat transfer. For instance, William et al. [15] conducted a comprehensive analysis of green roof performance and found that green roofs can lower roof surface temperatures by 20–30 °C compared to conventional roofs. These results highlight the significant cooling potential of green roofs in urban environments.

In contrast, the bare roof was unable to dissipate heat effectively and became significantly hotter than the green roof, with a temperature difference of 0.917 °C at 14:00. These results attest to Ahmed et al. [33]who reported a daily average temperature difference of 0.95 °C between green and bare roof steel containers. This difference was obtained after comparing the green and non-green cubicles. When compared to the ambient temperature, the ambient was consistently lower throughout the day. The average temperature difference of the green roof was 2.7 °C higher than the ambient temperature. This means that the green roof is not able to provide complete insulation from the outdoor heat. However, it is still able to reduce the temperature of the roof surface compared to the bare roof. This is important because it can help to reduce heat transfer into the building, which can in turn reduce the energy required for cooling.

3.1.2 Comparative analysis of green roof effects on temperature in comparison to bare roof and ambient temperature

Figure 7 shows the hourly temperature measurements for the ambient, bare, and cool roofs. Regarding the peak and average temperatures, the cool roof had the lowest peak temperature and average temperature compared to the bare and ambient roofs. The peak temperatures for the cool, bare, and ambient roofs were 40.52 °C, 40.97 °C, and 40.9 °C, respectively. The average temperatures for the cool, bare, and ambient roofs were 29.6 °C, 30.8 °C, and 28.01 °C, respectively. It appears that the average temperature of the cool roof was higher than that of the ambient roof. However, the peak temperature of the cool roof was lower than that of the bare and ambient roofs. Although the average temperature of the cool roof was higher than that of the ambient roof in this study, it is important to note that the cool roof still had a lower peak temperature than the ambient roof. This means that while the cool roof may not always have the lowest average temperature, it can still effectively reduce the peak temperature of the roof surface. Additionally, the cool roof's higher average temperature compared to the ambient roof may be due to the cool roof's ability to absorb less heat during peak hours, leading to a slower release of stored heat during non-peak hours. Overall, the study suggests that the cool roof was effective at reducing the peak temperature and average temperature of the roof

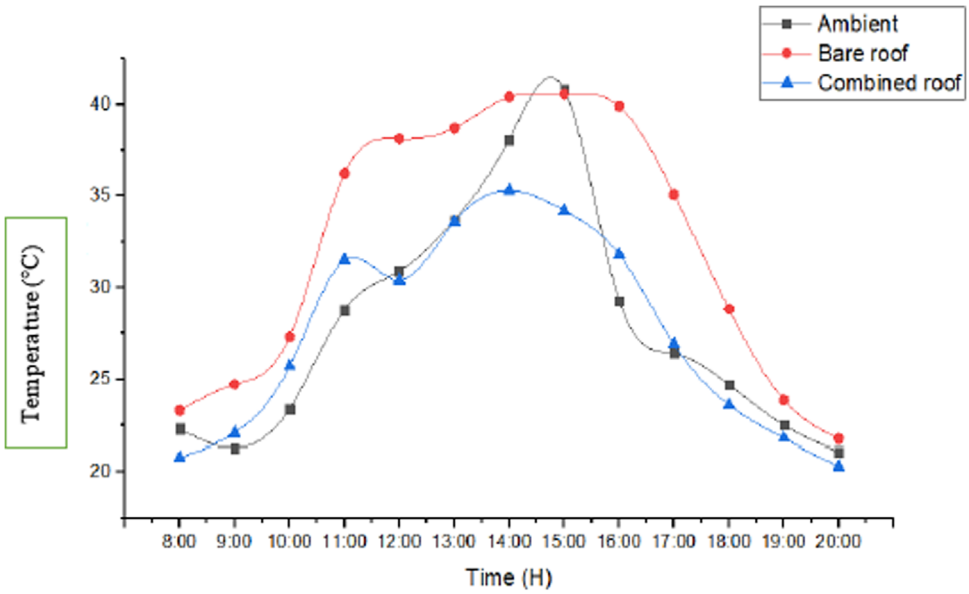

Fig. 8. Comparative analysis of temperature profiles: combined roof, bare roof, and ambient temperature.

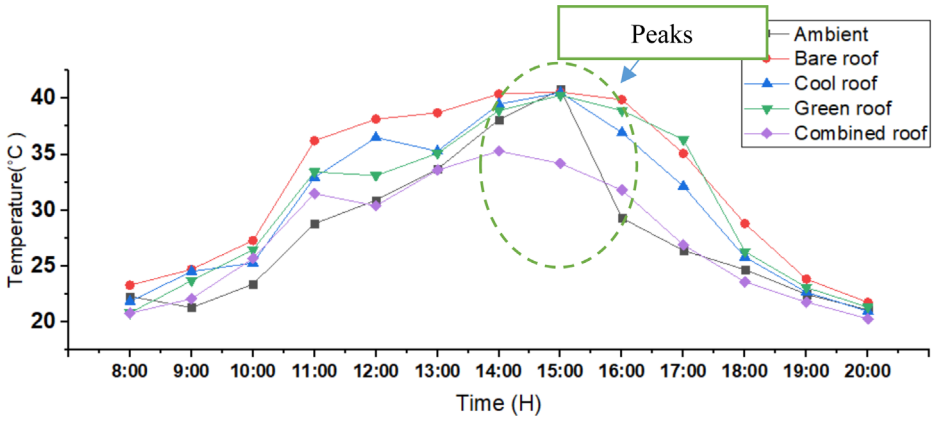

Fig. 9. Temperature profile captured on September 21, 2022, during a closed-window scenario. This day marked the highest temperature with an average of 28 °C and relative humidity at 43.48%.

surface compared to the bare and ambient roofs, but the extent of the reduction varied depending on the time of day. This is consistent with other studies that have found that cool roofs are most effective during peak hours when solar radiation is the highest. For example, a study by Wang et al. [24] found that cool roofs were most effective in reducing peak roof temperatures during the summer months in Beijing, China. Additionally, the results demonstrate that the bare roof had the highest peak and average temperatures, indicating that the roof surface absorbs and retains more heat than the cool and ambient roofs. This is consistent with previous studies that have found that the use of cool roofs can significantly reduce the roof surface temperature and decrease the amount of heat absorbed by buildings.

For instance, a study by Li et al. [34] found that the installation of cool roofs in urban areas could reduce the urban heat island effect and lead to energy savings by decreasing the cooling load of buildings. Furthermore, the lower peak of the cool roof in this study suggests that it can help improve indoor thermal comfort, particularly in buildings without air conditioning or those with limited access to it. This is because lower roof surface temperatures can reduce heat transfer to the building interior, leading to a more comfortable indoor environment.

3.1.3 Comparative analysis of combined roof effects on temperature in comparison to bare and ambient temperature

Using a combination of green roofs and cool roofs is more effective in reducing cooling energy demand than using them separately as shown in Figure 8. This combination not only lowers indoor temperatures but also decreases the temperature difference between indoor and outdoor environments. Compared to a bare roof, this technique reduces peak temperatures and average temperature differences by 5 °C and 1.01 °C, respectively. The combined

Table 4. The table presents the daily average and peak temperature differences inside the four cubicles (Cases 1, 2, 3, and 4) when the windows are open and the doors are closed.

Open-window state	Ambient	Bare roof	Green roof	Cool Roof	Combined roof
Peak Temperature	40.9 °C	40.97 °C	40.29 °C	40.52 °C	34.2 °C
Daily average temperature	28.01 °C	30.8 °C	30.2 °C	29.6 °C	27.1 °C

Table 5. The table illustrates the daily temperature difference between the green, cool, and combined cubicles compared to the bare roof cubicle in both the open window-closed door and closed window and door states.

States	Green roof cubicle against bare roof temperature difference	Coof roof cubicle against bare roof temperature difference	Combined roof cubicle against bare roof temperature difference
Open-window state	2. 67 °C	3.64 °C	4.24 °C.
Closed-window state	0.72 °C	0.79 °C	4.14 °C

roof performed better than when the techniques were used in isolation because it incorporates both green and cool roof technologies.

The green roof reduces heat by absorbing and evaporating water, while the cool roof reflects sunlight and reduces the absorption of heat. When used in isolation, the green roof can still absorb some heat, and the cool roof can only reflect a certain amount of sunlight. However, when combined, the green roof can provide a cooling effect for the cool roof, which in turn can reflect more sunlight and reduce the overall heat absorbed by the roof.

The study suggests that integrating various cooling techniques can have a more significant impact on reducing energy consumption and indoor temperature. The use of green roofs and cool roofs is an energy-efficient solution for building design and construction, but their effectiveness may vary depending on location, climate, building design, and material properties. It is important to consider the specific conditions and requirements of each building when deciding on roofing materials and cooling techniques. The orientation and movement of solar radiation significantly impact temperature reduction in combined cubicles. The combination of a green roof and a cool roof provides protection the roof from solar radiation, which helps prevent heat storage and results in lower temperatures compared to using them separately. Additionally, the green roof acts as insulation and helps retain moisture, which slows down heat transfer from the roof to the interior. The cool roof reduces the amount of solar radiation absorbed by reflecting it, thus reducing the temperature of the roof surface.

3.1.4 Comparative analysis of temperature effects: green roof, cool roof, combined roof, bare roof, and ambient conditions

Figure 9 shows the results of the open window experiment show that all five types of roofs (ambient, bare, green, combined, and cool) experienced different temperature variations throughout the day. The provided data shows the temperature measurements for four different types of roofs (bare, green, cool, and combined) at various times of the day with an open window condition. The ambient temperature was also measured for comparison.

The results indicate that the combined roof had the lowest peak and average temperatures among all four types of roofs. The green roof had lower temperatures than the bare roof, but still higher than the ambient temperature. The cool roof had lower temperatures than the green roof, but higher than the combined roof. One possible explanation for the superior performance of the combined roof is that the green roof was able to absorb and evaporate some of the heat, while the cool roof reflected the rest of the heat away from the building. This suggests that combining different cooling techniques can lead to more effective temperature reduction than using each technique in isolation. It is important to note that the effectiveness of these cooling techniques can vary depending on various factors such as climate, building design, and usage patterns. These results agree with Kim et al. [35] who reported that open windows combined with green roofs provided better thermal comfort and reduced the need for mechanical cooling systems. In contrast, Radhika et al. [36] showed that the combination of cool roofs and open windows enhanced indoor thermal comfort by reducing heat gain. However, the results of this study suggest that the combined use of green and cool roofs can provide a promising solution for reducing urban heat island effects and improving building energy efficiency The results of the open window condition for all four types of roofs showed that the temperatures were generally lower compared to the closed window condition. The ambient temperature remained relatively constant throughout the day, with a peak of 40.9 °C at 3 p.m. The bare roof had the highest temperatures among all the roofs, with a peak of 40.97 °C at 3 p.m. and an average temperature of 30.8 °C. The green roof had the lowest temperatures among all the roofs, with an average temperature of 29.94 °C. However, the peak

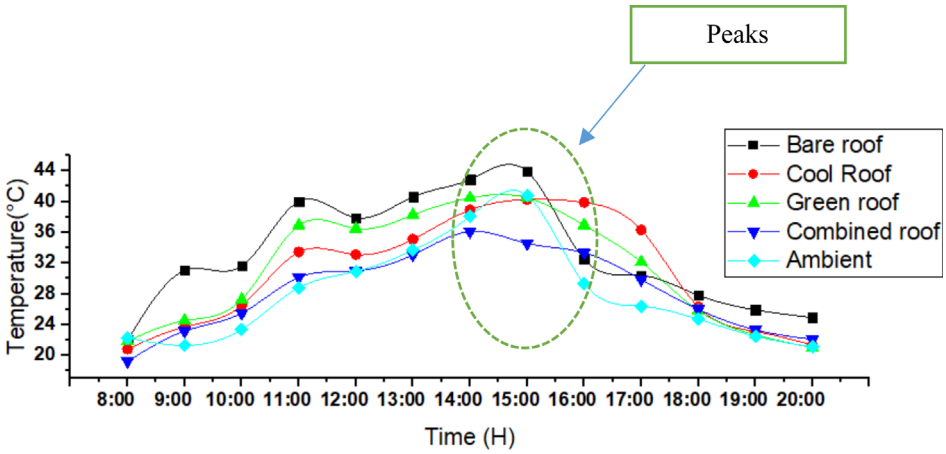

Fig. 10. Temperature profile on a closed-window condition taken on 21 October 2022, the hottest day with a daily average temperature and relative humidity of 28.1 °C and 43.48%, respectively.

temperature of the green roof was still higher than the ambient temperature, reaching 38.92 °C at 2 p.m. The cool roof had an average temperature of 29.51 °C, which was lower than the bare roof but higher than the green roof

.The peak temperature of the cool roof was 40.52 °C at 3 p.m., which was only slightly lower than the peak temperature of the bare roof.

Finally, the combined roof had the lowest temperatures among all the roofs, with an average temperature of 27.1 °C and a peak temperature of 34.2 °C at 11 a.m. as shown in Table 4. The combined roof performed better than all other roofs, indicating that the combination of green and cool roof techniques was more effective in reducing temperatures than using either technique in isolation. In conclusion, the open window condition resulted in lower temperatures for all four types of roofs, with the combined roof performing the best.

In this study, open windows provided better natural ventilation and increase air movement within the building, which reduced indoor temperatures. This is because it allows for hot air to escape and cool air to circulate, creating a more comfortable environment. Additionally, it indirectly helped to reduce the cooling energy required from air conditioning (Tab. 5).

3.2 Temperature distribution in the cubicles-closed-window closed door state

Based on the results of the study in Figure 10, it is clear that the closed window condition resulted in higher temperatures for all types of roofs compared to the open window condition. This finding is consistent with previous research that has shown that natural ventilation can significantly reduce indoor temperatures, particularly in buildings with high thermal mass and high levels of insulation. In addition, it has been observed that natural ventilation can improve indoor air quality by reducing the accumulation of pollutants and moisture.

Interestingly, the results also showed that the combined roof had the lowest peak and average temperatures among all four types of roofs, even under the closed window condition. This suggests that the combination of green and cool roof techniques can still be effective in reducing indoor temperatures, even in buildings where natural ventilation is limited.

Furthermore, the cool roof performed better than the green roof in terms of reducing indoor temperatures under a closed-window state. This finding is consistent with previous research that has shown that cool roofs are particularly effective in reducing heat transfer through the roof, which can help to reduce the amount of heat that is absorbed into the building [37]. In contrast, in a study conducted by Guo et al. [38] it was observed that the cool roof exhibited superior performance in reducing indoor temperatures compared to the green roof when windows were closed. This indicates that cool roofs have a stronger ability to reflect solar radiation and prevent heat transfer, thus contributing to lower indoor temperatures.

Moreover, the results of this study suggest that natural ventilation is an effective way to reduce indoor temperatures, but combining green and cool roof techniques can further enhance the cooling performance of buildings, even when natural ventilation is limited. The results attest to a study conducted by Li et al. [39] that investigated the combined effects of green roofs and cool roofs on building cooling performance. The findings showed that the integration of these two techniques resulted in a significant reduction in indoor temperatures, even in situations where natural ventilation was restricted.

3.3 Distribution of relative humidity in cubicles: a comparison between open-window closed-door state and closed-window closed-door state

The average relative humidity values for different roof types in both the open-window and closed-window states are presented in Figures 11 and 12.

In the open-window state, the green roof has an average relative humidity of 44.7%, the cool roof cubicle has 44.79%, the combined roof cubicle has 52.03%, and the bare roof has 38.7% (Table 6).

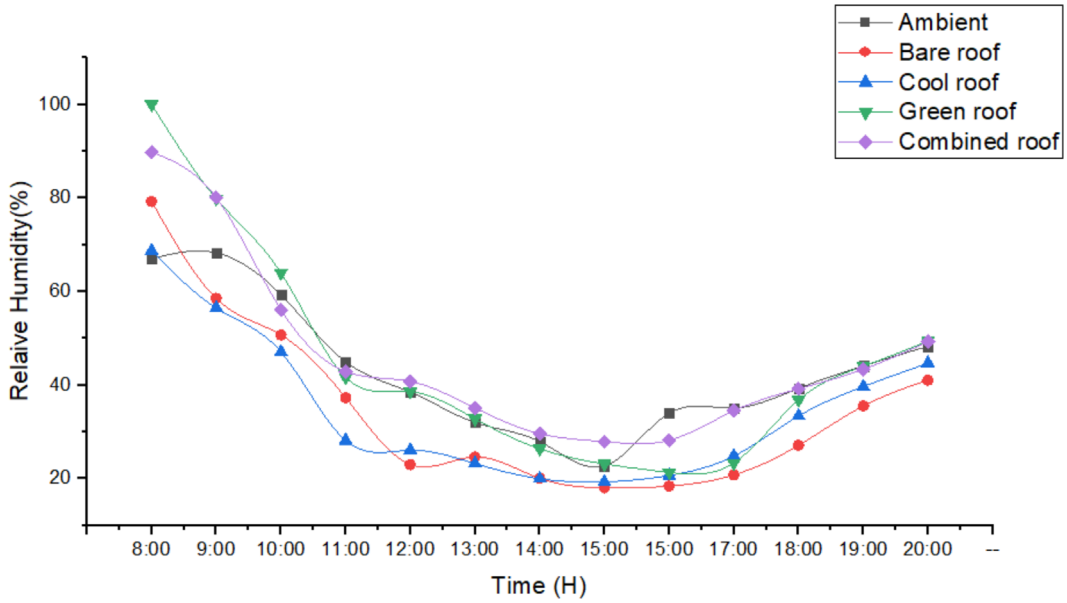

Fig. 11. Open-window state relative humidity.

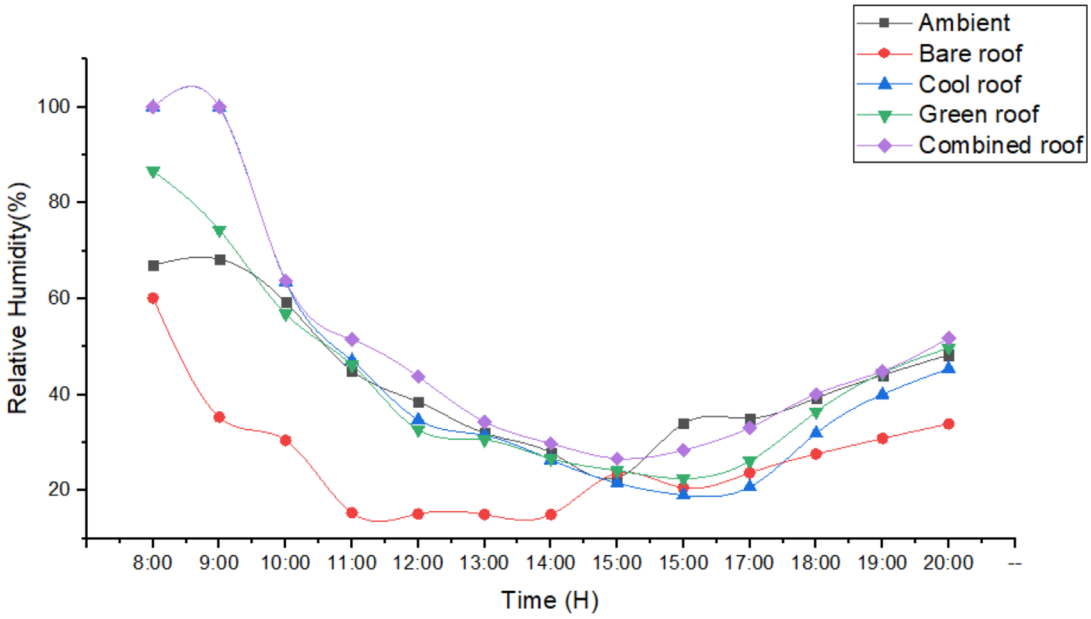

Fig. 12. Closed-window state relative humidity.

Table 6. Presents the daily average and peak temperature differences inside Cases 1, 2, 3, 4, and the cubicle during the closed window-closed door state.

Open-window state	Ambient	Bare roof	Green roof	Cool Roof	Combined roof
Peak temperature	40.9 °C	43.97 °C	41.5 °C	42.5 °C	36.12 °C
Daily average temperature	28.01 °C	32.43 °C	31.71 °C	31.65 °C	28.12 °C

Table 7. Close and open window state relative humidity results.

States	Green roof	Coof roof cubicle	Combined roof cubicle	Bare roof
Open-window state	44.7%	44.79%	52.03%	38.7%
Closed-window state	42.9%	34.8%	42.5%	26.6%

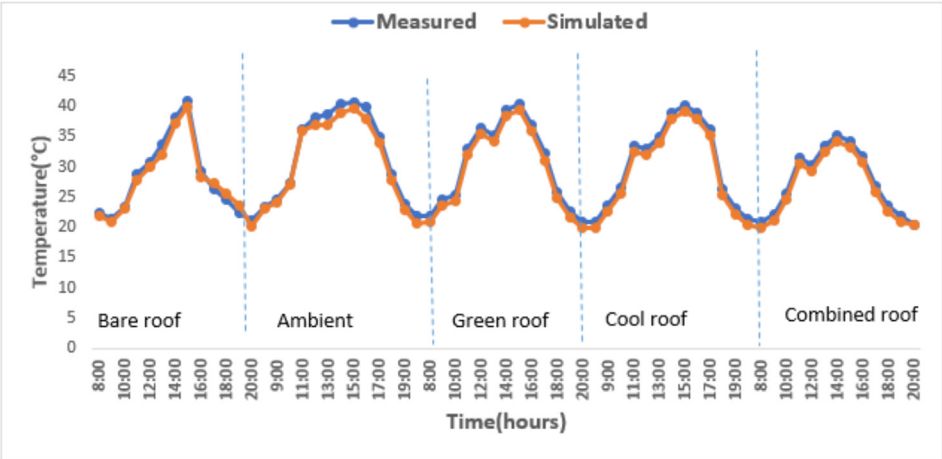

Fig. 13. The comparison between the simulated and measured temperature profiles of the ambient, bare roof, green roof, cool roof, and combined roof in the open-window closed door state.

Table 8. Comparison of simulated and measured error results (RMSE and NSEC).

Roof	Closed-window state		Open-window state	
	RMSE(°C)	NSEC	RMSE(°C)	NSEC
Original roof	1.38	0.89	1.03	0.89
Green roof	0.91	0.91	0.81	0.94
Cool roof	0.80	0.90	0.72	0.91
Combined roof	0.71	0.92	0.76	0.89

Table 9. The cooling energy savings for the green, cool, and combined cubicles compared to the bare roof over a three-month period with closed windows and doors.

Combined cubicle	Green roof	Cool roof energy
53.57 kJ	20.074 kJ	3.68 kJ

In the closed-window state, the green roof has an average relative humidity of 42.9%, the cool roof cubicle has 34.8%, the combined roof cubicle has 42.5%, and the bare roof has 26.6%.

In the open-window state, the RH values for the green roof, cool roof, and combined roof cubicles fall within the recommended range, indicating favorable moisture levels. This suggests that these roof types contribute to a comfortable indoor environment by helping to retain moisture and prevent excessive dryness. However, the bare roof exhibits a lower RH value, falling below the recommended range. This indicates that the bare roof may result in drier indoor conditions, which could potentially lead to discomfort and respiratory issues for occupants.

In the closed-window state, it is observed that both the cool roof and bare roof cubicles have lower RH values compared to the green and combined roof cubicles. The cool roof cubicle exhibits a notably lower RH value, suggesting that the cool roof technique may contribute to drier indoor conditions when natural ventilation is restricted. On the other hand, the green and combined

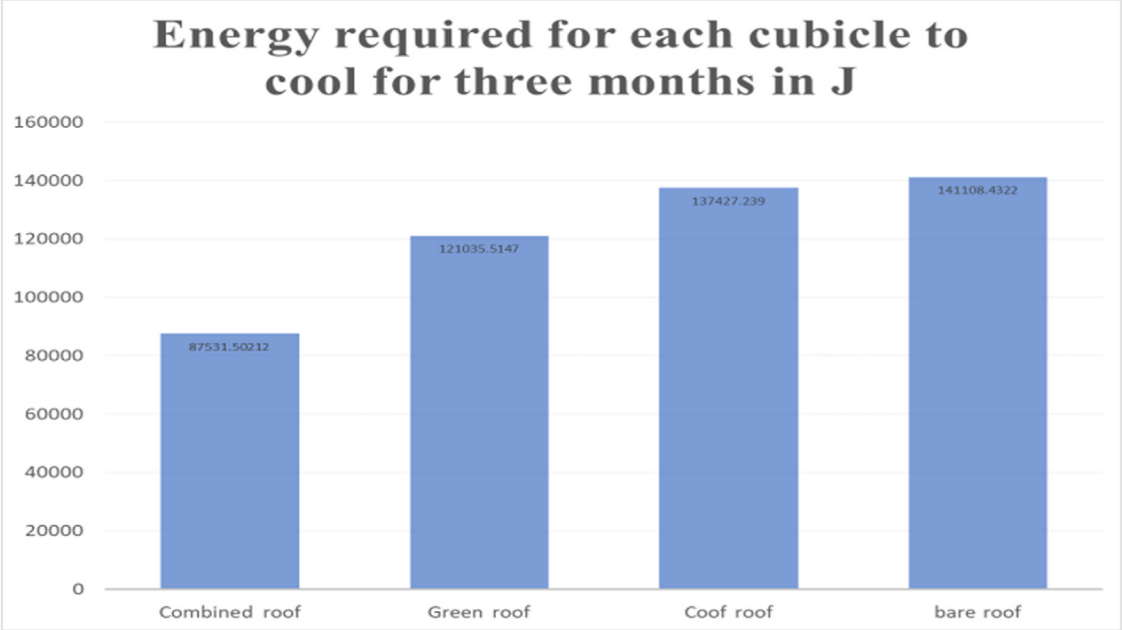

Fig. 14. Depicts the simulated cooling requirements inside each cubicle over a 3-month period, from 24th September 2022 to 18th November 2022, between 8 a.m. and 8 p.m.

Table 10. Energy-saving values and corresponding monetary savings.

Cubicle type	Energy saving (kJ)	Monetary savings (KSH)
Combined cubicle	53.57	444.63
Green cubicle	20.074	166.55
Cool Cubicle	3.68	20.46

roof cubicles maintain relatively higher RH values, indicating better moisture retention and potentially creating a more comfortable indoor environment.

Comparing the open-window and closed-window states, it can be observed that the relative humidity values are generally higher in the open-window state for all roof types. This is expected as the open window allows for increased air exchange between the indoor and outdoor environments, leading to higher moisture content inside the building.

These findings align with Liu et al. [24] that have shown the positive impact of green roofs on indoor humidity levels. The moisture retention properties of green roofs help to maintain optimal RH levels, contributing to occupant comfort and well-being. The combined roof cubicle, which combines both green and cool roof techniques, performs well in terms of RH levels in both the open-window and closed-window states, highlighting the potential synergistic effects of using multiple cooling strategies.

Among the roof types, the combined roof cubicle exhibits the highest average relative humidity in both the open-window and closed-window states. This can be attributed to the combined effect of the green roof and cool roof techniques, which potentially enhance moisture retention and reduce moisture loss. The study by Liu et al. [39] investigated the influence of green roofs on indoor humidity levels in different climatic regions. The results indicated that green roofs can effectively increase relative humidity levels within the building, providing a more comfortable and healthier indoor environment. Additionally, Wang et al. [24] investigated the influence of different roof types on indoor relative humidity levels. The results showed that the combined roof cubicle had the highest average relative humidity in both the open-window and closed-window states, indicating the potential of the combined green and cool roof techniques to enhance moisture retention.

3.4 Energy analysis

3.4.1 Model validation and results

The results obtained from the EnergyPlus simulation were analyzed and compared to the experimental data to validate the accuracy of the simulation model. The simulation was performed under a closed-window and open-window state. The simulation results were compared with the measured indoor temperature (Tin) experimental data. The set point was set at 24 °C. The root-mean-square error (RMSE) and Nash-Sutcliffe efficiency coefficient (NSEC) were employed to quantify the agreement between the simulated and measured data, as summarized in Table 7. RMSE assesses the consistency and accuracy of the model's results by comparing measurements and

simulations as shown in equation (1) [14]. NSEC measures its efficiency and ranges from 0 to 1, 0 denoting a perfect match between predicted and measured values, and 1 denoting an inaccurate prediction as shown in equation (2). Their equations are illustrated in equations (1) and (2) [14]. The NSEC and RMSE results show that the model is accurate and can be used to determine energy saving in the building the results are shown in Figure 13 and Table 8.

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(Value^t - Value^t)^2} \tag{1}$$

$$NSEC = 1 - \frac{\sum_{t=1}^{n}(Value^t - Value^t)^2}{\sum_{y=1}^{n}\left(Value^t - Value_{observed}\right)^2}. \tag{2}$$

3.4.2 Effect of green, cool, and combined roofs on energy

The energy-saving values for cooling inside each cubicle, including the combined cubicle, green roof, and cool roof, are presented in Table 9 (Fig. 14).

The combined cubicle exhibits the highest energy-saving value of 53.57 kJ, followed by the green roof with 20.074 kJ and the cool roof with 3.68 kJ as shown in Table 9. This is in line with previous research by Li et al. [39], who highlighted the insulation properties and evaporative cooling effect of green roofs as contributing factors to reducing cooling load and achieving energy savings.

These energy-saving values indicate the reduction in cooling energy consumption achieved by implementing the respective roof techniques. The combined cubicle, which incorporates both a green roof and cool roof strategies, demonstrates the highest energy-saving potential. This is likely due to the synergistic effects of the two techniques, where the green roof helps to reduce heat gain through absorption and evapotranspiration, while the cool roof reflects a significant portion of solar radiation.

The green roof alone also contributes to energy savings by mitigating heat transfer through its insulation properties and evaporative cooling effect. However, it is noteworthy that the energy-saving value for the green roof (20.074 kJ) is lower compared to the combined cubicle, indicating the added benefit of integrating multiple strategies.

The cool roof technique shows the lowest energy-saving value among the three (3.68 kJ). While it still provides some reduction in cooling energy consumption through solar reflectance, its individual impact appears to be less significant than that of the green roof or the combined approach.

These findings highlight the importance of integrating multiple strategies to optimize energy efficiency in cooling buildings. Studies such as the one conducted by Chen et al. [40] have investigated the combined effects of green roofs and cool roofs, demonstrating higher energy savings compared to individual implementation. overall, the energy-saving values obtained from the study align with the findings in the literature. The combined cubicle, incorporating both a green roof and cool roof techniques, offers the highest energy-saving potential He et al. [22], [39]. The green roof alone also provides notable energy savings, while the cool roof has a comparatively lower impact on energy reduction.

3.4.3 Energy-saving values and corresponding monetary savings

Table 10 presents the three months' energy-saving values and corresponding monetary savings for each cubicle type in Kenya, considering the cost of energy as 8.3 KSH/kWh.

The findings of this study show the energy and financial savings made possible by the use of various cubicle types. The combination cubicle among the cubicle types demonstrated the biggest energy savings of 53.57 kJ, which translates to a financial saving of almost 444.731 KSH. This is due to the synergistic benefits of combining green and cool roof technologies in a single cubicle, which increases energy efficiency and results in cost savings.

The green roof cubicle saved 20.074 kJ in energy, translating to a financial savings of almost 166.655 KSH. The cost of plants for the green roof is estimated at 200 KSH/kg, while the painting cost is 5000 KSH . Despite being significant, the energy savings offered by the green roof alone were less than those offered by the combined cubicle. This demonstrates that the cool roof technique's added cooling advantages

The cool roof cubicle, on the other hand, had the lowest energy-saving value (3.68 kJ), corresponding to a financial savings of almost 30.478 KSH. Although the cool roof method helped to lower the amount of energy used for cooling, its effect was not as great as the green roof or the combination method.

Based on the findings, implementing different cubicle types, notably the combination cubicle, green roof cubicle, and cool roof cubicle, results in overall energy and monetary savings. Despite the upfront expenditures involved in installing various cooling techniques, the ensuing energy savings have a net beneficial financial impact.

The cubicle that combined green and cool roof technologies showed the most potential for energy reductions as well as financial benefits. Despite having a greater upfront cost, the combined approach's large energy savings help lower long-term costs, yielding a favorable return on investment. These results align with several studies in the literature. For instance, Wang et al. [41] conducted a study on the energy performance of green roofs and reported significant energy savings in cooling load. They emphasized the importance of combining green roof techniques with other energy-efficient strategies to maximize energy savings. Additionally, Li et al. [39] investigated the impact of cool roofs on energy consumption and found substantial reductions in cooling energy demand.

Similar energy and financial reductions were shown by the cool roof and green roof cubicles. The overall findings show that these cooling solutions contribute to lowering cooling energy consumption and creating financial benefits over time, even though the beginning expenses and energy savings may differ for each approach.

Therefore, it can be stated that using green and cool roof solutions results in net energy and cost savings after taking into account the original investment expenses and the eventual financial gains from lower energy usage. These methods offer a practical cooling option for buildings that is both environmentally friendly and economically advantageous.

4 Conclusion

In this study, the cooling effect of green roofs, cool roofs, and their combined implementation in the tropical climate of Kenya was investigated. The objective was to analyze the combined impact on indoor temperature and cooling energy consumption in comparison to a bare roof.

The findings of the experiments showed that the combined benefits of green and cool roofs had a stronger cooling effect compared to their individual implementation in both open and closed-window states. While the open-window state reduced the peak indoor temperature in all cubicles, the indoor temperature of the bare, green, and cool roof cubicles remained higher than the ambient temperature, indicating a continued need for cooling energy. However, the combined green and cool roof cubicle significantly reduced the peak temperature by a factor of 7, and its average temperature was 1.01 °C below the ambient level.

Moreover, the simulation results confirmed the superior cooling performance of the combined cubicle, with lower cooling energy requirements compared to the other cubicle types. The three-month cooling energy savings in the combined cubicle were quantified as 53.57 kWh, indicating substantial energy efficiency.

From a cost perspective, the combined cubicle also showcased the highest monetary savings. The integration of green and cool roofs contributed to significant energy savings, resulting in cost reductions in cooling energy consumption. The monetary savings achieved in the combined cubicle, estimated at approximately 123 KSH, further emphasize the economic advantages of implementing these techniques.

In conclusion, this study provides valuable insights into the effectiveness of combining green and cool roofs in achieving improved cooling performance and energy efficiency in buildings. These findings have practical implications for promoting sustainable and cost-effective cooling solutions, particularly in tropical climates like Kenya.

For future studies, it would be useful to evaluate the long-term performance of green and cool roofs. Conducting extended studies to assess the durability and effectiveness of these systems over prolonged periods can provide valuable insights. Monitoring their performance under varying weather conditions, including extreme heat and heavy rainfall, can offer a comprehensive understanding of their long-term effectiveness and maintenance requirements.

Conflict of interest

The authors declare that there is no conflict of interest.

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