IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Design & Nature and Ecodynamics
Vol. 20, No. 5, May, 2025, pp. 989-997
Journal homepage: http://iieta.org/journals/ijdne

Optimizing Green Roof Design to Reduce Cooling Energy Demand in a Jordanian Hospital Building

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https://doi.org/10.18280/ijdne.200504

Received: 14 April 2025
Revised: 20 May 2025
Accepted: 25 May 2025
Available online: 31 May 2025

Keywords:
green roofs, thermal performance, building energy efficiency, hospital, arid climate

ABSTRACT

The drivers of the increasing demand for cooling energy include demographic factors such as population growth, urbanisation, economic growth, socio-economic development, and the impacts of climate change. Passive design strategies can reduce heating and cooling demands, leading to the integration of bioclimatic strategies in building energy efficiency. In this study, the impact of green roofs on thermal behavior—particularly cooling and heat transfer reduction—in a modern Jordanian hospital was analysed by comparing green roofs with traditional roofs. The analysis employed a co-simulation approach using Design-Builder software v6.1.8.021. The simulation was conducted from January 1, 2024, to January 1, 2025. The findings demonstrated that green roofs helped regulate the microclimate of hospital buildings in hot-dry climates like Jordan, positively contributing to energy savings. A green roof with a soil depth of 0.1 m and thermal conductivity of 0.9 W/m·K resulted in an 11% reduction in cooling energy compared to roofs with thicker soil layers. This configuration outperformed other tested variations in reducing cooling energy consumption. The study shows that optimizing cooling energy demand in hospitals located in arid climates can reduce costs and improve air quality by defining specific indicators for impact assessment. This can significantly promote sustainable alternatives to traditional roofing systems in such building typologies, which typically require vast material input and may endanger available resources. By establishing parameter standards for the design of energy-efficient green roofs in hospital buildings throughout arid regions like Jordan, these findings provide architects, engineers, and policymakers with practical guidance.

1. INTRODUCTION

The buildings and construction sector accounts for about 36% of the global energy consumption, which is higher than the energy requirements of the other main sectors, such as industry, agriculture, and transportation [1, 2]. Building energy requirements can be excessive, reaching several hundred kilowatt-hours per square meter annually. Ensuring thermal comfort in buildings is one of the primary goals of architectural design, particularly during hot weather when cooling energy accounts for a significant portion of overall energy consumption [3]. Over the past few decades, hot, arid regions have increasingly used passive cooling techniques, such as the use of vernacular architectural elements, to increase thermal comfort and reduce energy consumption. Green roofs are a new approach to lowering energy consumption and mitigating the harmful effects of urban heat islands. They achieve this through passive building design strategies that not only conserve energy but also enhance cooling performance [4-6].

In a time when environmental sustainability is a global priority, incorporating eco-friendly technologies has become essential. Green roofs are associated with contemporary social and economic standards in various urban systems. They enhance evaporative cooling, reduce the effects of solar radiation, and provide thermal insulation by balancing heat gain and heat loss. When combined with thermal insulating materials, green roofs further improve building energy efficiency. A green roof, also known as a living roof, is a system that incorporates a growing medium on a building's roof to support vegetation, as part of biophilic and bioclimatic architectural methods [7, 8]. This strategy not only reduces energy use but also has significant positive effects on the economy and the environment [6]. Because of these benefits, building owners are increasingly adopting green roofs to cut operating costs, and legislators are promoting their use as a more energy-efficient alternative to conventional roofing systems. These possibilities align well with global circular economy trends.

Recent studies have provided valuable insights into the advantages, challenges, and potential applications of green roof technology using methodologies such as empirical measurements, pilot-scale studies, and numerical modelling [9, 10]. Green roofs have been shown to be beneficial in a variety of climates by numerous studies. For instance, Ayata et al. demonstrated that green roofs in Turkey contribute to lowering the city's air temperature [11]. In Tehran, air temperatures over green roofs were 3.06 to 3.7℃ cooler than those over conventional roofs, according to Alhmoud [12] and Moghbel and Salim [13]. Furthermore, by promoting the dispersion of air pollutants, Rafael's research in Porto showed that green spaces enhance air quality [14]. A mathematical model was used to estimate the heating and cooling loads during different seasons. Another study carried out in Athens assessed the impact of green roofs on a nursery school by looking at its energy efficiency and environmental performance [15].

Although green roofs are increasingly recognized as an effective passive cooling technique, they are still underutilized in bioclimatic research. Most simulation studies to date have focused on isolated climates, often evaluating specific building envelope characteristics such as glazing performance and insulation adaptation [16]. Depending on the planting medium's depth, green roofs can be broadly divided into two categories: extensive and intensive. Extensive green roofs consist of a growing medium less than 20 cm deep, are lightweight, require minimal maintenance, and can be installed on existing rooftops without major structural modifications [17, 18]. Because of these qualities, extensive green roofs thrive in arid environments. Conversely, intensive green roofs, which have soil layers deeper than 20 cm, support a range of vegetation, including small trees and shrubs. However, because they require irrigation, frequent maintenance, and additional structural support, they are more appropriate for large urban developments and roof gardens [19].

Building a green roof requires a range of skills, including knowledge of environmental, climatic, social, and cultural aspects of sustainability. Multi-Criteria Decision Making (MCDM) is also relevant as an organized method for identifying the optimal system and managing this complexity [19-21]. Additionally, building codes, energy efficiency guidelines, and technical requirements for new construction should all be followed when developing green roofs. To ensure stability, performance effectiveness, and occupant well-being, national regulations state that green roofs must meet specific requirements [22-24]. For example, codes that require buildings to have adequate structural load-bearing capacity, proper drainage and waterproofing systems, and sufficient setbacks from the street must be followed.

The adoption of green roofs in Jordan is still limited because of a lack of awareness regarding their thermal and energy-saving benefits. Although they show great promise in enhancing building efficiency, green roofs remain underutilized globally. Princess Rahma Hospital in Jordan was selected as the case study due to its high electricity usage, particularly for cooling. The study examined various green roof designs to assess their effectiveness in improving indoor thermal comfort and reducing cooling energy demand. By providing useful information that can be applied to hospital buildings in Jordan and other regions with similar climates, the study's conclusions provide a workable path towards sustainable energy solutions.

A Jordanian hospital was chosen as the case study due to the country's unique climate. Building energy performance is greatly impacted by Jordan's hot, dry climate, which is marked by high solar radiation and protracted cooling seasons. Because of their 24/7 operations and strict indoor thermal comfort requirements, hospitals in these regions require continuous cooling. Because of this, Jordanian hospitals are especially pertinent when assessing passive cooling techniques like green roofs. Furthermore, these climatic conditions are representative of a broader geographic region, including many countries in the Middle East and North Africa (MENA).

This study examined the effects of soil thickness and thermal conductivity of green roofs on energy savings in Princess Rahma Hospital in Jordan. Important aspects like indoor thermal comfort and cooling energy consumption were evaluated in a comparison between green roofs and conventional roofs. The results provide insight into how well green roofs work to enhance building efficiency and reduce energy consumption in a range of environmental settings.

2. METHODS

This study utilized a quantitative approach to examining the energy cooling demands of Princess Rahma Paediatrics Hospital's interior and its thermal performance of green roof integration. In order to meet the targeted objectives of this study, simulation software, Design-Builder version v6.1.8.021, was employed. The tool helped to carry out the evaluation of energy requirement, carbon emissions, lighting efficiency, and thermal comfort [25]. Two types of roofs were checked: the first one was a regular roof made of specific materials (Table 1), and the second was a green roof with ideal depth and thermal conductivity (Table 2).

Table 1. Summary of the regular roof's data entries

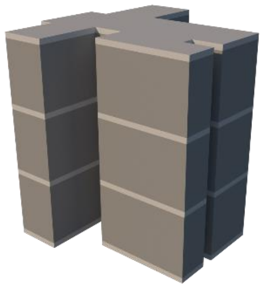
Material	Thickness (mm)	U-Value (W/m²·K)
Cement tiles	20	1.3
Mortar	20	0.72
Sand	60	1.4
Ordinary concrete	70	1.7
Bitumen layer	4	0.17
Expanded polystyrene	30	0.035
Reinforced concrete	150	2.5
Gypsum plaster	20	0.35

Table 2. Summary of the green roof's data entries

Material	Thickness (mm)	U-Value (W/m²·K)
Vegetation layer	-	0.269–0.353[1]
Soil (Substrate)	100–200	-
Filter layer	5	-
Drainage layer	60	-
Waterproof layer	7	-
Expanded polystyrene	30	-
Reinforced concrete	150	-
Gypsum plaster	20	-

DesignBuilder v6.1.8.021 was used to conduct a comparative simulation-based analysis for the study. A conventional roof system based on standard construction layers and a green roof system with different soil depths (0.1, 0.15, and 0.2 m) and thermal conductivities (0.3, 0.6, and 0.9 W/m·K) were the two roof systems that were modelled. The climate of Irbid, Jordan, was used to simulate each configuration for a full year. For every case, indoor operating temperatures and cooling energy consumption were examined. Real utility consumption data and environmental measurements (relative humidity and air temperature) captured with a HOBO U12 data logger were used to validate the model. An accurate evaluation of the effects of each green roof configuration on building energy performance was made possible by this structured simulation framework.

Princess Rahma Hospital is a state public hospital built on February 23, 1995. Its main purpose is to be a center for children's health care, and situated on Zaki Al-Tall Street in Irbid, Jordan. This project consisted of three floors, was picked as a case study because of its high cooling demand, structural suitability for a green roof, and relevance to Jordan's public healthcare sector. Its location in an arid climate underscores the need for passive cooling, and the study addresses the limited adoption of green roofs in similar buildings. Apart from the ground floor and the third floor, the building has a spacious and well-arranged design featuring several parts connected via a central unit. The whole land area of the building is 10,540 square metres. Each patient room is designed to fit a specific number of people and is adequately ventilated mechanically. Similarly, the labs and the staff rooms are air-conditioned and actively ventilated. After the recent extension for increased functional capacity and renovation of the existing building, additional HVAC control systems were introduced to some of the old wards to enhance the comfort of patients.



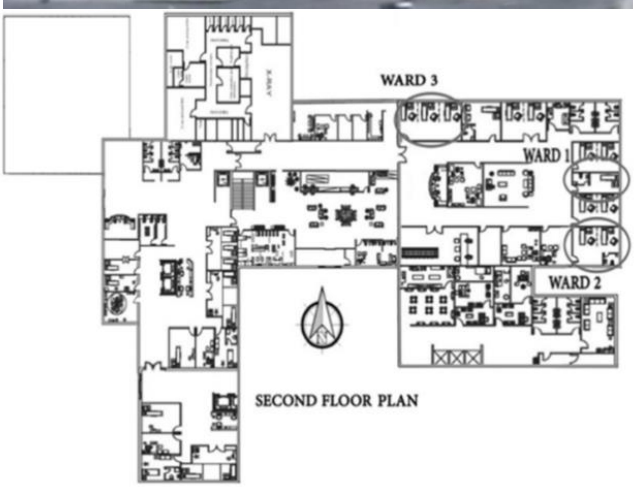


Figure 1. A typical floor plan, the hospital building's facade
Source: by authors

However, it was presupposed for this particular study that all rooms were mechanically ventilated. The features of the site were used to determine the hospital building's orientation, which is north-south, aligning with other buildings. Medical facilities standards in hot arid climates, such placement from bioclimatic principles led to improved distribution of natural daylight in specific areas, which enhanced the indoor environment and increased patient comfort (Figure 1), According to the Housing and Building Research Centre (HBRC), Jordan's regional climates based on solar heat gains, humidity, and temperature. Covering 88,778 square kilometres, the target area is located between Longitudes 30°11'N and 34°23'N and Latitudes 18°38'E and 19°34'E. East of the Mediterranean, it is situated 300 kilometres away (Figure 2) [26].

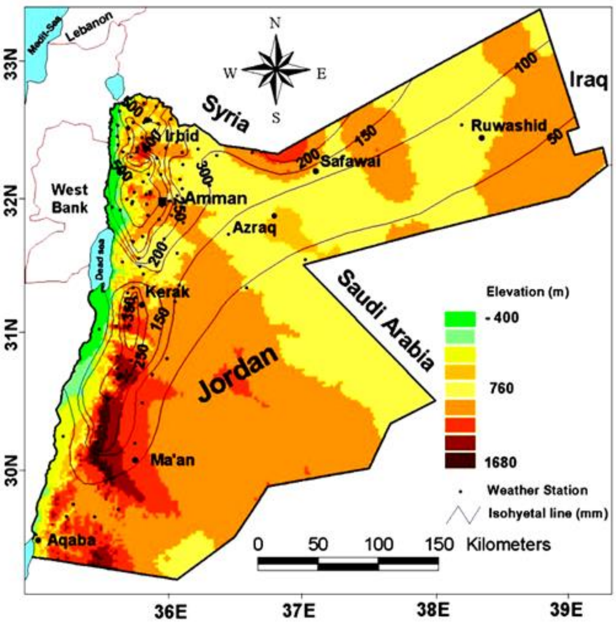
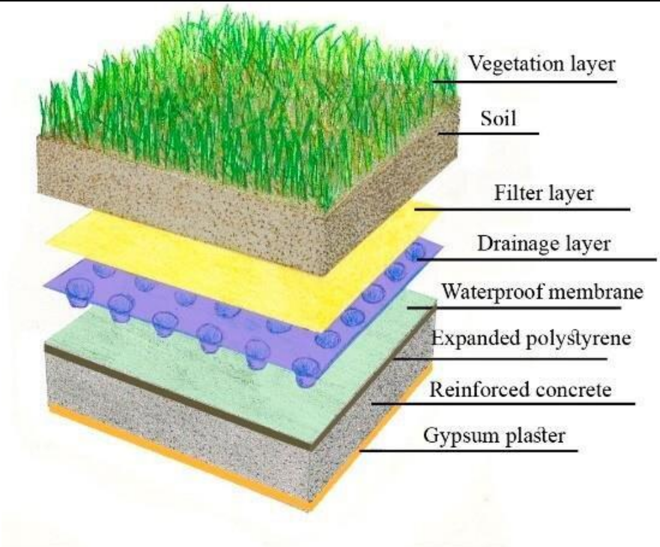


Figure 2. Climatic regions of Jordan

The eight layers of the green roofs are proposed to make them more energy efficient and control the water consumption. The highest layer was planted with vegetation, which is mainly grass that has an average height of 10 cm. Under no circumstances, different soil types characterized by multiple thermal conductivity values (0.3, 0.6, and 0.9 W/m·K) and various thicknesses (100, 150, and 200 mm) were the factors tested to see if they would influence the energy efficiency or not.

The main function of a filter layer is to separate the growth substrate from the drainage layer, thereby preventing small media particles such as plant debris from entering the pipes, and it also acts as a root barrier membrane.

Table 3. Green roofs types simulation matrix

General Specifications	Thermal Conductivity of the Soil (W/m·K)	Soil Depth (m)
	0.3	
Characteristics of the soil: Specific heat = 1000 (J/kg·K), D = 400 Kg/m^3	0.6	0.1 0.15 0.2
Characteristics of the plants: Leaf area index = 4, height of plants = 0.1 m, leaf emissivity = 0.9	0.9	0.1 0.15 0.2

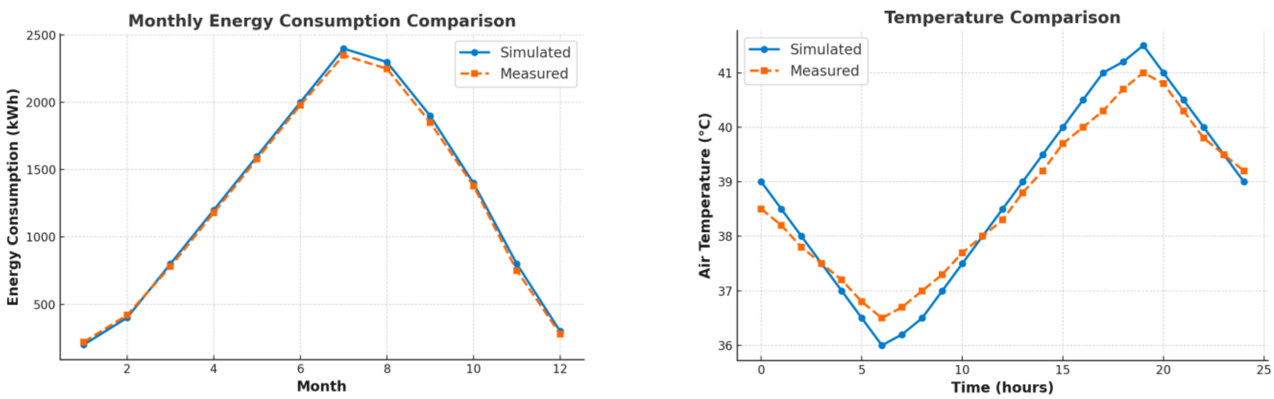


Figure 3. Thermal and energy performance validation of the hospital building model
Source: by authors

The fourth layer, which was the drain layer, was designed for the purpose of removing the excessive water, thus avoiding the buildup of water on the roof's surface. Next, a waterproofing layer was placed below the drainage layer to prevent the infiltration of water into the structural elements.

Some of the other layers, e.g., green roof insulation, reinforced concrete, and interior plastering, were typical of the roof in all instances and also added to the thermal performance of the building. The input parameters, such as the specific heat capacity (SH, J/kg·K), the density (D, kg/m^3), leaf area index (LAI, m^2) the height of the plant (HP, m), and the leaf emissivity (EI) that helped with the simulation process of the green roofs were the root components. The proper values for these parameters are given in Table 3.

The traditional method for roofing was validated with a yearly simulation held in Irbid, Jordan. In a direct thermal analysis of the model, a trial was conducted on January 5, 2025. The actual energy consumption data derived from utility bills over a year was compared with the simulation output. The average deviation of the energy simulation was determined and found to be 10.6%, as shown in Figure 3.

3. RESULTS AND DISCUSSION

3.1 Two-way role of soil thermal conductivity

The cooling effect of the green roof is influenced by soil thermal conductivity in two ways. Higher thermal conductivity facilitates more effective cooling and evapotranspiration during the day by improving the downward transfer of surface heat. On the other hand, this same characteristic may cause a thermal hysteresis effect at night, which could cause cooling to be delayed as heat stored during the day is progressively released into the interior. This dynamic emphasises how soil conductivity must be balanced for best results throughout the day. Under Jordan's arid conditions, our study found that shallow soil (0.1 m) combined with higher thermal conductivity (0.9 W/m·K) maximised cooling during the day and minimised heat release during the night.

3.2 Leaf Area Index (LAI) and evapotranspiration

The shading and evapotranspiration potential of a green roof are greatly influenced by the Leaf Area Index (LAI), which measures the canopy density of vegetation. The best surface coverage in our simulations was achieved with an LAI of 4, which decreased solar gain and improved evapotranspiration-driven cooling. Higher LAI lowers the temperature of the surface and the interior space beneath it by increasing the leaf surface area available for moisture evaporation and removing latent heat from the system. LAI is therefore a crucial factor in optimising the efficiency of green roofs.

3.3 Hospital-specific challenges

Hospitals face special challenges when implementing green roofs. In clinical settings, vegetation may draw rodents, birds, or insects that could compromise infection control and hygiene. Additionally, patients and employees with respiratory sensitivities may be impacted by the allergenic pollen that certain plant species emit. Careful plant selection, pest management techniques, and low-maintenance, non-allergic species should be given priority in order to reduce these risks. To guarantee functionality and safety, structural factors like weight load and drainage must also adhere to hospital design guidelines.

The findings of the research are divided into three main sections. The first section investigated the efficiency of the given types of green roofs with different soil heights and thermal conductivities in cooling and the reduction of annual energy consumption by increasing the cooling process. The second section indicated the best combinations of green roofs that not only cool the interior but also improve the thermal conditions of interior spaces in buildings. To achieve this, the air conditioning units were designed as a model that self-quantifies the uncertainty and randomness of AC usage behaviour and incorporates the model into simulations to determine the energy used by the cooling. However, the model was run without air to evaluate the cooling potential of green roofs and solar thermal shading in buildings.

An essential construction issue regarding green roofs is the additional structural load they impose on buildings, which requires strict adherence to safety standards and building codes. The condition of the actual building has to be evaluated according to the load-bearing capacity for the particular type of green roofs (extensive or intensive). Extensive green roofs have thinner soil layers and thus require little maintenance. Thus, they are the most appropriate for retrofitting the existing hospital buildings because of the lower weight and structural requirements. Besides the structural point of view, ecological and health challenges are also consequences of green roofs. Vegetation tends to be a source of attraction for insects, birds, and rodents, and this can pose a critical problem in the healthcare setting, with safety being the main concern. Proper maintenance of the green roof includes regular inspections, and pest control will help in dealing with the problems that come with bug and rodent infestation. Some of the plant species that are less appealing to insects and rodents are chosen to help deal with these problems.

Another concern could be the presence of allergenic plants, which may have a negative impact on asthmatic and hay fever patients and hospital staff. The lack of these plants and low-pollen plant species is what can prevent the occurrence of adverse health effects. In hospitals and other industrial environments, the use of air purification systems and constant monitoring of the indoor air quality are other measures that can help in the reduction of the risk of allergens that enter hospital spaces.

The percentage decrease in cooling load attained by different green roof configurations in comparison to a conventional roof is summarised in Table 4. The findings demonstrate that thermal conductivity and soil depth both have a major impact on green roof performance. The greatest cooling load reduction of 11.0% was obtained with the ideal configuration, which involved a soil depth of 0.1 m and a thermal conductivity of 0.9 W/m·K. Performance somewhat declined with increasing soil depth because there was less heat dissipation at night, particularly in dry conditions. These results aid in establishing precise design guidelines for green roofs that maximise thermal efficiency in Jordan's climate.

Table 4. Cooling load reduction by green roof configuration

Soil Thermal Conductivity (W/m·K)	Soil Depth (m)	Cooling Load Reduction (%)
0.3	0.10	6.2%
0.3	0.15	5.8%
0.3	0.20	5.3%
0.6	0.10	8.7%
0.6	0.15	8.2%
0.6	0.20	7.6%
0.9	0.10	11.0%
0.9	0.15	10.2%
0.9	0.20	9.4%

With various structural and ecological causes being in line with the use of energy [27-29], it is indisputable that green roofs in hospital buildings are adequately consistent [30]. Consequently, the benefits associated with them can be maximized at the same time as potential risks are minimized. A detailed thermal simulation for various configurations of green roofs was performed to assess energy savings using DesignBuilder. The process included the evaluation of green roofs' impacts on hospital cooling loads under diverse climatic conditions. Furthermore, energy consumption simulation was found to produce 3 $W/m^2/h$ cooling effect on the hospital ward with three different variations in soil depth (0.1, 0.15, and 0.2 m), as well as in thermal conductivity (0.3, 0.6, and 0.9 W/m·K), this was an accurate description of the roof's topography stress stability.

The results showed that green roofs in arid climatic conditions could only provide a limited insulation effect for most buildings. In contrast, green roofs were able to optimize the cooling load by approximately 11% for thermostatically controlled buildings. Even at a high soil thermal conductivity of 0.9 W/m-K, Figure 4 demonstrated that green roofs with 0.1 m soil thickness exhibited higher cooling efficacy than the other tested roofs. This suggests that the green roof technique works best in hotter, drier environments like Jordan.

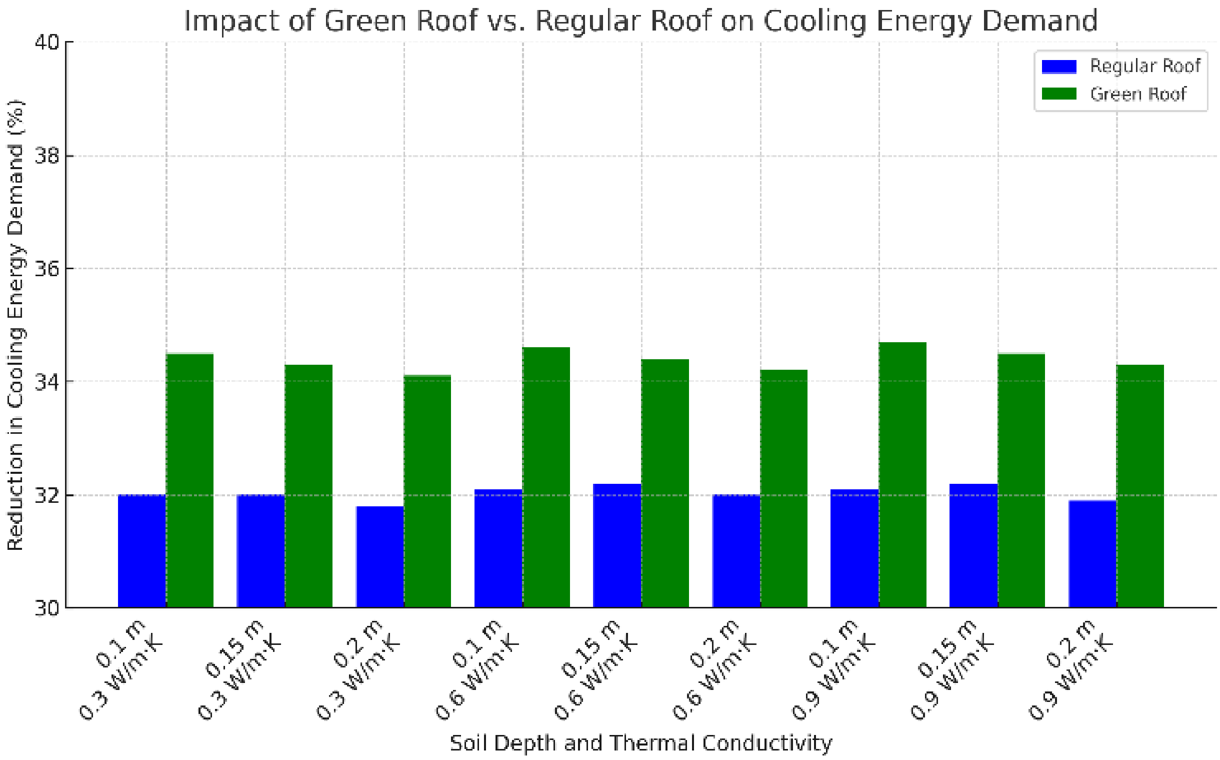


Figure 4. Impact of soil thermal conductivity (W/m·K) and green-roof soil depth (m) on the decrease (%) in cooling energy demand

According to the findings, a shallower soil layer performed marginally better in terms of cooling than a deeper layer. The reason for this effect was that the former has a greater capacity to dissipate excess heat that has accumulated during the night in the early hours of the day. Because of the green roofs' increased thermal inertia, the interior temperature stays warmer at night. Passive night cooling is less effective on very hot days because the temperature does not drop for an extended period of time to dissipate the heat that has built up during the day. Higher leaf area index (LAI) values also improved the shading effect on the roof surface, which lessened the impact of soil thickness on cooling during the day [31-33]. This result agreed with the thermal conductivities that were tested. Additionally, it was discovered that higher soil thermal conductivity outperformed lower thermal conductivity in terms of enhancing the cooling process. This finding is consistent with earlier research [29], which indicated that higher soil moisture content and increased soil thermal conductivity increase evaporation rates on the one hand, and on the other hand decrease heat transfer to interior spaces.

The thermal efficiency of the most effective green roof type among the variations studied (K = 0.9 W/m·K, soil depth = 0.1 m) was calculated. In contrast to the traditional and different vegetation cover models in the selected area, the study with the aid of the measurement of the operative temperature. In the case of both the traditional and the green roof models, operative temperatures during the working hours (9:00-16:00) were studied carefully on the sunny day of July 15. The operating temperatures are listed in Table 5.

The data supported the relationship between the temperature of the day and the energy consumption of the buildings, and hence the energy-saving properties of green-roof technology. The goal of Irbid Jordan decision-makers has always been to lower the running expenses of public buildings. However, rather than putting long-term energy-efficient solutions into place, efforts have frequently concentrated on limiting the use of air conditioners. The government has recently introduced policies that support passive climate strategies, but their widespread adoption has been hampered by different issues. Using primary hospital buildings as case studies, this study investigated the viability of incorporating green roof systems as a more effective substitute for cooling energy optimization in hospital buildings in arid climates. Also, assessing their potential to lower energy consumption and improve indoor thermal comfort. Focusing on Princess Rahma Hospital, Jordan, as a case study with potential qualities for its application.

Table 5. The operating temperatures of the green and traditional roofs

Time	Regular Roof	Green Roofs
9:00	33.91	28.48
10:00	34.28	28.75
11:00	34.63	29.02
12:00	35.00	29.30
13:00	35.28	29.51
14:00	35.52	29.74
15:00	35.84	30.02
16:00	36.00	30.22

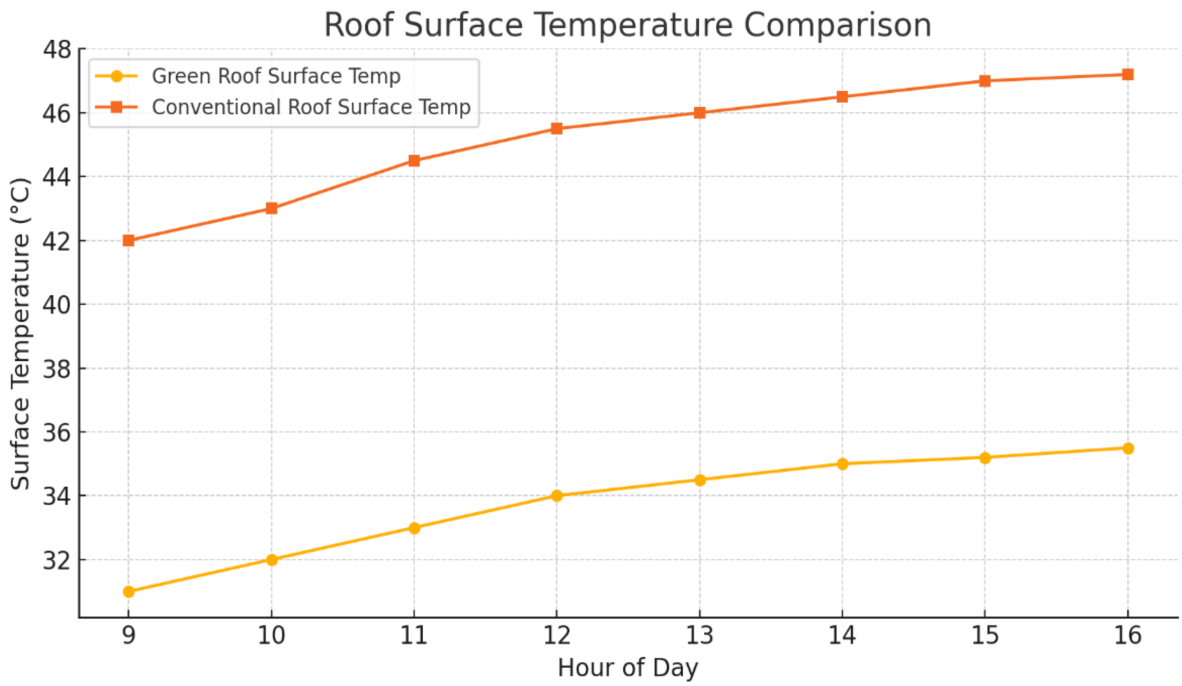


Figure 5. Surface temperature comparison – Green roof vs. Conventional roof on 15th June, 2024

The operative indoor temperature variation from 9:00 AM to 4:00 PM on June 15, the study's hottest simulated day, is shown in Figure 5. With an average difference of 5–6°C during peak hours, the green roof continuously kept indoor temperatures lower than the conventional roof. This curve shows how well green roofs work to improve occupant comfort, lessen reliance on air conditioning systems, and moderate indoor thermal conditions during daytime heat peaks.

Surface temperature comparisons (Figure 5) further revealed that the green roof was 10–12°C cooler than the conventional roof throughout the day. This thermal buffering effect stems from insulation, evapotranspiration, and vegetation shading in the green roof layers, which collectively reduce heat transfer into the building.

Green roofs represent a viable solution for Jordan's government to incentivize as a complement to existing energy-saving measures in hospitals. Future research will focus on optimizing water retention, plant species selection, and maintenance protocols to maximize long-term benefits in public buildings.

The study findings deduced that green roofs with a soil depth of 0.1 metres and thermal conductivity of 0.9 W/m·K as the highest cooling efficiency. These values were obtained indirectly by consuming energy by a little less than 11%. These discoveries coincide with Santamouris et al. [15], who showed that green roofs in Athens, Greece, formed a part of a meaningful process in decreasing the cooling load by insulation of the heat transfer medium through the building envelope. The study likewise aligned with that of Theodosiou [8], that green roofs enhanced the thermal capacity of buildings in Mediterranean climates by lowering peak indoor temperatures during summer.

Further strengthening the cooling benefits detected in this study was its agreement with Moghbel and Salim [13]. They earlier identified green roofs' performance in Tehran with a similar climate to Jordan, with air temperatures at the roof level of the green roofs to be at 3.06°C to 3.7°C cooler than the air temperature at the level of the conventional rooftops. Still, Ayata et al. [11] indicated that the green roofs in Turkey decreased the heat island effect in urban areas. They were found to cut down the heat island effect to approximately 11% and thus made for an overall energy-efficient environment. Our study's findings concur with those outcomes, that green roofs perform well in hot and dry climatic settings. On the other hand, different green roof setups, containing variables such as the depth of the soil, the kind of vegetation, and the climate, affect the outcomes of performance. For example, the investigations by Williams et al. [19] illustrated the need for plant species to be chosen appropriately to maximize green roof efficiency. On the other hand, the studies by Zeng et al. [29] focused on the fact that soil moisture retention helps the building to be cooler. This study added to these positive contributions to knowledge by showing that a thin soil layer with higher thermal conductivity is more effective in arid conditions than a thicker soil layer because of its capability to dissipate heat more efficiently.

4. CONCLUSION

The principal aim of this research was to assess the thermal performance and energy-saving potential of the hospital green roofs in Jordan, focusing on the influence of soil depth and thermal conductivity on the cooling energy demands. It was evidenced that green roofs are an important means of enhancing the energy efficiency of buildings, and having a soil depth of 0.1 m and a thermal conductivity of 0.9 W/m-K provides the highest cooling benefits in arid climates. When the current work was compared to other similar works, the findings agreed with previous studies' propositions carried out in Greece, Turkey, and Iran. Our study shows a comparable reduction of about 11%, validating the applicability of green roofs in hot, dry regions, in contrast to similar works in Turkey, Iran, and Greece that report cooling energy reductions in the range of 7–14%. This case-specific knowledge offers fresh, useful recommendations for incorporating green roofs into Jordanian and comparable public healthcare infrastructure. The trending common ground was that green roofs lowered the ambient temperature, resulting in a certain degree of energy savings. However, this research particularly reveals the useful input for a hospital building in Jordan as green roof usage is currently relatively restricted in Jordan. Furthermore, a 10 cm soil layer with a high leaf area index (LAI) outperformed the thicker 15 cm and 20 cm soil layers in terms of efficiency. In general, adding green roofs to hospital structures was consistent with Jordan's new energy policy, optimizing financial and environmental gains while reaffirming sustainability and energy-saving concepts. Green roof systems should be included in the early phases of architectural design in order to further improve energy efficiency in public buildings. These systems ought to be required for the design and operation of public buildings. In order to maximise cooling energy efficiency with a focus on reducing energy consumption in hot, arid regions. Future research on green roof technologies should take into account exploring long-term maintenance, irrigation needs, and integration with other passive systems. Such prospective works should consider factors such as vegetation type, soil moisture retention, and integration with other passive cooling strategies. By incorporating these considerations, green roofs can be optimized for widespread implementation in healthcare facilities and other public buildings as a sustainable energy strategy in arid regions.

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