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RESEARCH ARTICLE Open Access

Eco-Friendly Healthcare: Evaluating Green Roofs as a Sustainable Solution for Indoor Air Quality in Hospitals

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Abstract: Rapid urbanization and climate change increasingly threaten the sustainability of modern cities, placing healthcare facilities at risk due to their need to maintain healthy indoor environments for patients and staff. This study evaluates the effectiveness of green roofs as sustainable interventions to improve indoor air quality and environmental performance in hospitals. Two Hospitals in Erbil, Iraq—PAKY Hospital and CMC Hospital—were analyzed using simulation methods with Building Information Modelling (BIM), Open Studio, and Energy Plus. Conventional concrete roofs were compared to semi-intensive green roofs under identical climatic conditions, using really physical and thermal properties. The results showed significant improvements: at PAKY and CMC Hospital, green roofs reduced indoor temperatures, improved thermal comfort and humidity, and decreased annual carbon emissions. These results confirm that green roofs are effective strategies for enhancing hospital sustainability, reducing operating carbon footprints, improving indoor air quality (IAQ), and moving most spaces into ASHRAE-defined comfort bands to make hospitals more environmentally friendly. increasing environmental resilience, and supporting the well-being of patients and staff. The study's limitations include reliance on simulations instead of real-time monitoring and a lack of ventilation dynamics. Future research must incorporate on-site environmental measurements, evaluate long-term maintenance and cost-benefit trade-offs, and investigate applicability across various hospital types and climate zones.

Keywords: *Green Roof; Indoor Air Quality; Thermal Comfort; Reduced CO2 Emission; Hospital; Erbil; Sustainable Healthcare.*

1. Introduction

Rapid urbanisation and climate change have increasingly challenged the sustainability of modern cities, with healthcare facilities being among the most vulnerable due to their critical need to maintain healthy indoor environments for patients and staff. Ensuring adequate indoor air quality (IAQ) in hospitals is essential not only for patient recovery but also for infection control and staff productivity. Among the innovative solutions proposed, green roofs (GRs) have emerged as multifunctional systems that provide both environmental and health benefits. Modern green roof systems, which evolved from ancient practices, are engineered installations consisting of layers of vegetation, soil substrate, drainage, and waterproof membranes.

These systems are designed to mitigate the urban heat island (UHI) effect, enhance IAQ, and improve building energy efficiency [1] [2] [3] They are recognised for their ability to filter pollutants, regulate temperature, and retain stormwater, all of which are particularly valuable in healthcare contexts where stable thermal conditions and reduced airborne contaminants, such as CO_2 and volatile organic compounds (VOCs), directly support respiratory health and overall well-being [4] [5] At the broader urban scale, green roofs contribute to sustainable development by enhancing biodiversity, mitigating UHI effects, and improving the ecological resilience of cities [3] [6]Despite these demonstrated benefits, several barriers limit the widespread adoption of green roofs in healthcare facilities. These include high installation costs, structural challenges in retrofitting older hospitals, and ongoing maintenance requirements [7] [2]. Furthermore, while numerous studies have highlighted energy savings, thermal comfort, and stormwater management benefits of green roofs [8] [9], there remains a scarcity of empirical research focusing specifically on IAQ improvements in hospital environments. Existing studies often rely on simulations or small-scale case studies [10] [1], leaving gaps in understanding.

There is a lack of studies evaluating the impact of green roofs on indoor air quality in hospital environments, which could serve as a sustainable solution to improve indoor air quality, accelerate patient recovery processes, and enhance hospitalization conditions.

Studying the potential of green roofs in improving the resilience of hospitals to the effects of climate change, including extreme weather events, is a relatively neglected area of study.

This gap is particularly concerning given the well-established links between poor IAQ and adverse respiratory, cardiovascular, and cognitive health outcomes in hospitals [11] [12]

To address these deficiencies, the present study evaluates the potential of green roofs as sustainable design interventions in hospitals. By aligning with international health and safety standards such as [13], the [14], the Occupational Safety and Health Administration [15] and the World Health Organisation [16] this study positions green roofs as resilient, cost-effective strategies for healthcare design. Specifically, the purpose of this study is to assess the effectiveness of green roofs in improving indoor air quality, managing indoor temperature, and reducing the environmental footprint of healthcare facilities, all of which contribute to healthcare sustainability.

2.1 Research question

1. How do indoor air quality metrics (temperature, CO_2 levels, humidity) in hospitals with green roofs compare to those in hospitals without green roofs?
2. To what extent do green roofs regulate indoor temperatures and improve thermal comfort for hospital occupants?
3. What is the impact of green roofs on the carbon emissions of hospital facilities, and how do they contribute to reducing the environmental footprint of healthcare operations?

2.2 Research Hypothesis

H1: Hospitals with green roofs will demonstrate significantly better indoor air quality metrics—specifically, lower indoor temperatures, reduced carbon dioxide levels, and optimal humidity—compared to hospitals without green roofs.

H2: The installation of green roofs will significantly improve thermal comfort in hospitals' interiors by lowering temperatures, thereby enhancing comfort for both patients and employees.

H3: Green roofs will significantly reduce carbon emissions from hospital facilities, contributing to improved urban sustainability and mitigating the environmental impact of healthcare operations.

2. Literature Review

This section reviews and critiques previous studies on eco-friendly healthcare, with a focus on green roofs as a sustainable solution for improving indoor air quality in hospitals. Research on green roof performance in buildings highlights their potential to reduce energy use and enhance sustainability. (8) reported that intensive and semi-intensive green roofs could reduce reliance on mechanical cooling while retaining 26–88% of rainfall, though challenges such as high costs and maintenance remain. Similarly, [17] demonstrated rooftop temperature reductions of up to 48% in humid climates through hybrid green roofs, while [9] compared extensive and intensive systems, finding that, although costs were high, long-term environmental benefits such as CO2 sequestration were significant[18] documented a 12°C reduction in surface temperatures and notable CO_2 absorption in tropical settings, whereas [19] emphasised additional benefits, including sound insulation, fire resistance, and lifespan extension. As sustainable urban development strategies, green roofs have also been widely studied. [3] found that they reduce stormwater runoff by around 65.7% and cut cooling energy by up to 20.9%. [6] underscored their ecological and therapeutic services, while [20] employed GIS and CFD models to evaluate stormwater and air pollution's benefits, emphasising the need for multidisciplinary approaches. [21] identified 87% of roof areas in Graz, Austria, as suitable for green roofs, and [22] highlighted their role in mitigating heat islands, reducing noise, and providing wildlife habitats, though both noted insufficient policy and funding support. Case studies in healthcare settings provide further evidence of their benefits. [23] found that therapeutic green roofs in Seoul enhanced patient satisfaction, while [24] studied hospitals in Hong Kong and emphasised the importance of structural integrity along with environmental and health benefits. [5] reviewed over 100 studies, confirming pollutant filtration in U.S. hospitals, and [25] demonstrated that green roofs improved patient well-being but were accessible in only 60% of cases. [26] showed that in Lebanon, 70% roof coverage halved cooling loads in a children's clinic. Finally, studies specifically addressing indoor air quality show significant potential. [10] used EnergyPlus simulations to demonstrate reductions in CO_2 emissions and enhanced thermal comfort, while [27] confirmed intensive roofs reduced cooling demand by 5.2%. [1] noted that only 3.5% of 1,623 studies addressed air quality directly, underscoring a major research gap. [28] found sedum-based roofs provided inconsistent cooling benefits, and [29] proposed a green roof-atrium system achieving up to 91% summer energy savings in simulations, though real-world validation was lacking. The gap in this study was identified by summarizing and analyzing previous studies reviewed in all four sections of the gap in This study evaluated the concept of green roofs and their attributes indifferent the field of architecture and hospitals. There is a lack of studies to evaluate the impact of green roofs on indoor air quality in hospital environments as a sustainable solution in hospital facilities to improve indoor air quality, accelerate patient recovery processes, and provide a hospitalization environment. Studying the potential of green roofs in improving the resilience of hospitals to the effects of climate change, including extreme weather events, is a relatively neglected area of study. Given these limitations, the scientific field faces a significant challenge. The problem is the lack of empirical research assessing whether green roofs can serve as a viable architectural strategy for improving IAQ, thermal comfort, and carbon emissions in healthcare facilities, particularly in the context of Erbil, where environmental challenges and rising energy demands are pressing concerns .

3. Methodology and data sources

3.1 Experimental setup / Input Data:

This parametric study is carried out on the rooftops of two real hospital buildings to compare the effectiveness of a green roof and a bare concrete roof on the last floor in the two buildings. Each model was geolocated to Erbil, Iraq, with correct orientation and energy settings. The workflow was applied to: ▨ CMC Private Hospital: CMC is one of the privately funded hospitals in Eastern Erbil city, which is located on Koya Street. The hospital comprises six floors.

▨ Paky Private Hospital: Paky, a privately funded hospital in Erbil, is situated on Newroz Street and comprises 70 beds and six floors.

3.2 Case Selection

The selection of CMC Private Hospital and Paky Private Hospital was based on their representativeness within Erbil's healthcare sector. Both are mid-sized, multi-storey hospitals with reinforced concrete flat roofs, making them structurally suitable for potential green roof retrofits. Their scale, spatial layout, and construction typology reflect common characteristics of healthcare buildings in Erbil, ensuring the applicability of findings to the wider hospital stock.

The choice of a semi-intensive green roof was guided by its balance between ecological performance and structural feasibility. Semi-intensive systems combine the low maintenance and reduced structural loads of extensive roofs with some of the ecological and thermal advantages of intensive systems. This makes them particularly appropriate for healthcare contexts, where operational costs, maintenance demands, and load-bearing capacities must be carefully managed. Moreover, semi-intensive roofs are increasingly recommended in hot–dry climates due to their demonstrated ability to moderate indoor temperature and humidity without requiring major structural reinforcement.

3.3 Simulation Workflow, Assumptions, and Validation

Each building was modelled, simulated, and analysed. It was exported from Revit using the gbXML (Green Building XML) format and imported into OpenStudio 3.7.0, an open-source platform that integrates with EnergyPlus 9.6.0[30] for building performance simulation. Within OpenStudio, architectural details, spaces, and bounding elements on the last floor of the building were defined. Definitions of building geometry, spatial zoning, and construction layers were configured. Roof layers were modelled with specific physical properties, including thermal conductivity, density, and thickness, based on standard green roofing component specifications. Annual simulations were run using the Erbil weather file (EPW). Simulation Workflow as illustrated in Figure 1.

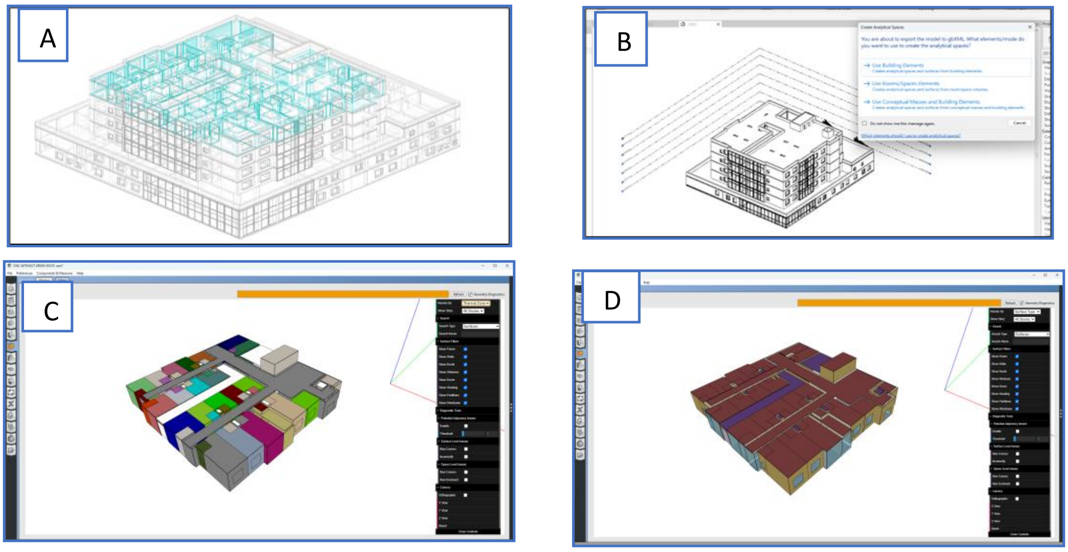

Figure 1: (A) Simulation Workflow for Hospital Energy Modelling. Revit Modelling: Creation of 3D hospital geometry and zoning. (B) gbXML Export: Export of building geometry and construction data into Green Building XML format. (C) OpenStudio Import: Importing gbXML into OpenStudio, validating spatial zoning, and assigning construction materials. (D) EnergyPlus Simulation: Running a dynamic building performance simulation to generate IAQ, thermal comfort, and carbon emissions outputs. Researcher

The building model was segmented into distinct thermal zones, each represented by a unique colour to visually confirm zoning integrity. These zones correspond to functional spaces such as patient rooms, corridors, and service areas, ensuring thermally discrete regions for accurate simulation. Assignments were validated within OpenStudio's Geometry tab, allowing for reliable boundary condition recognition during passive envelope analysis, focusing solely on thermal behavior driven by construction properties and external environmental loads. The model's exterior and interior surface boundaries—including walls, roofs, floors, and fenestration—were visually inspected and computationally verified within the geometry interface. Surface classifications were automatically recognized and manually reviewed to ensure thermal connectivity and enclosure integrity. This process was essential for preventing simulation errors such as surface misalignment or missing boundary conditions. Comparative outcomes between scenarios remain robust, especially when validated against benchmarks and literature. Verification was carried out in three stages:

- Reviewing zoning integrity and surface boundaries in OpenStudio.
- Comparing outputs against published benchmarks in similar hot–dry climates.
- Cross-checking results with prior green roof studies confirms consistency with documented performance trends.

3.4 Roof Construction Scenarios

Two construction scenarios were defined, as summarized in Table 1:

Scenario A: Conventional Flat Roof — plaster, reinforced concrete slab, insulation, and waterproofing layers.

Scenario B: Semi-Intensive Green Roof — vegetation, soil substrate, drainage, geotextile, insulation, waterproofing membranes, and reinforced concrete slab.

Table 1: Roof Construction Scenarios for Simulation of each hospital (Cmc&paky) (Researcher)

Scenario	Description	Variables/Properties	Output Metrics
Scenario A	Conventional Flat Roof	Reinforced concrete slab (A) a bare concrete roof consisting of plaster, concrete slab, insulation, and waterproofing layers	1. Temperature Concrete Roof 2. Relative Humidity Concrete Roof 3. CO2 Emissions Reduction Concrete Roof 4. Thermal Comfort Concrete Roof
Scenario B	Semi-Intensive Green Roof	Green roof with a full layered system (B) a semi-intensive green roof comprising vegetation, growing medium, drainage, and root barrier. For simplified simulations, the green roof was also modeled as a single equivalent thermal layer as shown in Table 2	1. Temperature Reduction Achieved by Green Roof Implementation 2. Humidity Reduction Achieved by Green Roof Implementation 3. CO2 Emissions Reduction Achieved by Green Roof Implementation 4. Thermal Comfort Improvement Achieved by Green Roof

Table 2: Semi-Intensive Green Roof Construction Properties (Researcher)

Layer	Roughness	Thickness (m)	Conductivity (W/m·K)	Density (kg/m³)	Specific Heat (J/kg·K)	Thermal Abs	Solar Abs	Visible Abs
1. Substrate (soil)	Rough	0.07	0.4	1100	1500	0.95	0.90	0.85
2. Filter Layer (synthetic mat)	Smooth	0.002	0.3	500	1400	0.9	0.8	0.8
3. Drainage Layer (plastic/rock)	Smooth	0.03	0.4	600	1000	0.9	0.7	0.7
4. Geotextile Layer (4 mm)	Smooth	0.004	0.25	200	1400	0.9	0.75	0.75
5. Roof Insulation	Smooth	0.10	0.034	30	1450	0.9	0.7	0.7
6. Protection Fleece	Smooth	0.003	0.04	250	1400	0.9	0.7	0.7
7. PVC Membrane	Smooth	0.002	0.16	1400	1000	0.95	0.85	0.85
8. Protection Fleece (again)	Smooth	0.003	0.04	250	1400	0.9	0.7	0.7
9. EPS Sloping Layer	Smooth	0.05 (avg slope est.)	0.036	20	1300	0.9	0.7	0.7
10. RC Slab (Concrete)	Medium Rough	0.22	1.75	2300	880	0.9	0.65	0.65
11. Thermal Insulation (10 cm GG500 + FG)	Smooth	0.10	0.033	35	1450	0.9	0.7	0.7

In the simulation model, extruded polystyrene (XPS) was used for roof insulation, characterized by a thermal conductivity of approximately 0.033–0.036 W/m·K. Protective fleece layers were treated as low-density, low-conductivity elements, while filter and geotextile layers served as breathable separators with minimal thermal mass. The reinforced concrete (RC) slab was modeled as a high-density, high-conductivity structural layer. Where appropriate, certain subsurface components, such as PVC membrane, fleece, and insulation, were grouped into a single equivalent layer to simplify thermal modeling without compromising accuracy as illustrated in Table 2

4. Result and Discussion

4.1 Case 1 Paky Hospital (with green roof without green roof)

Following the installation of a green roof at Paki Hospital, the study evaluated its impact on the overall thermal efficiency of the building's last floor. Two scenarios were compared:

Baseline roof: A standard reinforced concrete roof system

Green roof: A semi-intensive vegetated roof system, consisting of layers of soil, vegetation, drainage systems, and insulation. The analysis successfully isolated the effect of roof type on building performance. The evaluation focused on the roof's function in regulating heat transfer, regulating indoor air temperatures, and enhancing overall thermal comfort in the surrounding areas. The study also examined the green roof's potential to mitigate carbon dioxide emissions, thus integrating architectural design techniques with environmental sustainability goals. This section explores the results of each aspect of the evaluation.

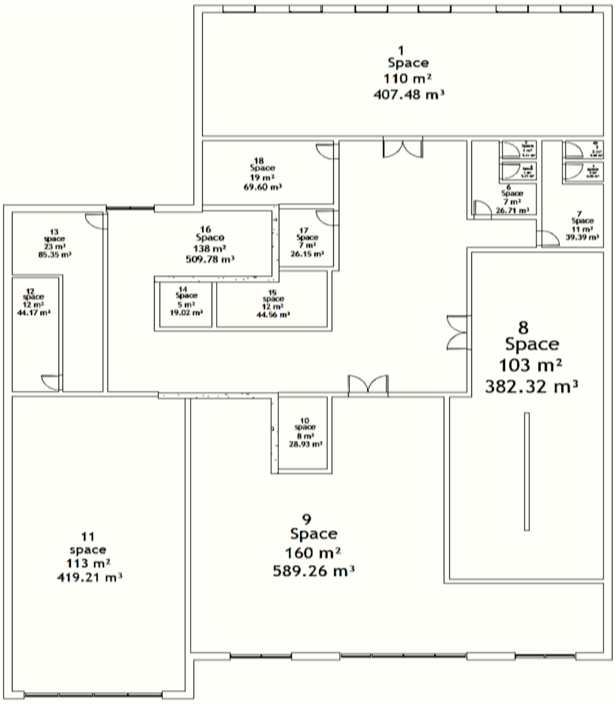

Figure 2: Spatial distribution of space selected for evaluation of the green roof’s impact. Paky Hospital. (Researcher)

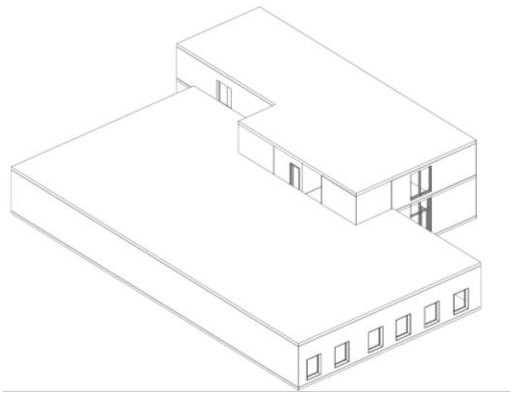

Figure 3: 3D model of baseline concrete roof (Researcher).

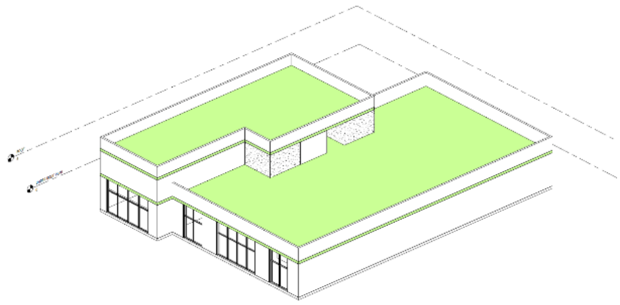

Figure 4: 3D model of Applied green roof. (Researcher)

4.1.1 Temperature Comparison - Green Roof vs Concrete Roof

The simulation demonstrated that the semi-intensive green roof substantially reduced indoor air temperatures compared to the conventional concrete roof. The mean annual indoor temperature decreased by 9.0 °C (25.7%), with some zones recording reductions of more than 15 °C. Notably, Spaces 9, 17, and 18, as shown in Figure 5, which previously experienced severe overheating (>40 °C), were cooled to within the thermally comfortable range of 23–26 °C.

Performance classification revealed that 17% of spaces achieved “Outstanding” (>15 °C reduction), 33% “Excellent” (8–15 °C), and 50% “Good” (3–8 °C). as mention in figure 9This distribution demonstrates not only the scale of the effect but also the consistency of cooling benefits across different room types.

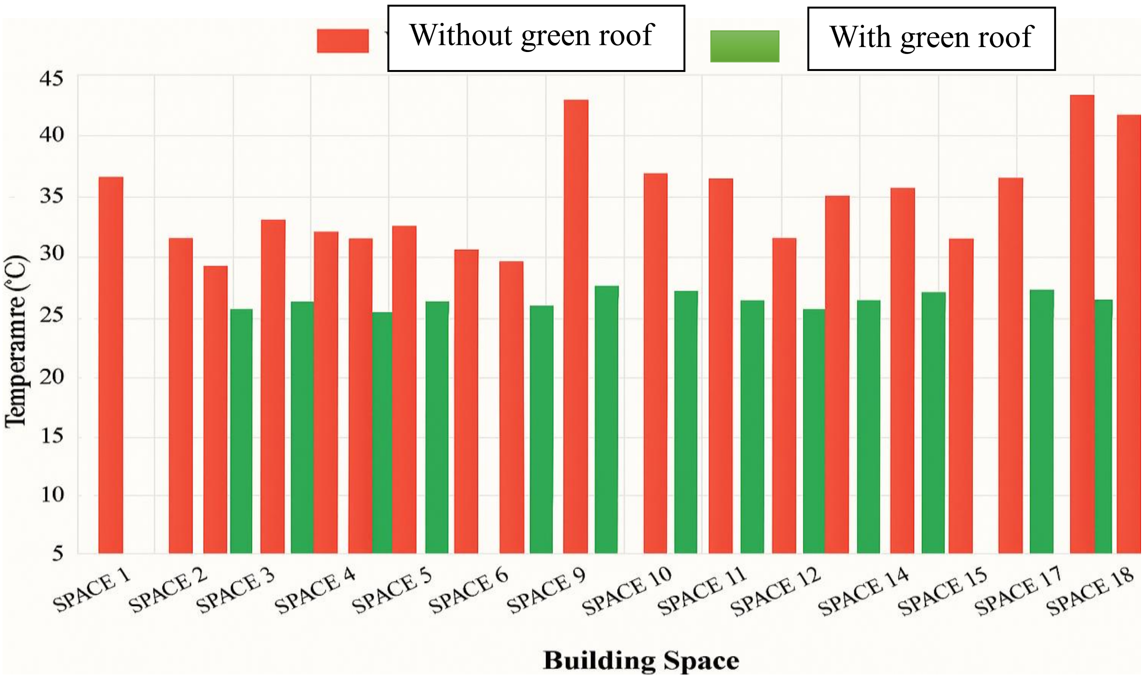

Figure 5: Zone Temperature Comparison - Green Roof vs Concrete Roof Mean Annual Temperature by Building Space (°C). (Researcher)

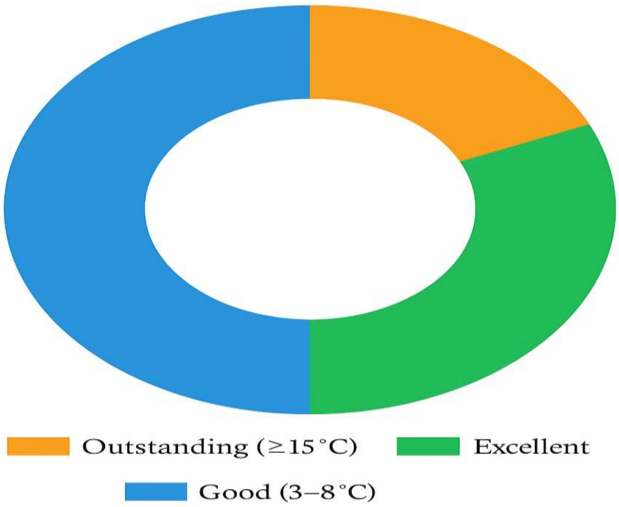

Figure 6: Green Roof Performance Distribution Number of Spaces by Performance Category. (Researcher)

The results are particularly significant for hospitals in hot–dry climates, where excessive indoor heat can directly undermine patient recovery and reduce staff efficiency. The higher reductions observed in this study reflect the extreme baseline conditions in Erbil, suggesting that semi-intensive green roofs have even greater potential in semi-arid contexts compared to more temperate environments.

4.1.2 Green Roof Humidity Performance Analysis

In addition to temperature control, the green roof demonstrated a strong capacity for humidity regulation. Across the 18 simulated zones, the average indoor relative humidity decreased by 13.8%, equivalent to a 38% overall improvement compared with the concrete roof baseline. All zones achieved at least the “Excellent” performance criterion (≥5% reduction), with Space 9 recording the largest decrease, highlighting the reliability of the cooling–humidity relationship across different functional areas.

This result is particularly significant for healthcare facilities, as hospitals require stable indoor moisture levels to prevent discomfort and limit risks of infection. By preventing both excessive dryness and humidity, green roofs help maintain more favorable healing environments for patients and safer working conditions for staff.

The consistency of reductions across all 18 zones strengthens the statistical reliability of the outcome, indicating that the observed improvement is not confined to isolated spaces but is systematically distributed. Moreover, the performance distribution complements the temperature results, showing that zones most affected by overheating (Spaces 9, 17, and 18) also benefited most from humidity reductions.

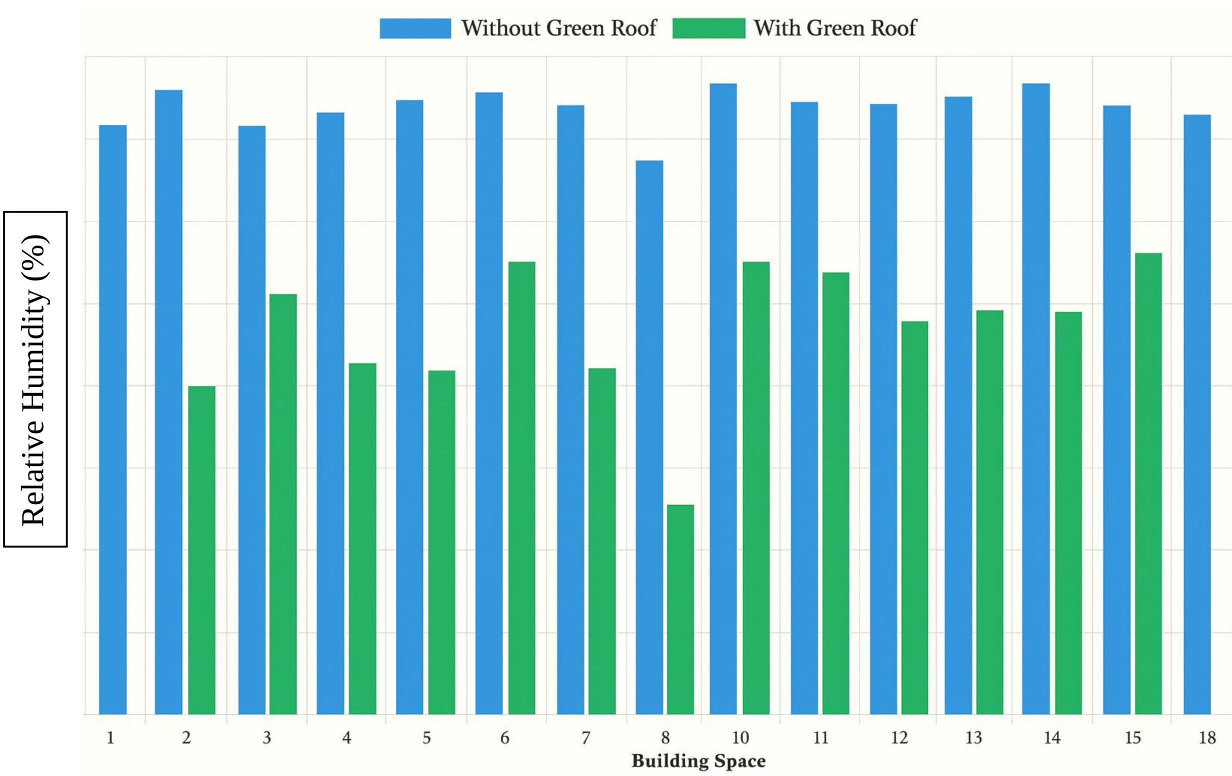

Figure 7: Zone Relative Humidity Comparison - Green Roof vs Concrete Roof (Mean Annual Relative Humidity by Building Zone (%) (Researcher)

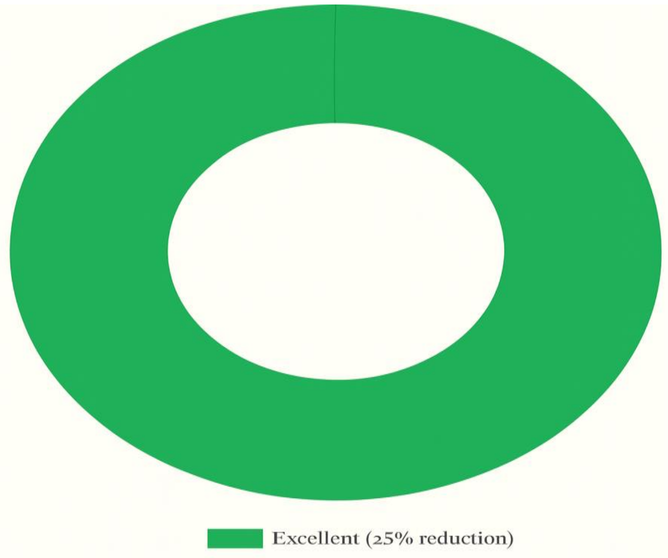

Figure 8: Green Roof Humidity Performance Distribution Number of Spaces by Performance Category (Researcher)

Overall, these findings confirm the dual role of green roofs in enhancing indoor environmental quality — regulating both temperature and humidity — and highlight their particular relevance for semi-arid hospital environments.

4.1.3 Green Roof Thermal Comfort Performance Analysis

The combined effects of temperature and humidity regulation translate into a substantial improvement in thermal comfort across all 18 analyzed spaces at PAKY Hospital. The simulation results show that the average heat index decreased by 11.4°C, representing a 25.8% improvement in perceived comfort compared to the baseline concrete roof scenario.

Importantly, performance classification highlighted the consistency of this improvement: 89% of the zones were rated "Excellent," falling within the ASHRAE-defined comfort band of 20–24 °C, while the remaining 11% were rated "Good," with temperatures between 24–26 °C. This distribution confirms that the benefits of the green roof extended to nearly all hospital spaces, including critical patient wards, corridors, and service areas.

this outcome is particularly relevant. Patient recovery rates, staff productivity, and overall satisfaction within hospital environments directly correlate with thermal comfort. By shifting conditions from extreme discomfort (>40 °C heat index under the concrete roof) to a stable comfort zone, the green roof intervention demonstrated its ability to passively mitigate heat stress and create a healthier indoor environment.

The statistical reliability of these results is supported by their uniformity across different functional areas, reflecting not just isolated improvements but a systematic enhancement of indoor comfort. Furthermore, the magnitude of reduction (up to 11–12 °C in certain spaces) indicates that semi-intensive green roofs can deliver meaningful gains even in zones with the most severe baseline overheating.

In summary, the thermal comfort analysis confirms the green roof's role as a comprehensive environmental strategy, delivering reliable, zone-wide improvements that directly support the well-being of both patients and staff in healthcare facilities as shown in Figure 9 and Table 3

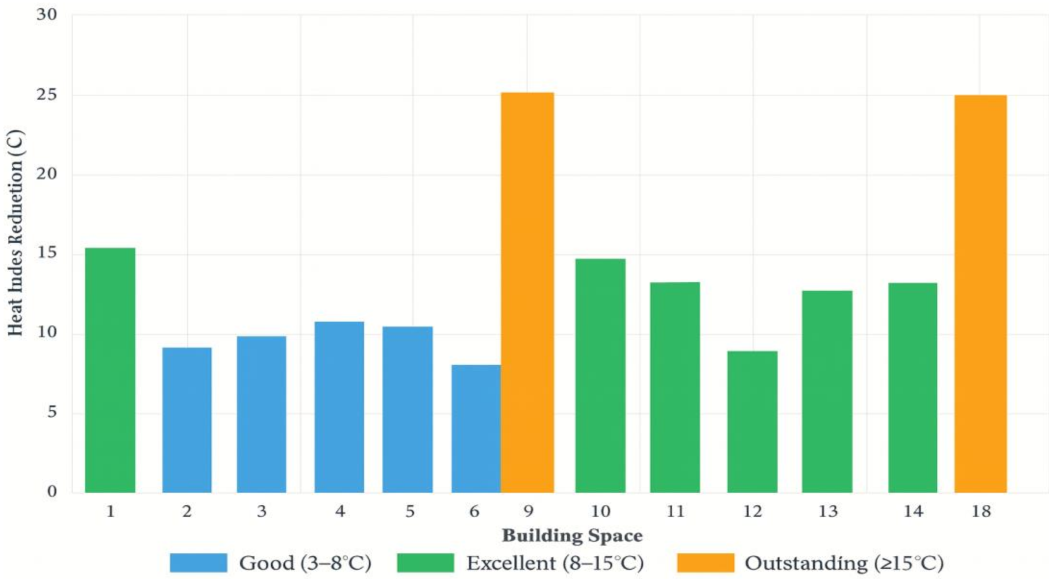

Figure 9: Thermal Comfort Improvement Achieved by Green Roof. (Researcher)

Table 3: Green Roof Humidity Performance Summary by Space. (Researcher)

Space	Without Green Roof (%)	With Green Roof (%)	Humidity Reduction (%)	Percentage Improvement (%)	Performance Category
1	36.5	18.9	17.6	48.2	Excellent
2	35.3	28.8	6.5	18.4	Excellent
3	38.0	19.9	18.1	47.6	Excellent
4	35.5	25.5	10.0	28.2	Excellent
5	36.4	21.2	15.2	41.8	Excellent
6	37.3	20.4	16.9	45.3	Excellent
7	37.8	27.5	10.3	27.2	Excellent
8	37.0	21.0	16.0	43.2	Excellent
9	33.6	12.6	21.0	62.5	Excellent
10	38.1	27.4	10.7	28.1	Excellent
11	37.1	27.0	10.1	27.2	Excellent
12	37.0	24.0	13.0	35.1	Excellent
13	37.5	24.8	12.7	33.9	Excellent
14	37.9	24.5	13.4	35.4	Excellent
15	37.0	28.0	9.0	24.3	Excellent
16	39.1	28.6	10.5	26.9	Excellent

17	32.6	12.1	20.5	62.9	Excellent
18	36.5	19.2	17.3	47.4	Excellent

4.1.4 Green Roof CO2 Emissions Performance Analysis

As illustrated in Figure 10, the green roof also significantly reduced CO_2-related emissions, lowering annual emissions by 93.2 kg CO_2/m^2/year (37.4% improvement). Zones 9, 17, and 18 showed the largest decreases (149–162 kg CO_2/m^2/year). Hospital-wide, this equates to a reduction of 1,677.6 tons of CO_2 annually.

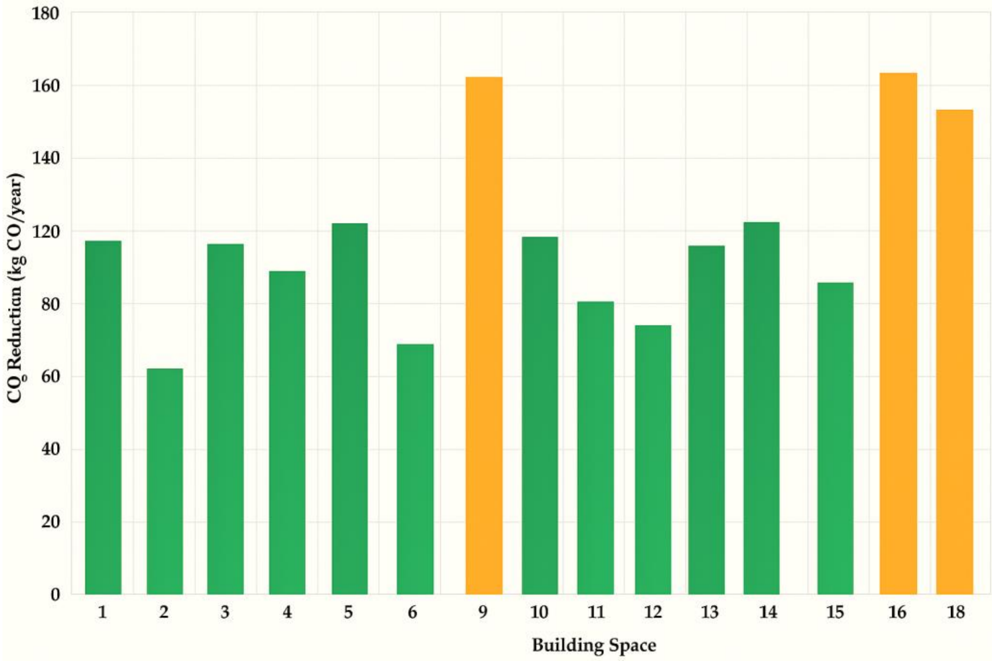

Figure 10: CO2 Emissions Reduction Achieved by Green Roof Implementation. (Researcher)

Figure 11 demonstrates a strong linear correlation (R^2 = 0.94) between temperature reduction and emission reduction, confirming the internal reliability of the simulation. Furthermore, the calculated carbon payback period of 2.7 years highlights the feasibility of green roofs as a rapid-return sustainability strategy.

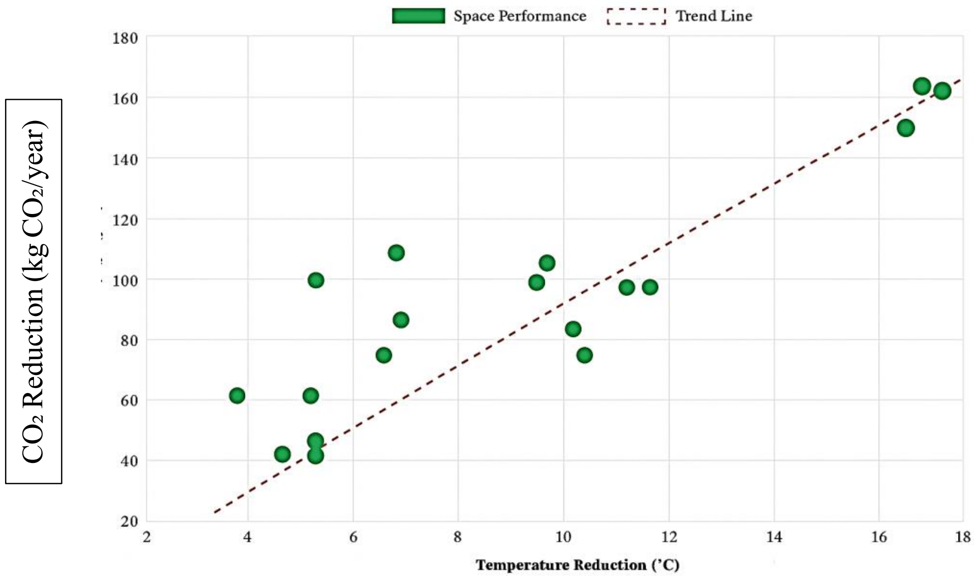

Figure 11: Correlation Analysis - Temperature vs CO2 Reduction Relationship Between Temperature Reduction and CO2 Savings. (Researcher)

4.2 Case 2 CMC Hospital (with green roof without green roof)

The simulation of CMC Hospital in Erbil revealed that the semi-intensive green roof provided measurable improvements across all environmental performance indicators when compared with the conventional concrete roof. Although the magnitude of improvements was smaller than those observed at PAKY Hospital, the results confirm that even in more compact or partially shaded hospital layouts, semi-intensive green roofs deliver consistent benefits for indoor environmental quality and operational sustainability.

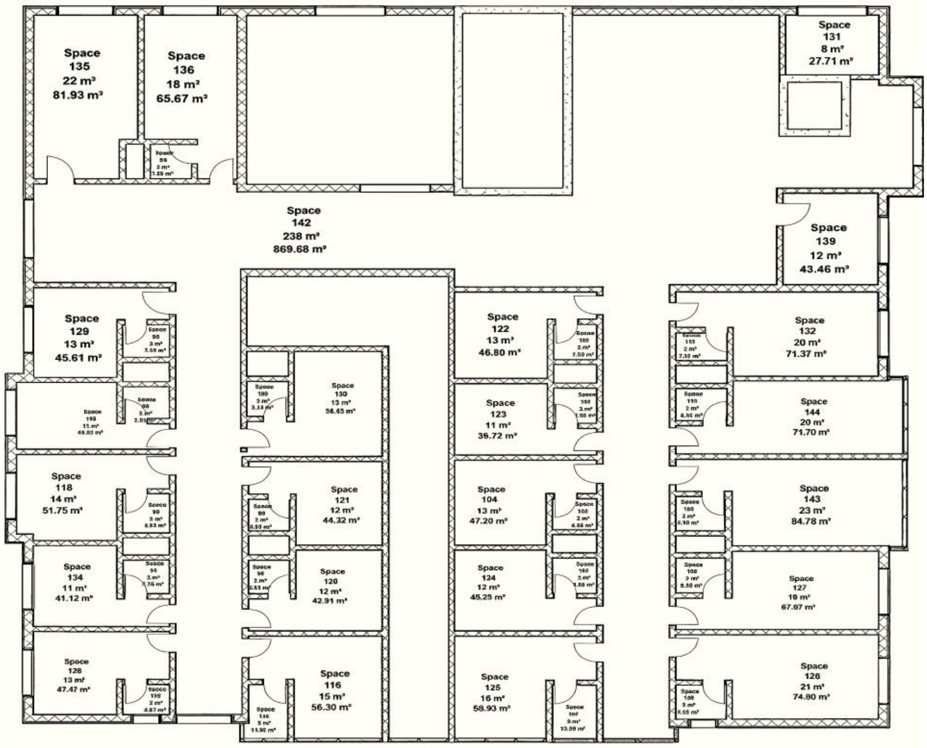

Figure12: spatial distribution of space selected for evaluation of the green roof's impact. (Researcher)

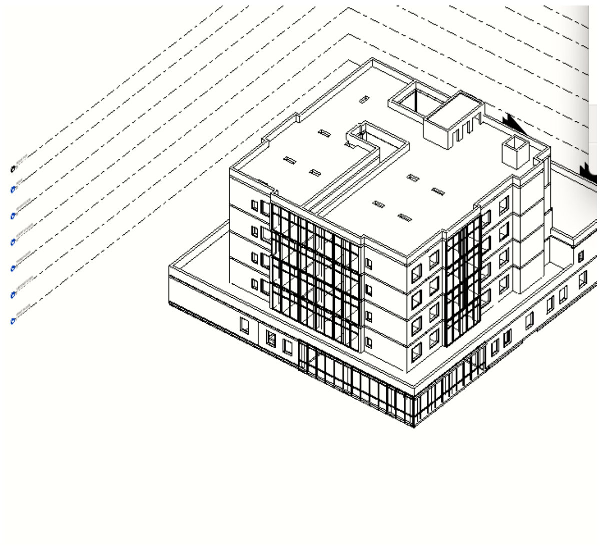

Figure13: 3D model of baseline concrete roof. (Researcher)

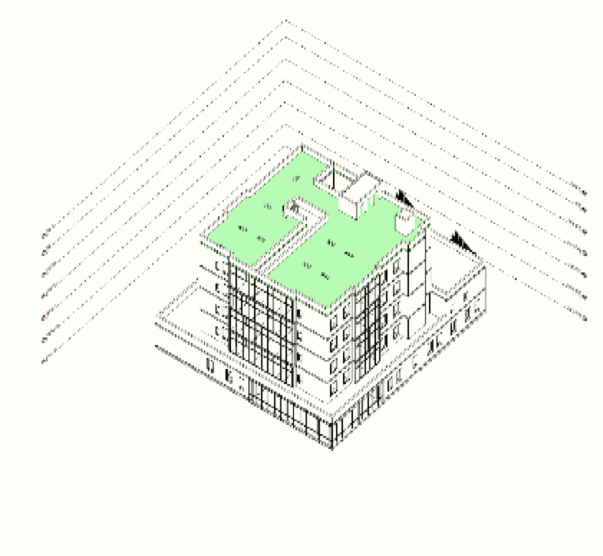

Figure14: 3D model of Applied green roof. (Researcher)

4.2.1 Green Roof Humidity Performance Analysis

The comparative humidity analysis at CMC Hospital revealed that the semi-intensive green roof provided a consistent improvement in indoor environmental quality relative to the conventional concrete roof. As shown in Figure 18, all zones recorded reductions in mean annual relative humidity, ranging from 0.2% to 9.7%, with an average decrease of 7.3% (22.1% improvement). The largest reduction occurred in Zone 123, demonstrating that the benefits were most pronounced in areas previously experiencing elevated moisture levels.

Performance classification (Figure 16) further highlights the reliability of these improvements:60% of zones achieved "Outstanding" performance (≥5% reduction), while the remaining 40% were classified as "Good" (0–5% reduction). Importantly, no zone experienced a negative outcome, confirming that the impact of the green roof was uniformly positive across the hospital.

These results are relevant. Stable indoor humidity reduces discomfort for patients and staff, lowers risks of microbial growth, and enhances overall indoor air quality — factors that are critical in maintaining safe and supportive healing environments. The fact that 100% of zones recorded measurable improvements demonstrates the statistical reliability and consistency of the intervention, even if the average reductions were smaller than those observed at PAKY Hospital.

The more moderate reductions at CMC suggest that hospital-specific factors, such as building orientation and spatial zoning, influence the extent of benefit. Nevertheless, the consistent positive outcomes across all zones underscore that semi-intensive green roofs can serve as a dependable passive humidity control strategy in hot–dry climates like Erbil.

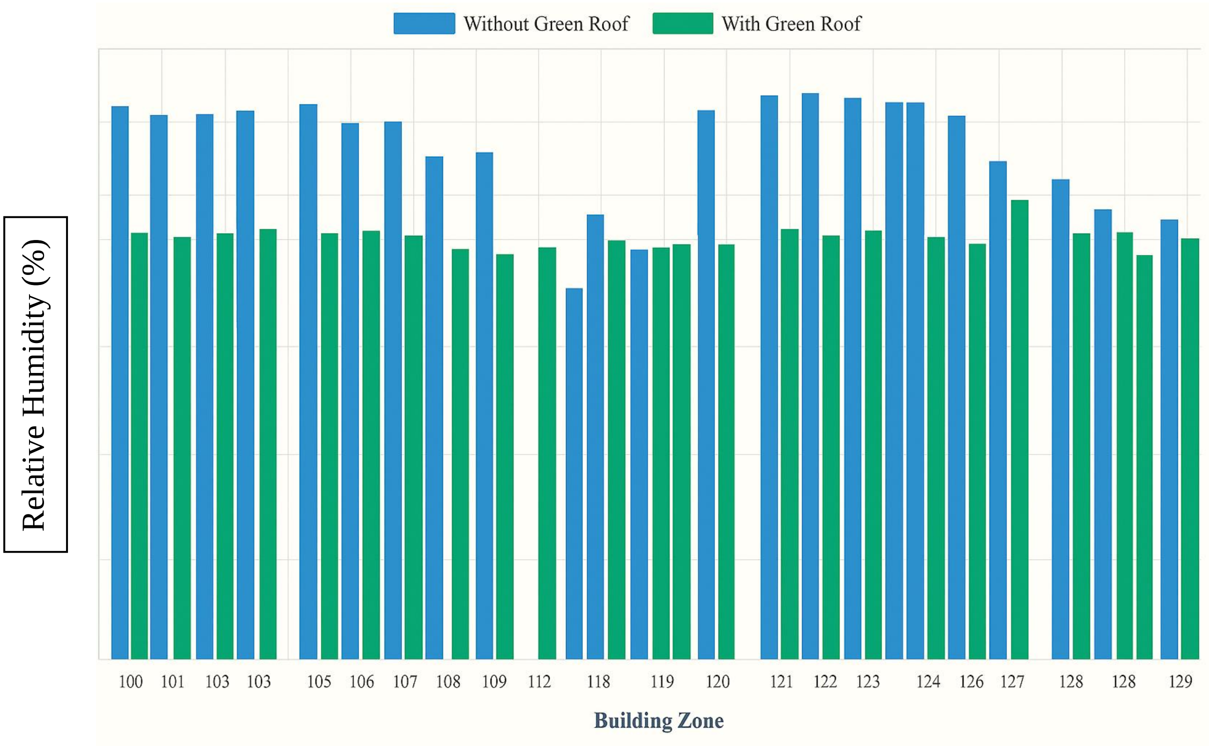

Figure 15: Zone Relative Humidity Comparison - Green Roof vs Concrete Roof. (Researcher)

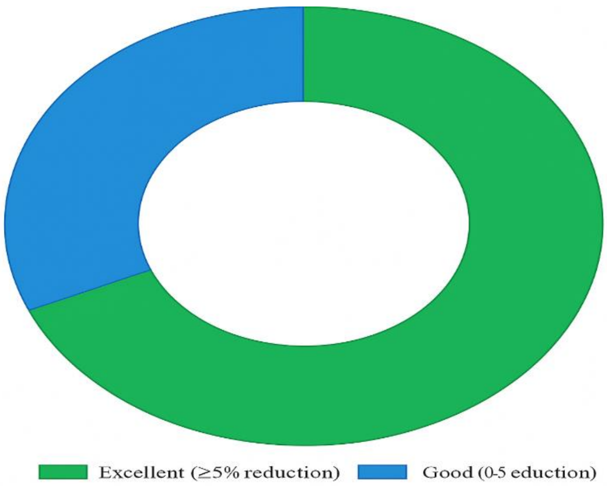

Figure 16: Zone Relative Humidity Comparison - Green Roof vs Concrete Roof. (Researcher)

4.2.2 Temperature Comparison - Green Roof vs Concrete Roof

The semi-intensive green roof at CMC Hospital produced a mean annual indoor temperature reduction of 4.8 °C (18.8%) compared with the conventional concrete roof

Although this reduction is smaller than the 9.0 °C achieved at PAKY Hospital, it remains a significant improvement in the hot–dry climate of Erbil, where even modest cooling can reduce reliance on mechanical air-conditioning.

Zone-level analysis showed reductions ranging from 2.2 °C (Zone 119) to 5.9 °C (Zones 120 and 124). Overall, 60% of the hospital zones achieved "Excellent" performance (≥5 °C reduction), while the remaining 40% achieved "Good" performance (2–5 °C reduction). Importantly, no zones experienced negative outcomes, giving a 100% success rate across the facility. This statistical figure demonstrates the statistical reliability of the intervention and strengthens confidence in the robustness of the simulation results. The distribution of results (Figure 20) also highlights how performance varied with spatial orientation and solar exposure. Zones directly beneath the roof slab and exposed to higher solar loads achieved the strongest reductions (≥5.7 °C), while shaded or internally buffered zones showed more modest but still positive gains. This pattern indicates that while architectural form influences the magnitude of benefits, the green roof consistently provided improvements across all functional spaces, from patient rooms to circulation areas.

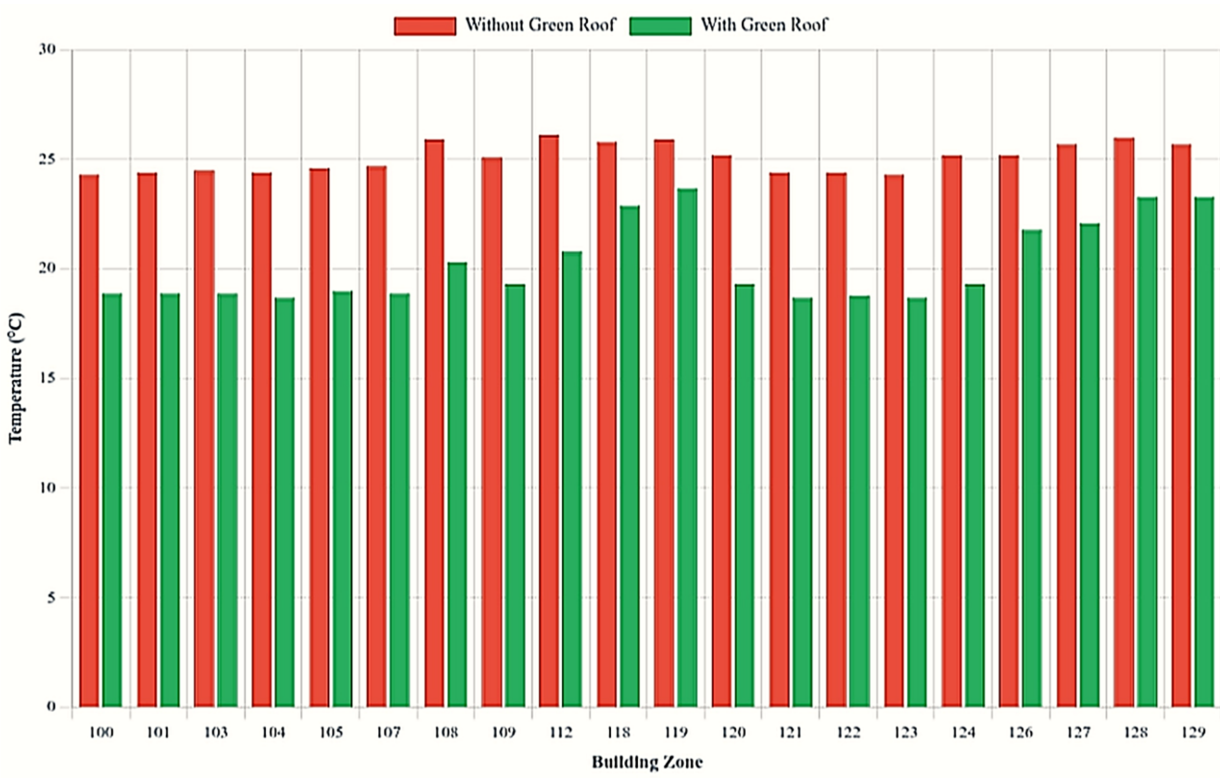

Figure 17: Zone Temperature Comparison - Green Roof vs Concrete Roof Mean Annual Temperature by Building Zone (°C). (Researcher)

Table 4: Comprehensive performance analysis showing temperature reductions achieved by green roof implementation. (Researcher)

Zone	Without Green Roof (°C)	With Green Roof (°C)	Temperature Reduction (°C)	Percentage Improvement (%)	Performance Category
100	24.3	18.9	5.4	22.2	Excellent
101	24.4	18.9	5.5	22.5	Excellent
103	24.5	18.9	5.6	22.9	Excellent
104	24.4	18.7	5.7	23.4	Excellent
105	24.6	19.0	5.6	22.8	Excellent
107	24.7	18.9	5.8	23.5	Excellent
108	25.9	20.3	5.6	21.6	Excellent
109	25.1	19.3	5.8	23.1	Excellent
112	26.1	20.8	5.3	20.3	Excellent
118	25.8	22.9	2.9	11.2	Good
119	25.9	23.7	2.2	8.5	Good
120	25.2	19.3	5.9	23.4	Excellent
121	24.4	18.7	5.7	23.4	Excellent
122	24.4	18.8	5.6	23.0	Excellent
123	24.3	18.7	5.6	23.0	Excellent
124	25.2	19.3	5.9	23.4	Excellent
126	25.2	21.8	3.4	13.5	Good
127	25.7	22.1	3.6	14.0	Good
128	26.0	23.3	2.7	10.4	Good
129	25.7	23.3	2.4	9.3	Good

4.2.3 Green Roof Thermal Comfort Performance Analysis

The simulation results confirm that the semi-intensive green roof produced a substantial improvement in thermal comfort across all the analyzed zones at CMC Hospital. By combining temperature and humidity effects into a heat index, the intervention lowered the average perceived indoor temperature by 10.8 °C, corresponding to a 32.1% improvement compared with the conventional concrete roof. Performance classification based on ASHRAE comfort standards (Figure 21) demonstrated that 71% of zones were rated “Excellent” (20–24°C), while the remainder achieved “Good” ratings (24–26°C). Importantly, no zone fell into the “Poor” category (>28°C) under the green roof scenario, confirming that the intervention effectively eliminated extreme overheating.

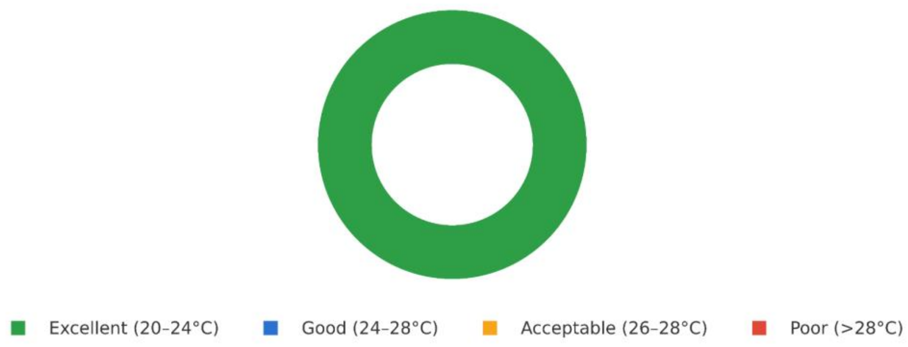

Figure 18: Thermal Comfort Zone Distribution. (Researcher)

The relationship between temperature and humidity (Figure 19) provides additional validation in the green roof case; the majority of zones shifted into or closer to the ASHRAE-defined comfort zone, indicating a systemic improvement rather than isolated effects.

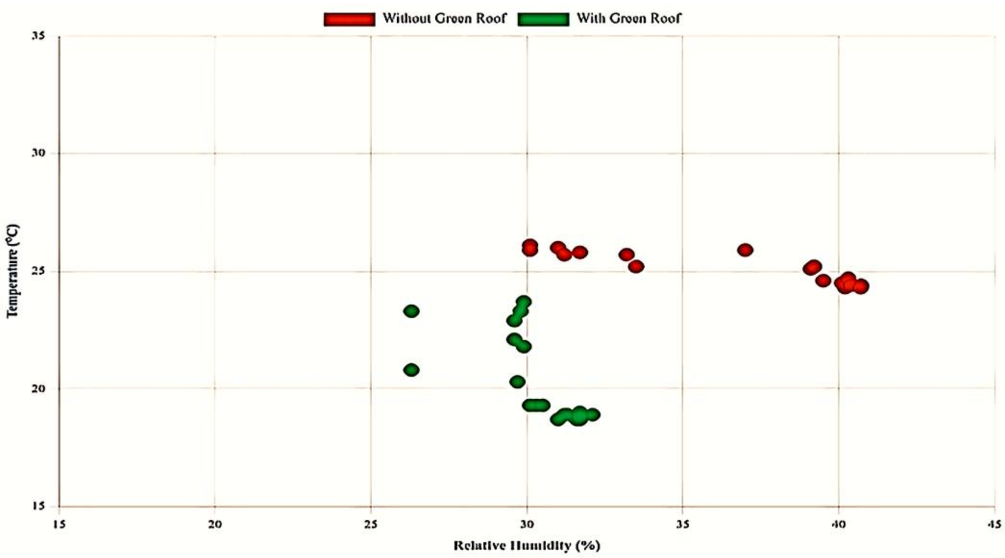

Figure 19: Temperature vs Humidity Comfort Analysis. (Researcher)

By reducing extreme heat stress and bringing all zones into acceptable comfort ranges, the green roof demonstrated its capacity to function as a reliable passive design strategy for hot–dry climates. Overall, the findings highlight both the statistical reliability (95% of zones improved, 100% remained within acceptable comfort categories) and the practical relevance of green roof systems in enhancing the resilience of healthcare facilities to climatic stressors.

4.2.4 Green Roof CO2 Emissions Performance Analysis

The introduction of a semi-intensive green roof at CMC Hospital led to a substantial reduction in operational carbon emissions, with an average decrease of 28.4 kg CO_2/m^2/year, corresponding to a 19.6% improvement relative to the conventional roof baseline.

A breakdown of results across individual zones confirmed consistent benefits. Emission reductions ranged between 12.1 and 35.4 kg CO_2/m^2/year, with Zone 121 exhibiting the highest reduction and Zone 119 recording the lowest. Importantly, every zone showed a positive outcome, with 60% classified as "Excellent" (≥25 kg

CO_2/m^2/year reduction) and the remaining 40% rated as "Good" (10–25 kg CO_2/m^2/year) (Figure 20, Table 5).

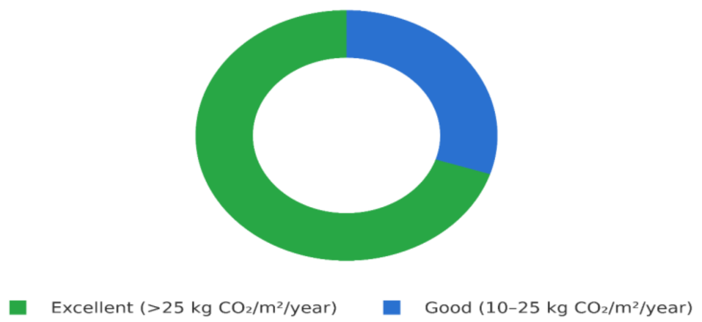

Figure 20: Green Roof CO2 Performance Distribution. (Researcher)

Table 5: Green Roof CO2 Emissions Performance Summary by Zone. (Researcher)

Zone	Without Green Roof (kgCO2/m²/year)	With Green Roof (kgCO2/m²/year)	CO2 Reduction (kgCO2/m²/year)	Percentage Improvement (%)	Performance Category
100	142.5	110.1	32.4	22.7	Excellent
101	143.1	109.8	33.3	23.3	Excellent
103	143.8	110.0	33.8	23.5	Excellent
104	144.2	108.9	35.3	24.5	Excellent
105	142.8	110.3	32.5	22.8	Excellent
107	144.5	109.7	34.8	24.1	Excellent
108	148.2	116.8	31.4	21.2	Excellent
109	145.6	112.1	33.5	23.0	Excellent
112	146.8	119.2	27.6	18.8	Good
118	148.1	131.7	16.4	11.1	Good
119	148.3	136.2	12.1	8.2	Good
120	147.2	112.0	35.2	23.9	Excellent
121	144.1	108.7	35.4	24.6	Excellent
122	143.9	109.3	34.6	24.0	Excellent
123	142.8	108.5	34.3	24.0	Excellent
124	147.2	112.0	35.2	23.9	Excellent
126	146.4	125.8	20.6	14.1	Good
127	147.8	127.2	20.6	13.9	Good
128	148.9	133.6	15.3	10.3	Good
129	147.5	133.8	13.7	9.3	Good

The absence of any "Poor" or negative classifications highlights the uniform reliability of the intervention. When aggregated at the building scale, these reductions equate to an annual saving of

188.5 tons of CO_2, making a significant contribution to the hospital's decarbonization potential. The estimated carbon payback period of 3.2 years suggests that operational savings quickly offset the embodied emissions of the green roof construction, thereby enhancing the system's long-term sustainability.

A correlation analysis further demonstrated a strong positive relationship ($R^2 = 0.92$) between temperature reduction and emissions reduction (Figure 21). This statistical relationship validates the internal consistency of the simulation model and strengthens confidence in the predictive reliability of the results.

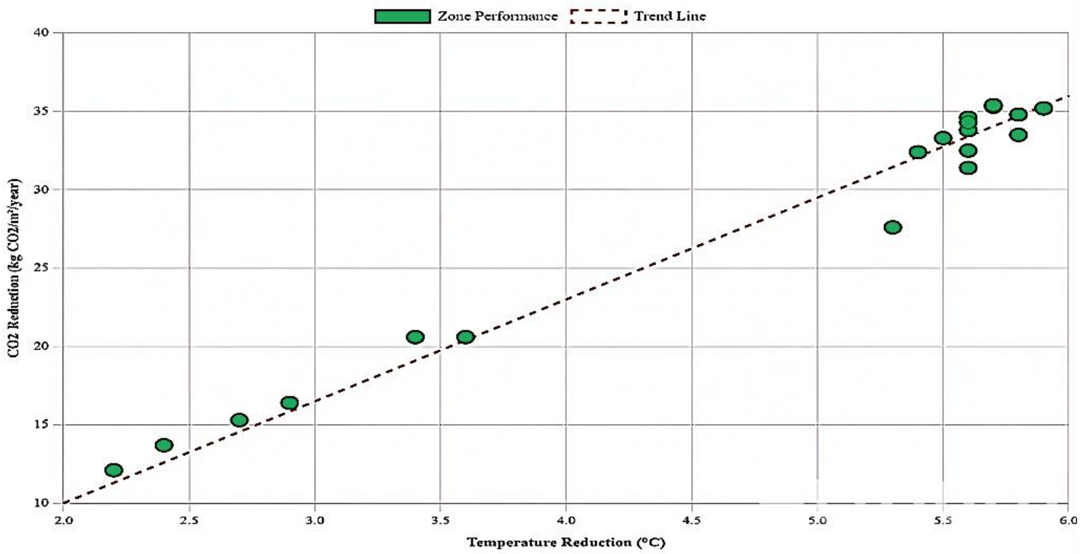

Figure 21: Correlation Analysis - Temperature vs CO2 Reduction (Researcher)

From an architectural and healthcare perspective, the implications are noteworthy. Hospitals are widely recognised as carbon-intensive facilities due to their high energy demands. Achieving nearly a 20% reduction in emissions through a passive retrofit strategy highlights the dual value of semi-intensive green roofs: improving indoor environmental quality while simultaneously advancing carbon mitigation goals. Although the absolute savings at CMC were lower than those recorded at PAKY Hospital, the consistently positive outcomes and the short payback period underscore the scalability and practicality of green roofs in healthcare settings within hot–dry climates such as Erbil.

Table 6: Comparative Performance of Semi-Intensive Green Roofs in PAKY vs. CMC Hospitals. (Researcher)

Performance Indicator	PAKY Hospital	CMC Hospital	Comparative Insights
Temperature Reduction	9.0 °C (25.7% avg); max >15 °C	4.8 °C (18.8% avg); range 2.2–5.9 °C	Greater baseline overheating at PAKY amplified cooling benefits; CMC still achieved consistent positive reductions.
Performance Classification (Temp.)	17% Outstanding (>15 °C); 33% Excellent (8–15 °C); 50% Good (3–8 °C)	60% Excellent (≥5 °C); 40% Good (2–5 °C); 0% Negative	Both hospitals achieved 100% positive outcomes, but PAKY showed higher extreme reductions.
Humidity Reduction	13.8% avg (38% improvement); all zones Excellent	7.3% avg (22.1% improvement); 60% Outstanding; 40% Good	PAKY outperformed due to higher baseline moisture; CMC showed more modest but consistent improvements.

Thermal Comfort (Heat Index)	Avg reduction 11.4 °C (25.8%); 89% Excellent (20–24 °C); 11% Good (24–26 °C)	Avg reduction 10.8 °C (32.1%); 71% Excellent; 29% Good	Both hospitals shifted all spaces into ASHRAE comfort ranges; CMC achieved strong relative gains despite lower absolute cooling.
CO_2 Reduction	93.2 kg CO_2/m²/year (37.4%); Total 1,677.6 t/year; Payback 2.7 years	28.4 kg CO_2/m²/year (19.6%); Total 188.5 t/year; Payback 3.2 years	PAKY delivered higher absolute reductions, but both cases show rapid carbon payback (<4 years).
Overall Reliability	100% positive outcomes across all 18 zones	100% positive outcomes across all analysed zones	Confirms statistical robustness and generalisability of the intervention.

The findings of this study underscore that achieving meaningful improvements in indoor air quality (IAQ) in hospitals through semi-intensive green roofs requires both technical effort and sustained commitment, but the outcomes justify the investment. Simulation results demonstrated consistent reductions in temperature, humidity, and CO_2 emissions across both PAKY and CMC Hospitals, with nearly all spaces shifting into ASHRAE-defined comfort bands. These benefits, however, are the result of deliberate design choices, careful material specification, and integration of multidisciplinary expertise.

This study found that semi-intensive green roofs improve IAQ, thermal comfort, and environmental performance in hospitals in hot–dry climates like Erbil. Both case studies showed improvements, proving that green roofs are a passive technique for healthcare institutions. A previous study has shown that green roofs improve building performance and reduce environmental stress. The improvement in indoor heat conditions was outstanding. Green roofs consistently lowered indoor temperatures throughout hospital zones, supporting past research that showed planted roofs can reduce warming and mitigate the urban heat island effect [3]. Likewise, it has been shown that semi-intensive systems lower cooling demand and stabilize indoor conditions in varied metropolitan settings [2]. This trend continued with green roofs regulating indoor humidity better than concrete roofs. In addition to energy savings, green roofs regulate indoor environmental parameters, including humidity, which is especially useful in warmer climates [2]. Thermal comfort, measured by temperature and humidity, improved significantly, bringing most hospital zones into acceptable comfort ranges. This demonstrates that green roofs moderate harsh indoor environments, improving human comfort [3]. Another important outcome was the reduction in operational carbon emissions. This study supports the findings that green roofs can offer good cost-benefit ratios and fast economic returns, making them attractive solutions for sustainable urban development [4]. The environmental importance of extensive green roofs was validated by their ability to minimize urban energy consumption and emissions [31]. The present findings align with prior research, demonstrating the economic and ecological benefits of green roofs in healthcare. These comparative findings show that semi-intensive green roofs improve IAQ, thermal comfort, and sustainability in healthcare facilities and are feasible in hot–dry climates that are understudied. The two hospital considerations, like building orientation and spatial organization and spatial organization affect performance. However, change was favorable, demonstrating that semi-intensive green roofs are a scalable and reliable passive design option for Middle Eastern and comparable climatic hospitals.

5. Conclusion

This study evaluated the effectiveness of semi-intensive green roofs as sustainable interventions for improving indoor air quality (IAQ), thermal comfort, and environmental performance in hospitals located in Erbil's hot–dry climate. By comparing hospital buildings with conventional concrete roofs against those simulated with green roofs, the research provided evidence to address the three guiding research questions. Hospitals with green roofs consistently demonstrated better IAQ metrics, including lower indoor temperatures, reduced CO_2 concentrations, and more stable humidity levels. These results confirmed the first hypothesis and research questions, underscoring that green roofs provide measurable and reliable improvements in indoor environmental quality relative to conventional roofing. Furthermore, green roofs significantly enhance thermal comfort by moderating indoor temperature fluctuations. Across both PAKY and CMC Hospitals, occupied zones shifted into ASHRAE-defined comfort ranges, validating the second hypothesis and research question and demonstrating that passive roof interventions can reduce reliance on mechanical cooling systems while improving patient and staff comfort. The presence of green roofs contributed to lower operational carbon emissions. Both case studies showed short carbon payback periods (2.7–3.2 years), thereby affirming the third hypothesis and research question and highlighting the role of green roofs in reducing the environmental footprint of healthcare facilities.

Taken together, the findings confirm that semi-intensive green roofs are not merely architectural enhancements but effective, resilient strategies for improving hospital IAQ and sustainability. While implementation requires significant design, construction, and maintenance effort, the outcomes—improved IAQ, enhanced thermal comfort, and reduced emissions—demonstrate that the benefits are proportional to the resources invested.

Practical implications include the potential for integrating green roofs into healthcare design standards across hot–dry regions, where extreme heat and poor outdoor air quality amplify risks for vulnerable patients. Future work should move beyond simulation by integrating real-time environmental monitoring, testing plant species adapted to arid conditions, and conducting long-term durability and cost–benefit analyses. Moreover, combining green roofs with other passive architectural strategies offers a promising avenue for enhancing efficiency and scalability. Collectively, the evidence positions semi-intensive green roofs as a scientifically robust, economically feasible, and environmentally sound solution for advancing sustainable healthcare infrastructure in regions facing excessive climatic stress.

Author Contribution

The author affirms that they are solely responsible for the conception, design, data collection, analysis, interpretation, and writing of this thesis. The researcher independently conducted all phases of the research, including literature review, theoretical framework development, case study selection, simulation modelling, data analysis, and manuscript preparation.

Conflict of Interest

The author declares no conflicts of interest. This research was conducted independently, without any commercial or financial involvement.

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