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Comparative Evaluation of the Effectiveness of Cool Roofs in the Hot and Dry Climate of Iran

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ABSTRACT: Escalating urban heat island effects and rising energy demands in Iran's hot, dry climate pose a serious challenge for educational buildings, where high occupant density intensifies cooling needs and operational costs. This research addresses the urgency of adopting cool roof technologies—such as reflective coatings, green roofs, high-albedo materials, and radiative cooling roofs—to mitigate extreme indoor temperatures, reduce carbon footprints, and enhance student and staff well-being. Drawing on empirical data, simulation models, and a comprehensive literature review, we employ a weighted-scoring framework that evaluates each technology's thermal performance, energy savings, cost factors, durability, and environmental impact. Findings reveal that while radiative cooling roofs offer the greatest potential for reducing cooling loads (up to 30–40%) and maintaining comfortable indoor temperatures, they demand more advanced materials and higher initial investment. Green roofs yield substantial insulation and environmental benefits, but are limited by water scarcity and elevated setup costs. Conversely, reflective coatings and high-albedo materials strike a balance between effectiveness and affordability, making them viable for retrofits in budget-constrained educational facilities. The results underscore the need for context-specific solutions that consider local climate, water resources, building typology, and policy incentives. By clarifying the strengths and trade-offs of each cool roof approach, this study provides actionable guidance for architects, policymakers, and school administrators seeking sustainable and cost-effective interventions. Future research should focus on long-term performance monitoring, integrating complementary passive strategies (e.g., shading, natural ventilation), and developing localized materials tailored to resource-limited contexts.

Keywords: *Cool roofs, Hot and dry climates, educational buildings, Sustainability, Passive cooling strategies, Energy efficiency, Thermal comfort.*

INTRODUCTION

Societies worldwide face escalating environmental challenges due to rapid urban development, rising energy demands, and climate change. In many arid and semi-arid regions, the urban heat island (UHI) effect exacerbates these concerns by intensifying outdoor temperatures and straining energy infrastructures. Iran, characterized by extensive hot and dry climatic zones, provides a compelling example of how these issues converge. Here, educational buildings—vital to community development—require substantial cooling to maintain indoor comfort, a factor that significantly elevates operational costs and carbon emissions (Freidooni et al., 2022; Jamshidi et al., 2023). Amid these pressures, cool roofs have emerged as a noteworthy strategy to reduce building energy consumption and enhance occupant thermal comfort (Elnabawi et al., 2022; Rawat & Singh, 2022). By reflecting a greater fraction of incoming solar radiation and minimizing heat absorption, cool roofs can curtail cooling loads and mitigate the UHI effect. While studies have demonstrated the broad effectiveness of these roofs in temperate or humid environments, comparatively fewer investigations address how specific cool roof typologies perform under hot, dry conditions, where diurnal temperature swings, limited water resources, and intense solar radiation present distinct technical and economic challenges (Yazdani & Baneshi, 2021; Heidari & Azizi, 2020).

In Iran's central and southeastern regions, summer temperatures frequently exceed 40°C, and the combination of low precipitation and low humidity further complicates maintaining stable indoor environments (Yang et al., 2020). Given that educational facilities are often large, densely occupied structures operating throughout the day, the choice of roofing system has a significant impact on thermal

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performance, energy expenditure, and, by extension, the well-being of students and staff (Hessari & Seyf Shojaee, 2021). Designing or retrofitting these buildings to leverage passive cooling measures—such as cool roofs—thus holds significant potential for economic, environmental, and health benefits (Saber, 2022).

Problem Statement and Knowledge Gap

Despite a growing body of research on cool roof technologies, a comprehensive understanding of how different roof types—such as reflective coatings, green roofs, radiative cooling solutions, and others—perform specifically in Iran's hot, dry conditions remains underdeveloped (Ashtari et al., 2021). The uniqueness of arid zones, characterized by extreme daytime heat and scarce water supplies, necessitates a contextualized assessment that considers installation feasibility, life-cycle costs, and user comfort (Bevilacqua, 2021). Educational buildings introduce additional design considerations, including occupant density, building orientation, and ventilation practices, all of which may influence the effectiveness of cool roofing strategies (Hosseini & Akbari, 2016).

Research Objectives

This study seeks to bridge these gaps by conducting a comparative evaluation of multiple cool roof technologies in Iran's hot and dry climate, with a focus on:

• Thermal Performance: Assessing how each roof type influences indoor temperature profiles and occupant comfort in educational buildings.

• Energy Savings and Cost-Benefit Analysis: Quantifying reductions in air-conditioning demand and examining financial feasibility, including installation, maintenance, and potential incentives.

• Technology Suitability: Identifying the most promising cool roof solutions that align with the unique climatic and infrastructural challenges faced by educational facilities in arid regions.

Scope and Significance

To achieve these objectives, the study synthesizes empirical data from past field experiments, simulation models tailored to Iran's climate, and a critical review of established best practices. In contrast to existing literature that focuses on temperate or humid contexts, this research foregrounds the combined effects of extreme heat, diurnal temperature fluctuations, and water scarcity. By clarifying how cool roof options perform under these specific constraints, we aim to provide architects, policymakers, and educational administrators with actionable insights that can inform building codes, design guidelines, and long-term strategies for sustainable development. Ultimately, the findings will contribute to broader goals of reducing carbon footprints in the educational sector, improving occupant well-being, and enhancing resilience against escalating temperatures. The results will serve as a foundation for further exploration into integrating cool roofs with additional passive strategies—such as optimized ventilation and shading—to establish holistic solutions that advance comfort, efficiency, and sustainability in hot and dry regions.

Literature Review

Buildings in hot and dry climates—particularly educational facilities—are subject to extreme daytime temperatures, high solar radiation, and significant diurnal temperature swings. In such conditions, optimizing thermal comfort and reducing cooling loads are paramount for both occupant well-being and operational cost savings (Freidooni et al., 2022; Hessari & Seyf Shojaee, 2021). Cool roofs have emerged as a promising intervention due to their capacity to reflect solar radiation and lower rooftop surface temperatures. However, a cohesive theoretical framework that connects cool roof technologies to the unique demands of educational buildings in arid zones remains underexplored. Recent research on cool roofs has primarily focused on general building types or temperate and humid regions, rather than hot and dry climates, where issues such as water scarcity and extreme heat pose additional challenges (Elnabawi et al., 2022; Rawat & Singh, 2022). Moreover, occupant comfort in educational settings—where indoor temperatures directly influence learning and productivity—requires tailored studies that examine multiple performance metrics (Heidari & Azizi, 2020). While many studies address energy savings or urban heat island mitigation separately, fewer integrate these facets with the specific design, cost, and environmental constraints of educational buildings in arid regions (Freidooni et al., 2022).

Overview of Previous Work on Cool Roofs

Cool roofs are characterized by their high solar reflectance and thermal emittance (Elnabawi et al., 2022), which enables reduced roof surface temperatures and, consequently, decreased cooling energy. Research to date has employed mathematical, experimental, or computational models to estimate the energy and thermal impacts of cool roofs (Costanzo et al., 2016). Computer simulations, in particular, provide precise and repeatable evaluations of energy performance under varying climatic scenarios (Rawat & Singh, 2022).

Reflective Coatings and High-Albedo Surfaces

• Widely studied for their ability to lower peak roof temperatures (Konopacki et al., 1998; Xu et al., 2012).

• Show energy savings of 10–25%, depending on reflectance levels and local solar intensity (Saber, 2022; Feng et al., 2022).

• Typically cost-effective, yet require periodic maintenance or reapplication to sustain reflectivity.

Green (Vegetative) Roofs

• Emphasized for their insulation benefits, stormwater management, and capacity to mitigate the urban heat island (Bevilacqua, 2021; Virk et al., 2014).

• Performance in hot, dry regions is more complex, often requiring irrigation to ensure the viability of vegetation (Yazdani & Baneshi, 2021).

• The potential for improved indoor comfort is high, but the high initial cost and water scarcity may limit widespread adoption.

Radiative Cooling Roofs

• Utilize materials with high emissivity to release thermal energy into the sky, which is especially effective at night when ambient temperatures drop (Chen & Lu, 2021; Wang et al., 2022b).

• Can achieve notable energy savings, particularly in clear-sky, low-humidity environments typical of many regions in Iran.

• More advanced materials and precision installation can elevate initial costs (Anand et al., 2021).

Hybrid or Dynamic Systems

• Some studies compare "dynamic" cool roofs (adjustable reflectivity) with static green roofs, finding that dynamic solutions often yield higher energy savings in arid zones (Yazdani & Baneshi, 2021).

• Interactions with additional passive strategies (e.g., natural ventilation, shading devices) remain understudied.

Despite these advances, key gaps persist in the literature. Many investigations either target broader climatic categories (temperate or humid) or focus solely on one cool roof typology (Ashtari et al., 2021; Virk et al., 2014). In the context of hot, dry climates, extreme temperatures, and water scarcity, as well as architectural typologies unique to educational buildings, a more nuanced evaluation is warranted (Jamshidi et al., 2023). Moreover, life-cycle assessments—including long-term performance, maintenance, and cost-effectiveness—are often overlooked in arid environments (Heidari & Azizi, 2020).

Conceptual Framework for Cool Roof Evaluation in Educational Buildings

Building upon prior studies, Figure 1 (conceptually described below) outlines a framework to evaluate cool roof performance in hot, dry climates, especially for schools and universities:

Climatic Inputs and Constraints

• Solar radiation, diurnal temperature variation, ambient humidity, and wind patterns.

• Water scarcity considerations significantly impact the feasibility of green roofs.

Roof Technologies

• Reflective/High-Albedo: Emphasize reflectivity to diminish daytime heat gain.

• Green Roofs: Leverage vegetation for insulation and evapotranspiration, but require irrigation.

• Radiative Cooling: Use high emissivity to discharge heat at night; effective under clear skies.

Evaluation Metrics

• Thermal Comfort: Indoor temperature reduction, measured via occupant surveys or operational data (Heidari & Azizi, 2020).

• Energy Savings: Decreased cooling load (kWh saved) in educational facilities (Hessari & Seyf Shojaee, 2021).

• Cost and Maintenance: Upfront Capital vs. Ongoing Upkeep.

• Environmental Factors: Stormwater retention, urban heat island mitigation, CO_2 footprint (Jamshidi et al., 2023).

Contextual Modifiers

• Building Typology: Classroom size, roofing materials, and building age.

• Policy and Incentives: Government subsidies, building codes, and public awareness (Freidooni et al., 2022).

Outcome

• Optimized Roof Selection: Matching specific roof types with the climate-driven challenges and infrastructural realities of educational buildings.

• Integrated Strategies: Possible synergy with other passive systems, such as natural ventilation or shading (Yazdani & Baneshi, 2021).

Within this conceptual framework, the performance of each roof solution can be systematically assessed by mapping climate data, cost parameters, and occupant comfort requirements. By incorporating studies focused on building forms, occupant well-being, and sustainability in extreme climates (Freidooni et al., 2022; Hessari & Seyf Shojaee, 2021; Heidari & Azizi, 2020; Jamshidi et al., 2023), researchers and practitioners gain a clearer framework for comparing and selecting suitable technologies. This approach

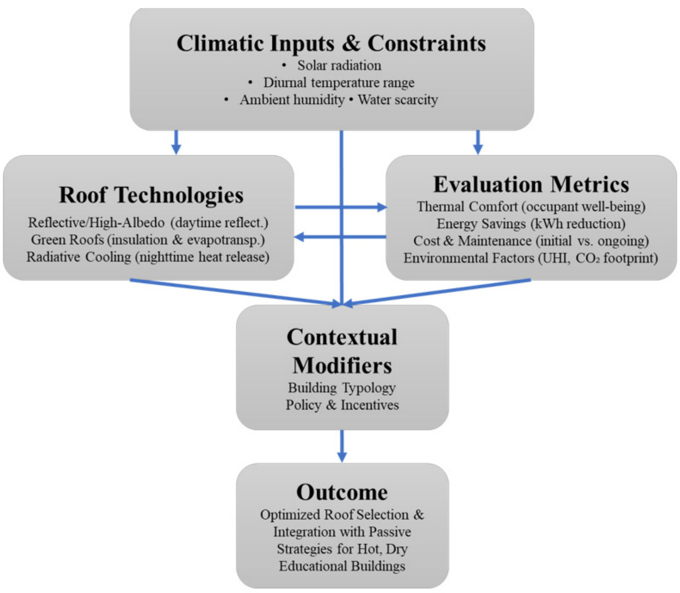

Table 13: Results of weighting the components of contemporary internal housing using the Shannon entropy method.

addresses the research gaps identified above, particularly the absence of comprehensive, long-term, and context-sensitive evaluations for hot, dry settings.

Types of Cool Roofs

Cool roof applications in hot, dry regions can be categorized into four primary groups, each reflecting distinct materials, construction methods, and operational requirements. These include: Reflective Coatings, Green Roofs, High-Albedo Materials, and Radiative Cooling Roofs. Table 1 summarizes their relative costs, energy reduction potential, and key benefits or limitations. Despite varying degrees of effectiveness, research consistently underscores the importance of matching each technology to local climatic conditions and building-specific requirements.

- Reflective Coatings: Particularly effective at reflecting solar radiation (Elnabawi et al., 2022), these coatings are applied to diverse roof surfaces and have demonstrated reductions in both surface and indoor temperatures.
- Green Roofs: Offer insulation and environmental co-benefits, but face challenges in meeting irrigation and structural requirements (Bevilacqua, 2021; Virk et al., 2014).
- High-Albedo Materials: Include specialized membranes or tiles that maintain cooler surfaces, offering moderate installation costs with substantial energy savings (Feng et al., 2022).
- Radiative Cooling Roofs: Harness high emissivity for heat dissipation, especially potent at night, but often require careful material selection and higher capital investment (Chen & Lu, 2021).

In summary, the existing literature suggests that these roof types are effective in reducing energy consumption and enhancing occupant comfort across various climatic scenarios. However, educational buildings in hot, dry climates present unique constraints—ranging from limited water resources to specific building layouts—that call for an integrated evaluative framework. By situating cool roof technologies within a conceptual model that addresses local climate challenges, maintenance considerations, and occupant health, it becomes possible to identify a truly optimized approach for sustainable, comfortable, and cost-effective educational environments.

Comparative Analysis of Cool Roof Types

Reflective coatings are particularly effective in hot and dry climates due to their ability to reflect a significant portion of solar radiation, thereby reducing heat absorption. In regions with intense sunlight, reflective coatings can significantly lower roof temperatures, reducing the cooling load on buildings. The construction cost is relatively low, ranging from $0.75 to $1.50 per square foot. Studies have shown that reflective coatings can achieve energy reductions of 10-19%, which is substantial considering the low investment (Konopacki et al., 1998).

Green roofs, while beneficial in many climates, present challenges in hot and dry environments due to the need for substantial irrigation to maintain vegetation. However, they provide significant insulation and reduce heat transfer through evapotranspiration. The initial cost of green roofs is higher, ranging from $10 to $50 per square foot. Despite the high cost, green roofs can reduce energy use for cooling by 20-30% (Virk et al., 2014). The environmental benefits, such as improved air quality and enhanced stormwater management, add to their value; however, their water requirements can be a limiting factor in arid regions.

High-albedo materials, which reflect a large portion of solar radiation, are highly suitable for hot and dry climates. These materials maintain cooler roof surfaces, thereby reducing the cooling load on buildings. The cost of high-albedo materials is moderate, ranging from $1 to $3 per square foot. Energy savings from high-albedo roofs can reach 20-25% (Feng et al., 2022), making them a practical and cost-effective solution for reducing heat absorption in arid climates.

Radiative cooling roofs utilize materials with high thermal emissivity to radiate heat away from the building, particularly effective during the night when temperatures drop. This type of roof is well-suited to hot and dry climates, where clear skies at night enhance radiative cooling. The construction cost for radiative cooling roofs ranges between $2 to $5 per square foot. These roofs can achieve energy reductions of 15-30% (Chen and Lu, 2021). The dual effect of daytime solar reflectivity and nighttime radiative cooling significantly reduces cooling loads in hot-arid regions. A comparative summary of this roof type, along with other cool roof technologies, is presented in Table 1.

In summary, reflective coatings are the most cost-effective option for reducing cooling energy use, though they offer moderate energy savings. Green roofs, although more expensive, offer substantial energy savings and additional environmental benefits. High-albedo materials strike a balance between cost and energy savings, making them a practical choice for many buildings. Radiative cooling roofs,

Table 1: Comparison of Cool Roof Types in Terms of Climate Suitability, Energy Savings, and Cost (adapted from Chen & Lu, 2021)

Roof Type	Construction Cost (($/sq ft	Energy Reduction (%)	Advantages	Limitations
Reflective Coatings	$0.75 - $1.50	10-19%	Low cost, significant energy savings	
Green Roofs	$10 - $50	20-30%	Significant insulation, environmental benefits	High water requirement, high initial cost
High-Albedo Materials	$1 - $3	20-25%	Moderate cost, substantial energy savings	
Radiative Cooling Roofs	$2 - $5	15-30%	Effective in both day and night cooling	Higher initial cost

despite being slightly more costly, offer the highest potential for energy savings, particularly in hot and dry climates like Iran. Each type of cool roof has its unique advantages and can be chosen based on specific needs and budget constraints. In hot and dry climates, each type of cool roof offers unique advantages and challenges. Reflective coatings and high-albedo materials are highly effective due to their cost efficiency and significant energy savings. Radiative cooling roofs provide the added benefit of nighttime cooling, making them particularly effective in arid regions with clear skies. Green roofs, while offering substantial environmental benefits, require careful consideration of water resources and higher initial investment.

MATERIALS AND METHODS

In response to reviewers' requests for a rigorous and transparent evaluation process, we developed a structured framework with clearly defined indicators and weighted scoring to compare and rank different cool roof types in the specific context of Iranian educational buildings.

Selection of Data Sources

Climatic Focus: Studies targeting hot, dry, or semi-arid regions, characterized by average summer temperatures above 35–40°C, low precipitation, and significant diurnal temperature swings (Yang et al., 2020).

Educational Context: Preference for research or case studies involving schools and universities. Where unavailable, we included large non-residential buildings with comparable occupancy patterns (Hessari & Seyf Shojaee, 2021).

Peer-Reviewed Publications: Journal articles, technical reports, and conference proceedings offering quantitative data (cooling load reduction, indoor temperature drops, cost analyses).

Indicators and Weighting

Identified five core indicators for evaluating each cool roof option:

Energy Savings (ES)

- Quantified as a percentage or kWh reduction in cooling loads relative to a baseline.
- Weight: 0.3 (reflecting the critical role of energy efficiency).

Thermal Comfort (TC)

- Measured by indoor temperature reduction (°C) or occupant comfort surveys.
- Weight: 0.25 (important for educational outcomes).

Cost Factors (CF)

- Encompasses initial installation cost (USD/ft²) and estimated maintenance over the roof's lifespan.
- Weight: 0.2 (budget constraints often drive decision-making).

Durability & Maintenance (DM)

- Estimated usable lifespan (years), reapplication frequency, and typical repair needs.
- Weight: 0.15 (ensuring long-term viability).

Environmental Impact (EI)

- Includes potential greenhouse gas reduction, stormwater benefits (for green roofs), or special resource requirements (e.g., water use).
- Weight: 0.1 (sustainability goals, though somewhat secondary to immediate cooling/cost needs).

Scoring Process

For each roof type, we compiled data from the literature (case studies, simulations, field measurements) and normalized it. We assigned a raw score from 1 (poor performance) to 5 (excellent performance) for each indicator. To derive an overall performance index (Roof Suitability Score), each raw score was multiplied by its assigned weight and summed:

Roof Suitability Score=(ES×0.3)+(TC×0.25)+(CF×0.2)+(DM×0.15)+(EI×0.1).

Data Collection and Analysis

Step 1: Literature Search: Databases (ScienceDirect, Web of Science) using keywords "hot dry climate," "cool roofs," "reflective coatings," "green roofs," "radiative cooling," "high-albedo," and "educational buildings."

Step 2: Inclusion/Exclusion: Retained 64 articles meeting climate, building typology, and data availability criteria (Rawat & Singh, 2022; Elnabawi et al., 2022).

Step 3: Data Extraction: Collected numeric ranges for energy savings, temperature drops, cost, and lifespan. Converted to consistent units (kWh, USD/ft², °C).

Step 4: Scoring & Weighting: For each roof type, assign a score of 1–5 based on relative positioning (e.g., the highest energy-saving method is often scored 5).

Step 5: Suitability Ranking: Calculated weighted sums to produce a final ranking. Conducted sensitivity checks (±5% changes in weights) to ensure robust results.

Cool Roof Technologies and Implementation

Selecting and implementing cool roof solutions in hot, dry regions requires understanding the technical requirements, costs, maintenance demands, and potential challenges associated with each technology. This section details four primary categories—reflective coatings, green roofs, high-albedo materials, and radiative cooling roofs—highlighting best-practice approaches for educational buildings. Tables at the end of each subsection synthesize practical guidelines.

Reflective Coatings

Reflective coatings are liquid or semi-liquid materials (e.g., elastomeric, acrylic, silicone-based) applied directly onto existing roof substrates. By having high solar reflectance and thermal emittance, these coatings reduce rooftop surface temperatures, thereby lowering indoor heat gains. In hot, dry climates, their performance can be substantial if the coating remains clean and intact.

1. Basic Implementation Steps

Surface Preparation: The roof must be thoroughly cleaned and inspected for leaks or structural damage.

Application: Coatings can be applied by spraying, rolling, or brushing, typically in multiple layers to achieve optimal thickness and reflectivity (Konopacki et al., 1998).

Drying/Curing: Adequate time for curing is essential to ensure long-lasting adhesion, especially in regions with high daytime temperatures.

2. Key Considerations

Cost: Generally low to moderate (USD 0.75–1.50/ft²).

Maintenance: Periodic cleaning is necessary; reapplication may be required every 5–10 years (Xu et al., 2012).

Challenges: Dust storms or air pollution can accumulate on roof surfaces, degrading reflectivity.

3. Suitability for Educational Buildings

Pros: Quick to apply, minimal disruption to school operations, relatively affordable.

Cons: The roof may require more frequent maintenance if it is exposed to harsh conditions or high levels of dirt and debris.

A comprehensive summary of implementation steps, costs, maintenance needs, and suitability factors is presented in Table 2.

Green Roofs

Green roofs (or vegetative roofs) consist of a multi-layer system: waterproof membrane, root barrier, drainage layer, growing medium, and vegetation. While they provide excellent insulation and can significantly reduce rooftop heat gain, they require regular irrigation in arid areas, raising questions about water availability.

1. Basic Implementation Steps

Structural Assessment: Determine if the existing roof can support the added weight of soil and plants.

Layered Installation: Install the waterproof membrane, root barrier, and drainage layer before adding the soil substrate and vegetation.

Plant Selection: Utilize drought-tolerant species adapted to the local climate; consider incorporating succulent or native plants to minimize irrigation requirements (Yazdani & Baneshi, 2021).

2.Key Considerations

Cost: Higher (USD 10–50/ft²) due to materials, labor, and potential structural reinforcements (Virk et al., 2014).

Maintenance: Routine watering, fertilizing, and weeding, as well as periodic checks for leaks.

Table 2: Reflective Coatings: Summary of Implementation Procedures, Cost, Maintenance, and Applicability (adapted from Konopacki et al., 1998; Xu et al., 2012)

Aspect	Details
Materials	Elastomeric or acrylic coatings, specialized reflective paints
Installation Steps	1) Inspect & repair the roof surface 2) Clean thoroughly 3) Apply coatings (brush/roller/spray)
Typical Cost Range	USD 0.75–1.50/ft²
Maintenance	- Annual/bi-annual cleaning - Reapply coating every 5–10 years (depending on UV exposure)
Major Challenges	- Dirt accumulation reduces reflectivity - Potential cracking under extreme daytime heat
Case Example	Andalusia, Spain: Up to 19% cooling demand reduction (Boixo et al., 2012); Iranian Schools: Up to 5°C reduction in indoor temperature (Elnabawi et al., 2022).

Table 3: Green Roofs: Summary of Implementation Procedures, Cost, Maintenance, and Applicability (adapted from Yazdani & Baneshi, 2021; Virk et al., 2014)

Aspect	Details
Materials	Waterproof membrane, root barrier, drainage layer, soil/growing medium, drought-resistant vegetation
Installation Steps	1) Assess structural load capacity 2) Install waterproof & drainage layers 3) Add soil & plant vegetation
Typical Cost Range	USD 10–50/ft²
Maintenance	- Watering (manual or automated) - Fertilizing, weeding, and monthly or quarterly inspections
Major Challenges	- Water scarcity - Higher upfront cost - Potential need for structural reinforcement
Case Example	Qatar: Despite scarce water resources, green roofs have achieved notable energy savings and improved comfort (Andric et al., 2020).

Challenges: Limited water resources in hot, dry climates; risk of plant failure without proper irrigation.

3. Suitability for Educational Buildings

Pros: Outstanding thermal comfort, potential for educational gardens, and ecological benefits.

Cons: High initial investment and ongoing irrigation needs can strain school budgets.

Green roofs offer compelling advantages, including improved thermal comfort, ecological value, and opportunities for learning through educational gardens. However, high upfront costs and continuous irrigation demands may pose significant financial and logistical challenges for school administrators. An overview of these aspects is detailed in Table 3.

High-Albedo Materials

High-albedo materials include light-colored membranes, tiles, or aggregates that exhibit elevated solar reflectance. They maintain relatively low surface temperatures compared to traditional dark roofs. While conceptually similar to reflective coatings, high-albedo materials often provide longer-lasting reflectivity if properly maintained.

1.Basic Implementation Steps

Surface Preparation: Remove any existing roofing layers as necessary; ensure a stable base is in place.

Installation: Place high-reflectance membranes or tiles uniformly, sealing edges and seams to prevent leaks (Feng et al., 2022).

Quality Assurance: Manufacturers typically provide reflectivity ratings; selecting higher SRI (Solar Reflectance Index) materials optimizes cooling.

2.Key Considerations

Cost: Moderate (USD 1–3/ft²).

Maintenance: Occasional cleaning to clear dust and debris; check seams for damage (Xiao et al., 2023).

Challenges: Albedo can decline over time due to wear; ensuring correct installation is critical to avoid water infiltration.

3.Suitability for Educational Buildings

oPros: Balanced cost-to-benefit ratio, simpler retrofit than green roofs, robust under high UV exposure.

oCons: Reflectance may degrade without periodic cleaning; not as transformative as green or radiative solutions in terms of peak heat reduction.

High-albedo roofing materials provide a practical balance between performance and affordability. Their relatively straightforward application makes them well-suited for retrofitting projects. Additionally, their resistance to ultraviolet radiation enhances long-term viability in hot and arid climates. However, the thermal performance may not match that of more advanced solutions such as radiative or vegetative roofs in extreme heat conditions. A comparative summary of their application characteristics is presented in Table 4.

Radiative Cooling Roofs

Radiative cooling roofs exploit thermal emissivity to radiate heat away, particularly effective in clear-sky, low-humidity environments typical of many parts of Iran. Roofs are coated or laminated with materials that strongly emit infrared radiation, allowing buildings to shed heat more efficiently during both day and night.

1. Basic Implementation Steps

Roof Preparation: Check for leaks, ensure a smooth substrate.

Coating/Film Application: Specialized films or coatings must be installed carefully, often requiring professional expertise (Chen & Lu, 2021).

Emissivity Verification: Manufacturers or installers typically test infrared emissivity to confirm performance.

2.Key Considerations

Cost: Moderate to high (USD 2–5/ft²).

Maintenance: Periodic cleaning; reapply or repair damaged film sections to maintain emissive properties.

Challenges: Advanced materials can be costly and may require specialized labor.

Table 4: High-Albedo Materials: Implementation Summary Including Cost, Maintenance, Challenges, and Suitability for Educational Buildings (adapted from Feng et al., 2022; Xiao et al., 2023)

Aspect	Details
Materials	Single-ply membranes, light-colored tiles, high-reflectance aggregates
Installation Steps	1) Ensure a stable roof substrate 2) Install membranes or tiles 3) Seal edges & seams thoroughly
Typical Cost Range	USD 1–3/ft²
Maintenance	- Regular cleaning (dust, debris) - Check seams and edges for integrity
Major Challenges	- Declining reflectivity if not cleaned - Potentially less dramatic cooling vs. radiative roofs
Case Example	Nanjing, China: 25% reduction in cooling use due to high-albedo roofs (Xiao et al., 2023).

Table 5: Radiative Cooling Roofs: Implementation Summary Including Cost, Maintenance, Challenges, and Suitability for Educational Buildings (adapted from Chen & Lu, 2021; Feng et al., 2022)

Aspect	Details
Materials	High-emissivity films, specialized nanomaterials, or polymers (coatings)
Installation Steps	1) Prepare/clean the roof membrane 2) Install radiative film/coating 3) Verify emissivity levels
Typical Cost Range	USD 2–5/ft²
Maintenance	- Annual or bi-annual inspection - Surface cleaning to maintain emissivity - Repair or recoat as needed
Major Challenges	- Higher capital cost - Technical expertise for the correct application - Film durability in harsh sun
Case Example	California, USA: A commercial warehouse achieved a ~40% reduction in cooling loads (Wang et al., 2022b).

3.Suitability for Educational Buildings

Pros: Highest potential energy savings and ability to lower indoor temperatures significantly (Feng et al., 2022).

Cons: Higher initial cost; not yet widely adopted, so local installation expertise may be limited in some regions.

Radiative cooling roofs offer substantial thermal comfort benefits and the highest energy-saving potential among passive roofing strategies (Feng et al., 2022). However, the relatively higher initial cost and limited local experience with advanced materials may pose challenges in widespread implementation. A comparative summary of their application parameters is provided in Table 5.

Key Takeaways for Implementation

• Educational Facilities often require short installation windows (e.g., during school breaks) to minimize disruptions to classes. Reflective coatings and high-albedo materials are relatively quicker to install.

• Maintenance Plans must be aligned with the school's operational schedule and budgets. Radiative roofs and green roofs may demand more specialized care.

• Water Scarcity remains a critical factor for green roofs; drought-resistant vegetation or greywater irrigation systems can mitigate these challenges.

By reviewing these four subsections and tables, facility managers and policymakers in hot, dry regions can better gauge the practical trade-offs in cost, performance, and feasibility for each cool roof technology, ensuring a tailored approach that meets local climatic demands and educational infrastructure needs.

RESULTS AND DISCUSSION

In this section, all results are organized into tables to provide a clear, data-driven picture of the performance of each cool roof technology in hot, dry educational contexts.

Findings

This section reports the numerical outcomes of the weighted-scoring approach (described in Section 3) applied to the four cool roof technologies. The findings highlight the strengths and weaknesses of each technology in terms of energy savings (ES), thermal comfort (TC), cost factors (CF), durability and maintenance (DM), and environmental impact (EI), all within educational buildings located in hot, dry climates.

Overall Weighted Scores

Based on the methodology, each cool roof type received a raw score ranging from 1 (lowest performance) to 5 (highest performance) across the five indicators. These raw scores were then multiplied by their respective weights to produce a composite index (Roof Suitability Score), ranging from 1.0 to 5.0. Table 6 presents the final weighted results.

As shown, Green Roofs exhibit the highest composite score (3.95) due to excellent thermal comfort and environmental impact ratings, but they fall short in cost factors. Radiative Cooling Roofs and High-Albedo Materials both achieve composite scores of 3.80, though they differ in specific indicators (with radiative roofs stronger in ES and TC, and high-albedo materials offering a more moderate cost profile). Reflective Coatings yield a composite score of 3.20, reflecting a cost-effective and simpler solution but with comparatively lower maximum potential for cooling performance.

Detailed Score by Indicator

To better understand the underlying reasons for each technology's overall ranking, Table 7 breaks down average raw scores (1–5) for each cool roof type by the five indicators, along with brief explanatory notes referencing the data sources.

From this breakdown:

• Radiative Cooling Roofs dominate in energy savings and thermal comfort, aligning well with clear-sky conditions.

• Green Roofs excel in thermal comfort and environmental impact, but are penalized for higher installation and irrigation costs.

• High-Albedo Materials balance moderate-to-high ratings across all indicators, especially in durability.

• Reflective Coatings remain attractive for low-cost retrofits despite

Table 6 Weighted Score Results for Each Cool Roof Technology

Roof Type	ES(w=0.3)Raw (Weighted)	TC(w=0.25)Raw (Weighted)	CF(w=0.2)Raw (Weighted)	DM(w=0.15)Raw (Weighted)	EI(w=0.1)Raw (Weighted)	Composite Score
Reflective Coatings	3 (0.90)	3 (0.75)	4 (0.80)	3 (0.45)	3 (0.30)	3.20
Green Roofs	4 (1.20)	5 (1.25)	2 (0.40)	4 (0.60)	5 (0.50)	3.95
High-Albedo Materials	4 (1.20)	4 (1.00)	3 (0.60)	4 (0.60)	4 (0.40)	3.80
Radiative Cooling Roofs	5 (1.50)	5 (1.25)	3 (0.60)	3 (0.45)	4 (0.40)	3.80

ES = Energy Savings
TC = Thermal Comfort
CF = Cost Factors
DM = Durability & Maintenance
EI = Environmental Impact
Composite Score = sum of weighted scores per indicator

Table 7: Indicator Breakdown and Rationale

Indicator	Reflective Coatings	Green Roofs	High-Albedo Materials	Radiative Cooling Roofs	Data Sources / Rationale
Energy Savings (ES)	3: Moderate cooling	4: High, but it depends on vegetation and evapotranspiration	4: Comparable to reflective coatings but longer-lasting reflectivity	5: Highest potential (day/night cooling)	(Wang et al., 2022a; Feng et al., 2022; Yazdani & Baneshi, 2021)
Thermal Comfort (TC)	3: Some improvement of indoor temps	5: Excellent insulation & evapotranspiration benefits	4: Strong heat reflection, stable indoor temps	5: Maintains lower roof temps, esp. at night	(Cheikh & Bouchair, 2004; He et al., 2020; Chen & Lu, 2021)
Cost Factors (CF)	4: Generally low installation cost	2: High installation + possible structural reinforcement	3: Moderate cost, depends on membrane/tiles	3: Moderate-to-high material costs	(Boixo et al., 2012; Virk et al., 2014; Rawat & Singh, 2022)
Durability & Maintenance (DM)	3: Reapplication every 5–10 yrs	4: 30+ yrs if properly maintained, but needs watering, weeding	4: 15–20 yrs lifespan with minimal maintenance	3: 10–20 yrs, coating integrity is key	(Elnabawi et al., 2022; Chen & Lu, 2021; Feng et al., 2022)
Environmental Impact (EI)	3: Moderate (reduced urban heat, lower GHG)	5: Stormwater mgmt, biodiversity, major UHI mitigation	4: High reflectance cuts UHI, moderate resource use	4: Significant energy/GHG savings but higher material inputs	(Bevilacqua, 2021; Saber, 2022; Andric et al., 2020)

relatively moderate energy gains.

Additional Observations and Cross-Comparisons

Beyond raw scores, certain qualitative insights emerged:

1. Budget Constraints

- For many educational institutions with limited funds, reflective coatings or high-albedo membranes can achieve moderate cooling improvements without hefty upfront investments in structural changes or specialized materials (Boixo et al., 2012).

2. Water Scarcity

- Green Roofs are challenging in arid environments unless schools implement drought-resistant vegetation or alternative irrigation sources (Yazdani & Baneshi, 2021).

3. Dust/Pollution

- Regions experiencing dust storms or high particulate matter must account for regular cleaning to maintain reflectivity and emissivity, particularly for reflective and radiative solutions (Saber, 2022).

4. Adaptation Over Time

- Field data indicate that albedo and emissivity can degrade if not maintained, making a planned maintenance schedule critical for long-term performance (Chen & Lu, 2021).

As shown in Table 8, each technology brings unique constraints and opportunities that must be carefully aligned with a school's financial resources, maintenance capacity, and environmental objectives.

Summary of Key Findings

1. Radiative Cooling Roofs and Green Roofs yield the highest

Table 8: Key Qualitative Observations

Factor	Green Roofs	Radiative Cooling Roofs	Reflective Coatings	High-Albedo Materials
Installation Disruption	Moderate (layers/soil)	Moderate (technical materials)	Low (applied on the existing roof)	Moderate (membrane/tiles replacement)
Synergy with Other Measures	Can be combined with solar panels or rooftop gardens	Enhanced by night ventilation, shading strategies	Compatible with solar PV, but reflectivity must be maintained	Often integrated with ventilation or shading upgrades
Scalability	Generally feasible but cost-intensive	Scalable for large facilities if budget allows	Highly scalable for quick retrofits	Scalable, though tile/membrane availability may vary regionally
Local Expertise	Varies; specialized training needed	Relatively new, might require the import of advanced materials	Common, local contractors are widely available	Membrane/tiles are commonly available, but SRI ratings vary

combined potential for energy savings and thermal comfort, but involve higher upfront or operational costs.

2. Reflective Coatings score well on cost and ease of application, making them an efficient solution for existing school roofs with limited renovation budgets.

3. High-albedo materials strike a middle path, offering solid performance in energy efficiency, durability, and moderate cost, making them potentially suitable for large-scale installations in new educational projects.

4. Local Context—especially water availability, dust levels, and budget—invariably shapes the final choice, underscoring the importance of site-specific evaluations.

The subsequent Discussion section will interpret these results within the broader context of policy, design practices, and resource considerations for hot, dry climates, with a particular focus on educational infrastructure needs.

Discussion

Most Effective Roof Options for Hot, Dry Educational Buildings

The results suggest that radiative cooling roofs and green roofs offer top-tier thermal comfort and energy efficiency in principle. However, real-world constraints—such as capital budgets and water resources—must be considered in educational contexts. Green roofs might be favored where environmental benefits (stormwater retention, vegetation) are priorities and additional water sources are available. In contrast, radiative cooling roofs are ideal for institutions seeking maximal energy savings under clear skies, but can manage the higher upfront expense.

High-albedo materials and reflective coatings emerge as pragmatic solutions, particularly for retrofitting existing school buildings with limited renovation budgets. They can still yield moderate-to-high cooling energy reductions without extensive structural modifications (Feng et al., 2022).

Policy and Implementation Implications

1. Financial Incentives: Tax rebates or subsidies could offset the higher initial costs of radiative and green roofs, accelerating their adoption (Freidooni et al., 2022).

2. Local Building Codes: Mandating a minimum solar reflectance index (SRI) for new construction can standardize the benefits of reflective and high-albedo surfaces, thereby enhancing the benefits of these surfaces.

3. Water Management: For green roofs to be viable, educational facilities must plan for efficient irrigation or drought-resistant plant species, possibly integrating greywater systems.

Limitations

• Data Consistency: The scoring framework depends on data aggregated from various studies. Some variability in local climate or building design may produce different outcomes.

• Long-Term Durability: Empirical evidence on the long-term performance of advanced radiative coatings in dusty or polluted environments remains limited (Chen & Lu, 2021).

• Focus on Schools: While the emphasis on educational buildings is valuable, some findings may be generalized to other types of large, public facilities.

CONCLUSION

This research has provided a comprehensive, indicator-based comparison of four leading cool roof technologies—reflective coatings, green roofs, high-albedo materials, and radiative cooling roofs—within the specific context of hot and dry climates and educational buildings in Iran. Using a weighted-scoring methodology, each technology was evaluated across five performance indicators: energy savings, thermal comfort, cost factors, durability and maintenance, and environmental impact. The findings indicate that radiative cooling roofs yield the highest scores in terms of energy efficiency and thermal comfort, though they require advanced materials and entail higher initial investments. Green roofs demonstrate strong performance in insulation and environmental co-benefits, but they are limited by high installation costs and irrigation demands, which can pose challenges in arid regions. On the other hand, reflective coatings and high-albedo materials offer cost-effective and technically feasible solutions, making them especially suitable for retrofitting existing school buildings or addressing budget constraints. These options offer moderate to high performance in improving indoor conditions while requiring minimal structural modifications and minimal long-term maintenance. Overall, the results emphasize that the selection of a cool roof strategy must be context-driven, taking into account local climate conditions, budget availability, structural capacity, and environmental goals. The study provides clear guidance for architects, educational planners, and decision-makers on selecting and implementing the most suitable cool roof technology for sustainable educational infrastructure.

In light of the findings, it is strongly recommended that the Ministry of Education, the Organization for Development, Renovation, and Equipping of Schools (DRES), and urban development agencies such as municipalities adopt a context-sensitive approach to integrating cool roof technologies in school buildings located in hot and dry regions of Iran—such as Yazd, Kerman, Sistan and Baluchestan, South Khorasan, and Isfahan. For cost-sensitive retrofits, reflective coatings and high-albedo materials should be prioritized due to their affordability, ease of application, and ability to improve thermal conditions quickly. In newly constructed schools, where budget and structural conditions allow, radiative cooling roofs and green roofs using drought-tolerant plants should be considered for their superior long-term energy performance and ecological benefits. Implementing these measures will not only reduce operational energy demand but also enhance student comfort, learning outcomes, and environmental responsibility in Iran's educational system.

AUTHOR CONTRIBUTIONS

In the literature review section, the experimental design, data analysis, and interpretation, as well as manuscript preparation and editing, were performed and written with the participation of all authors.

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CONFLICT OF INTERESt

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the authors have acknowledged the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy.

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