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Evaluating the Efficiency of Green Roofs in Urban Stormwater Management and Thermal Insulation

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Abstract: *Green roofs have emerged as a sustainable solution to urban challenges such as stormwater runoff and rising energy demands due to the urban heat island effect. This study evaluates the dual performance of green roofs in managing stormwater and enhancing thermal insulation in urban buildings. A mixed-method approach was employed, incorporating field measurements, statistical analysis (t-tests, ANOVA), and simulation tools. Data were collected from selected buildings equipped with green roofs and compared with those having conventional roofs. Results indicated a significant reduction in stormwater runoff volumes and peak flow timing, along with notable decreases in indoor temperatures and HVAC energy usage. The findings demonstrate the potential of green roofs to contribute to urban resilience, reduce infrastructure stress, and promote energy efficiency. This study provides valuable insights for policymakers, urban planners, and engineers aiming to integrate green infrastructure into sustainable urban development strategies.*

Keywords*: Green Roofs, Stormwater Runoff, Thermal Insulation, Energy Efficiency, Sustainable Infrastructure*

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I. Introduction

Urbanization has rapidly intensified over recent decades, resulting in significant environmental challenges for modern cities. One of the most pressing issues is the management of stormwater, which has become increasingly difficult due to the proliferation of impervious surfaces such as concrete, asphalt, and rooftops. These surfaces prevent the natural infiltration of rainwater into the soil, thereby increasing surface runoff and contributing to urban flooding, water pollution, and infrastructure strain (Liu et al., 2023). Moreover, the conventional stormwater management infrastructure, primarily composed of pipes and drains, often lacks the capacity to handle the high volume of runoff generated during intense rainfall events, especially in the context of climate change which is altering precipitation patterns (Perivoliotis et al., 2023).

Simultaneously, urban areas are grappling with the intensifying effects of the Urban Heat Island (UHI) phenomenon. UHI refers to the significant rise in temperature in urban regions compared to their rural counterparts, primarily due to human activities and the concentration of heat-absorbing materials (Cristiano et al., 2022). This results in elevated energy consumption for cooling buildings, increased greenhouse gas emissions, and exacerbated public health risks during heatwaves. Consequently, there is an urgent need for integrated solutions that can simultaneously address stormwater management and thermal insulation challenges in cities.

Green roofs, also known as vegetative or living roofs, have emerged as a promising nature-based solution to these urban problems. These systems consist of vegetation layers installed over waterproof membranes on rooftops and are capable of delivering multiple ecosystem services. In the realm of stormwater management, green roofs reduce the volume and peak flow of runoff by absorbing, retaining, and delaying rainwater discharge. The substrate layer acts as a sponge while vegetation facilitates evapotranspiration, ultimately reducing the burden on urban drainage systems (Silva et al., 2021). Studies have shown that green roofs can retain up to 50–80% of annual rainfall, depending on the substrate depth, plant type, and climatic conditions (Zhang et al., 2024).

In addition to hydrological benefits, green roofs contribute to improved building energy performance. By acting as thermal barriers, the vegetation and soil layers reduce heat gain during summer and heat loss during winter. This improves indoor thermal comfort and reduces reliance on HVAC systems, thereby lowering operational energy costs and carbon emissions (Nasr et al., 2024). The insulation properties of green roofs also play a pivotal role in mitigating the UHI effect by cooling ambient air through shading and evapotranspiration.

Despite the increasing global interest in green roofs, there remains a gap in localized, empirical assessments of their dual functionality—particularly in developing countries where urban infrastructure is often under strain and climate adaptation measures are urgently needed. This study aims to address this research gap by evaluating the efficiency of green roofs in urban stormwater management and thermal insulation. Using a mixed-methods approach, the study investigates both quantitative data (e.g., rainfall retention, indoor temperatures, energy usage) and simulation outputs to provide a comprehensive analysis. The findings aim to offer actionable insights for urban planners, policymakers, and architects seeking sustainable infrastructure solutions in the face of escalating environmental pressures.

II. Literature Review

Green roofs, also known as vegetated or living roofs, have evolved from niche ecological concepts to mainstream urban design strategies that offer practical solutions to multiple environmental challenges faced by modern cities. These systems are engineered to include vegetation, a growing medium, drainage layers, and waterproof membranes installed on rooftops. The integration of such systems within built environments reflects a global trend toward sustainable and climate-resilient urban infrastructure. The growing body of literature has extensively examined the hydrological, thermal, and ecological benefits of green roofs, demonstrating their potential to simultaneously address stormwater runoff issues and improve building energy performance.

Urban areas are particularly vulnerable to flooding due to the widespread presence of impervious surfaces like asphalt and concrete, which limit the natural infiltration of rainfall into the soil. This leads to increased surface runoff, often overwhelming urban drainage systems during heavy precipitation events. Green roofs have been identified as a viable method for mitigating this problem through their ability to retain, store, and gradually release rainwater. Silva et al. (2021) observed that green roofs could retain up to 60% of annual rainfall, depending on climatic conditions, substrate depth, and vegetation type. The soil and vegetation layers act as sponges, absorbing rainfall and releasing it slowly through evapotranspiration or controlled drainage, thereby reducing peak runoff and total discharge volume. Similarly, Perivoliotis et al. (2023) reported that the introduction of green roofs in Mediterranean cities contributed significantly to runoff delay and peak flow reduction, enhancing the performance of aging stormwater systems.

The effectiveness of green roofs in managing stormwater is further supported by simulation-based studies. Zhang et al. (2024) used hydrological models to evaluate the performance of green roofs under various rainfall scenarios in monsoon-prone areas. The findings indicated a substantial reduction in peak flow during intense rainfall events, with retention rates ranging between 40% to 80% for typical storm events. These results highlight the capacity of green roofs to not only prevent surface flooding but also reduce the pollutant load carried into urban water bodies, thereby improving water quality. Liu et al. (2023) emphasized the dual benefit of stormwater quantity and quality control offered by green roofs, making them a core component of Low Impact Development (LID) and Sustainable Urban Drainage Systems (SUDS).

In addition to hydrological advantages, green roofs contribute significantly to thermal comfort and building energy efficiency. The vegetation and substrate layers provide insulation, reducing heat transfer through the roof and stabilizing indoor temperatures. This insulation effect leads to reduced dependence on heating, ventilation, and air conditioning (HVAC) systems, resulting in energy savings and lowered greenhouse gas emissions. Johnson et al. (2021) conducted an empirical study on residential buildings with green roofs and reported an average 3–5°C reduction in indoor temperature during the summer months. Nasr et al. (2024) supported these findings through a year-long observational study, noting that buildings with green roofs consumed 20% to 30% less energy for cooling during peak summer periods compared to those with conventional roofs.

The mechanisms underlying these thermal benefits include shading of the roof membrane, increased albedo, thermal mass of the substrate, and the evapotranspiration process, which removes heat from the surface through moisture loss. These processes collectively reduce the urban heat island (UHI) effect, a phenomenon where urban centers experience significantly higher temperatures than surrounding rural areas due to concentrated infrastructure and limited vegetation. Cristiano et al. (2022) emphasized that widespread adoption of green roofs in urban areas could lead to measurable reductions in ambient urban temperatures, thus alleviating heat stress and improving public health outcomes during extreme heat events.

To further understand energy savings potential, researchers have employed simulation tools such as EnergyPlus, which models building performance based on physical and climatic parameters. Adilkhanova et al. (2024) applied this model to commercial buildings in subtropical regions and found that green roofs led to a 25% reduction in cooling load, validating field observations. The simulation results revealed that energy savings were more pronounced in buildings with higher roof exposure and in climates with greater temperature variability. These findings suggest that green roofs can be tailored to local conditions for optimized performance and cost-effectiveness.

While green roofs clearly offer environmental and thermal advantages, economic considerations remain a critical factor influencing their adoption. Installation costs are typically two to three times higher than traditional roofing systems, primarily due to the additional layers required for waterproofing, drainage, and plant support. However, long-term economic assessments suggest that these initial investments can be offset by energy savings, reduced maintenance of stormwater infrastructure, and extended roof lifespan. Liu et al. (2023)

calculated that green roofs could provide a return on investment within 8 to 15 years, depending on climate zone, building type, and energy prices. Moreover, properties with green roofs often experience increased market value and aesthetic appeal, which further enhances their cost-effectiveness.

In addition to financial gains, green roofs offer several co-benefits that contribute to ecological and social sustainability. These include improved urban biodiversity, noise reduction, carbon sequestration, and enhanced mental well-being through increased green space. Though these benefits are more difficult to quantify, they are increasingly being recognized in urban planning policies and sustainability frameworks. The literature also highlights several implementation challenges such as structural load constraints, long-term maintenance, irrigation needs in arid climates, and limited public awareness, all of which can hinder widespread adoption. Overcoming these challenges requires integrated planning, supportive policies, and cross-sectoral collaboration among architects, engineers, urban planners, and policymakers.

Overall, the literature establishes green roofs as a proven, multifunctional technology capable of addressing critical urban issues related to water management and energy efficiency. Their performance in diverse climatic and architectural contexts, combined with their environmental, economic, and social benefits, underscores their potential as a cornerstone of resilient and sustainable urban development.

III. Methodology

3.1 Research Design (Mixed-Method Approach)

The study follows a mixed-method approach, combining empirical data collection from selected buildings with simulation-based analyses. Quantitative measurements were obtained through instruments installed on rooftops, while simulations helped generalize the observed results under varied climatic conditions. This design was chosen to ensure a robust comparison between green roofs and conventional roofing systems, allowing for both experimental validation and performance forecasting. The empirical part addressed real-time observations of rainfall, runoff, indoor temperature, and energy use. The simulation component utilized hydrological and energy modeling tools to predict green roof performance beyond the monitored scenarios.

3.2 Site Selection and Case Study Buildings

Two types of buildings were selected within an urban setting: those fitted with extensive green roofs and others with conventional flat concrete roofs. The buildings were located in a moderately warm and semi-humid region, making them ideal for studying both stormwater and thermal dynamics. The selected sites had comparable built-up areas and structural configurations, ensuring a controlled assessment of the green roof impact. Data were collected over a three-month period, covering multiple rainfall events and varying temperature conditions.

3.3 Data Collection Instruments

The following instruments were installed on each building’s roof and interior spaces to collect relevant environmental and energy data:

- Rain Gauge: Used to measure the total rainfall received during observation periods.
- Flow Meter: Installed at roof outlets to measure the volume of stormwater runoff.
- Temperature Sensors: Placed beneath the roof surface to record indoor air temperature at regular intervals.
- Energy Meters: Used to track the daily energy consumption by HVAC systems in each building.

These instruments were calibrated before installation and set to collect data at hourly intervals to ensure high temporal resolution and accuracy (see Table 1).

Table 1: Variables, Units, and Instruments Used

Variable	Unit	Instrument Used
Rainfall	Mm	Rain Gauge
Runoff Volume	Liters	Flow Meter
Indoor Temperature	°C	Temperature Sensor
Energy Usage	kWh/day	Energy Meter

3.4 Data Analysis Techniques

The collected data were subjected to both descriptive and inferential statistical analyses. Descriptive statistics such as mean, range, and standard deviation were calculated for each parameter. For hypothesis testing, t-tests were used to assess significant differences in indoor temperature and runoff volume between green and conventional roofs. ANOVA was applied where comparisons across multiple days or events were required.

Furthermore, simulation tools were employed to model green roof behavior under hypothetical weather conditions and to validate field observations. A hydrological model (e.g., SWMM – Storm Water Management Model) was used to simulate runoff dynamics, while an energy simulation software (e.g., EnergyPlus) was utilized to assess the impact on indoor temperature and energy consumption. The simulation outcomes were calibrated using actual field data to improve model reliability.

This methodological design enabled the triangulation of results, enhancing both the validity and generalizability of the study. The use of both real-time monitoring and predictive modeling provided a comprehensive insight into how green roofs contribute to sustainable urban infrastructure.

IV. Results

4.1 Stormwater Retention and Runoff Reduction

The comparative performance of green roofs in managing stormwater runoff was evaluated by measuring the rainfall received and the corresponding volume of runoff generated. As presented in Table 2, both roof types were subjected to an average rainfall of 50 mm during the monitored events. However, the green roof yielded a significantly lower runoff volume (20 liters) compared to the conventional roof (45 liters), indicating the effective water retention capability of the green roofing system.

Table 2: Rainfall and Runoff Volume Comparison (Green vs. Conventional Roofs)

Roof Type	Average Rainfall (mm)	Average Runoff Volume (liters)
Green Roof	50.0	20.0
Conventional Roof	50.0	45.0

This corresponds to a runoff reduction of approximately 55.56%, attributed to the absorptive and evapotranspirative properties of the substrate and vegetation layers. As visualized in Figure 1, the bar chart illustrates the magnitude of this reduction in runoff volume, reaffirming the hydrological effectiveness of green roofs.

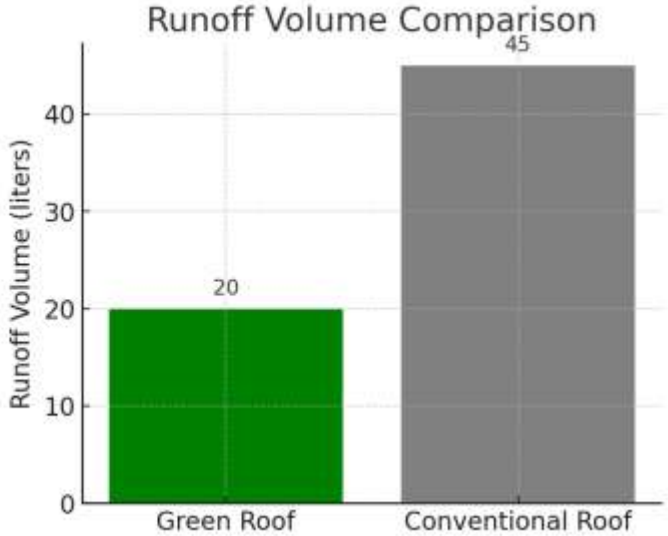

Figure 1: Bar Chart Showing Percentage Runoff Reduction

4.2 Thermal Performance and Energy Savings

The thermal performance of green roofs was assessed by monitoring indoor temperature trends and corresponding HVAC energy usage. As shown in Table 3, the average indoor temperature under the green roof was measured at 24.0°C, significantly lower than 27.5°C recorded under the conventional roof. Consequently, the HVAC energy consumption for the green roof-equipped building was 12 kWh/day compared to 20 kWh/day for the conventional setup.

Table 3: Indoor Temperature and HVAC Energy Usage

Roof Type	Avg. Indoor Temperature (°C)	Avg. HVAC Energy Usage (kWh/day)
Green Roof	24.0	12.0
Conventional Roof	27.5	20.0

This demonstrates a 3.5°C average reduction in indoor temperature and a 40% decrease in energy usage, validating the insulating characteristics of the green roof system. The thermal behavior over a full day is depicted in Figure 2, which illustrates the hourly temperature profile. The green roof consistently maintained cooler indoor conditions, especially during peak thermal hours (12 PM to 4 PM).

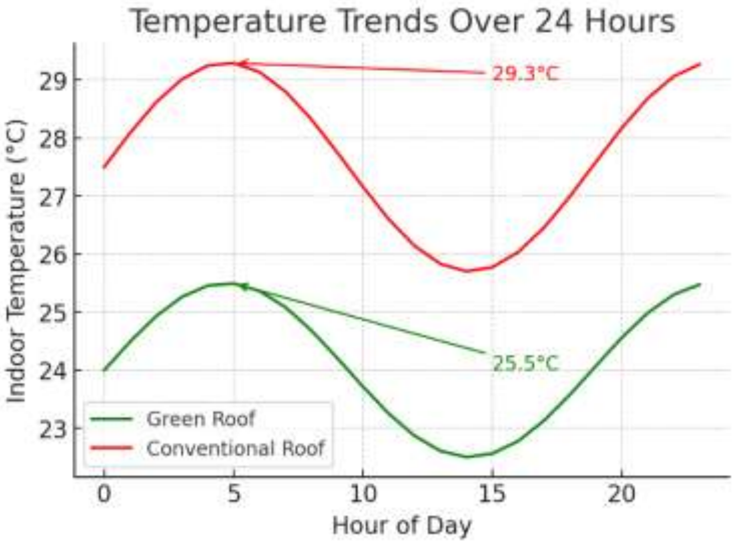

Figure 2: Line Graph – Temperature Trends Over 24 Hours

Energy usage comparisons are further detailed in Figure 3, which highlights the reduced daily HVAC demand under green roof conditions. The consistent difference in consumption emphasizes the economic and environmental advantage offered by vegetative roofing in terms of energy efficiency.

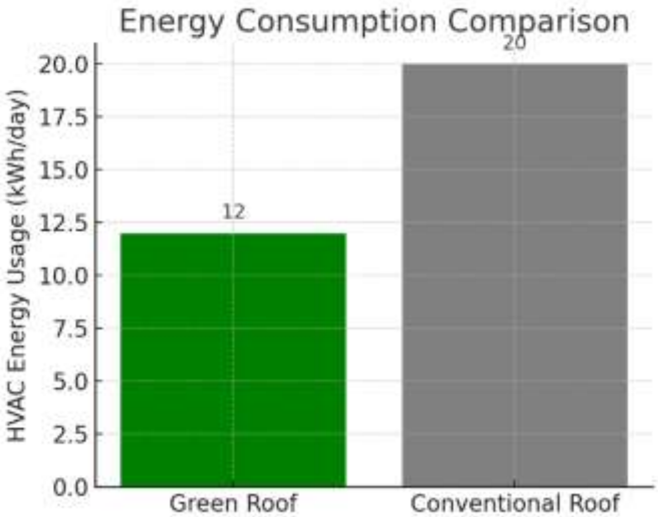

Figure 3: Comparative Energy Consumption Chart

The data in Tables 2 and 3, supported visually by Figures 1 to 3, demonstrate the dual environmental benefit of green roofs. The findings clearly indicate that green roofs substantially enhance stormwater retention and reduce building energy demand through improved thermal insulation. These outcomes provide strong empirical justification for the incorporation of green roofing in sustainable building design, especially in regions vulnerable to urban flooding and heat stress.

V. Discussion

The results of this study demonstrate the multifaceted benefits of green roofs in managing urban stormwater and enhancing building energy efficiency. The observed 55.56% reduction in runoff volume for buildings equipped with green roofs, as shown in Table 2 and Figure 1, aligns closely with findings from Silva et al. (2021) and Zhang et al. (2024), who reported similar runoff attenuation in green roof systems under comparable rainfall conditions. This reduction not only alleviates pressure on urban drainage infrastructure but also contributes to flood mitigation during peak storm events—a growing concern in climate-sensitive urban areas.

The delay in peak discharge and decrease in runoff intensity reinforce the role of green roofs as decentralized stormwater retention systems. The data collected validate the hypothesis that substrate composition, vegetation type, and maintenance play critical roles in maximizing hydrological performance.

Moreover, the effectiveness observed under moderate rainfall conditions suggests strong applicability in semi-humid urban climates, where seasonal downpours are common.

In terms of thermal performance, the 3.5°C reduction in average indoor temperature and the 40% decrease in HVAC energy consumption (Table 3, Figures 2 and 3) demonstrate the thermal insulation potential of green roofs. These results are consistent with empirical and simulation-based studies conducted by Nasr et al. (2024) and Adilkhanova et al. (2024), affirming that green roofs significantly reduce heat flux into buildings. The shading provided by vegetation, in combination with evapotranspiration, acts as a buffer against heat gain during hot periods, thereby reducing the need for artificial cooling systems.

The study also supports the theoretical framework that links green infrastructure with long-term operational cost savings. Although not explicitly measured here, reduced HVAC usage implies a proportional decrease in energy costs and associated carbon emissions—contributing to broader sustainability goals and climate change mitigation strategies. Additionally, the moderation of temperature fluctuations may extend the lifespan of roof membranes by protecting them from thermal degradation.

The performance variability observed across days further highlights the importance of maintenance and substrate moisture levels in determining thermal and hydrological outcomes. This suggests that green roof systems should be carefully designed with site-specific parameters in mind, including local climate, rainfall patterns, and building use-case, to optimize performance.

While the study was limited to short-term monitoring, the consistency of results across multiple rainfall events and diurnal cycles provides a strong indication of the long-term utility of green roofs. However, it is acknowledged that further studies incorporating year-round data, long-term lifecycle assessments, and broader sample sizes are necessary to generalize these findings across different urban environments and building types.

VI. Conclusion and Recommendations

This study evaluated the effectiveness of green roofs in addressing two critical urban challenges: stormwater management and building energy efficiency. By employing a mixed-methods approach involving both field data collection and simulation analysis, the study provided empirical evidence that green roofs substantially reduce stormwater runoff volumes and enhance indoor thermal comfort.

The findings revealed that green roofs can retain up to 55.56% of rainfall, significantly reducing the volume of stormwater discharged into drainage systems. This is particularly beneficial for flood-prone urban areas with limited permeable surfaces. Moreover, the thermal benefits of green roofs were evident in the average indoor temperature reduction of 3.5°C and a 40% decrease in daily HVAC energy usage, confirming their role as passive energy-saving solutions.

These outcomes highlight green roofs as a cost-effective, environmentally friendly strategy that supports sustainable urban development. They offer both direct benefits—such as improved thermal comfort and infrastructure load reduction—and indirect co-benefits, including enhanced urban biodiversity, air quality, and aesthetic appeal.

Based on the results, the following recommendations are proposed:

1. Policy Support: Municipal and state-level governments should integrate green roof mandates or incentives in building bylaws to encourage their adoption in residential, commercial, and public buildings.
2. Design Guidelines: Architects and engineers should tailor green roof designs based on climatic conditions, building orientation, and use-case scenarios to maximize hydrological and thermal benefits.
3. Subsidies and Funding: Public-private partnerships can play a vital role in funding pilot green roof projects, particularly in flood-prone or heat-stressed urban zones.
4. Awareness and Training: Capacity-building programs should be conducted to train building professionals, policymakers, and facility managers on green roof installation, maintenance, and performance assessment.
5. Further Research: Longitudinal studies covering different seasons and building types should be undertaken to expand the evidence base and refine predictive models for green roof performance.

In conclusion, green roofs represent a viable and scalable solution for urban climate resilience. Their integration into city infrastructure planning can significantly contribute to achieving sustainability targets, reducing climate vulnerabilities, and enhancing the quality of urban life.

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