JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(11), 398–409
https://doi.org/10.12911/22998993/207924
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Received: 2025.06.12
Accepted: 2025.08.01
Published: 2025.08.15

Green roofs as nature-based solutions: Design, implementation and evaluation in tropical rural environments

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ABSTRACT

Climate change and environmental degradation pose critical challenges in tropical rural regions, where housing infrastructure remains highly vulnerable to thermal stress and hydrometeorological extremes. This study presents the development and empirical assessment of a modular extensive green roof system designed specifically for humid tropical climates. Employing locally sourced materials such as coconut coir, pumice stone, and endemic plant species, the system fosters ecological integration and cost-effective scalability. Two prototype configurations, varying in substrate depth, were field-tested over nine months. Key performance indicators including rainfall retention (42.5%), infiltration delay (mean 192 s), indoor temperature reduction (2.43 °C), and relative humidity increase (13%) demonstrated significant environmental benefits. Estimated carbon sequestration reached 4.82 kg CO_2/m^2/year based on aboveground biomass accumulation. Statistical analyses using Student's t-test, one-way ANOVA, and Tukey HSD confirmed substrate depth as a critical determinant of thermal and hydrological performance ($p < 0.001$). These findings underscore the feasibility of low-cost, nature-based solutions for climate-resilient housing, supporting SDGs 6, 9, and 11 in vulnerable communities of the Global South.

Keywords: green roofs, substrate, water retention, relative humidity, infiltration, ANOVA, NbS, IWRM.

INTRODUCTION

The increasing scarcity of water resources has led to significant environmental impacts, primarily driven by climate change, accelerated urban expansion, and demographic growth. Among the most concerning consequences are the degradation of urban green spaces and the intensification of the urban heat island (UHI) effect (Qadourah, 2024; Jia et al., 2025; Priya and Senthil, 2024). These phenomena not only disrupt ecological balance but also pose serious threats to public health, water security, and urban livability. Moreover, they reflect broader global water challenges such as inadequate sanitation, hydrological disasters, pollution, and biodiversity loss (Grigg, 2025; Li et al., 2025).

In Latin America, integrated watershed management (IWM) began to gain prominence in the 1950s, initially focusing on infrastructure development for water export (Benegas-Negri, 2024). Over time, the focus shifted towards more inclusive criteria economic, environmental, productive and equitable leading to the promotion of integrated water resources management (IWRM). Despite being formally defined more than two decades ago and facing conceptual criticisms, IWRM remains a widely accepted framework (Da Silva et al., 2023). Its principles, such as basin scale planning and participatory governance, were already practised informally. However, implementation challenges remain, especially in developing countries where water governance is fragmented and institutional capacities are limited (Grigg, 2025).

IWRM represents a paradigm shift aimed at coordinating multiple water-related objectives within complex socio-ecological systems. Officially introduced at the UN Water Conference in Mar del Plata in 1977, it aimed to promote universal access to water and sanitation, while encouraging investment and political commitment in the sector (Basuki et al., 2022; Jat et al., 2025; Samantaray et al., 2021; Thapa et al., 2022). Today, countries such as Chile, Mexico and Brazil marked by high vulnerability and diverse governance models are struggling to meet Sustainable Development Goal 6 (Tinoco et al., 2022). Case studies from Peru (Pativilca River) and Ecuador (Napo River) reveal how climate change, population growth and land use pressures exacerbate water stress, underlining the need for improved planning, ecological restoration and adaptive territorial governance (Altemus Cullen, 2023; Fernandez et al., 2022).

Nature-based solutions (NbS) address growing water security concerns by integrating ecological principles into infrastructure planning. They offer adaptive responses to water quality decline, scarcity, and hydrometeorological risks, while enhancing climate resilience and socio-environmental sustainability (Apostolaki, 2025; Castaldo et al., 2025; Ndayambaje et al., 2024).

Among NbS, green roofs vegetated systems installed atop built structures have gained prominence as multifunctional ecological technologies (Clar and Steurer, 2023; Orozco and Madriaga, 2022). Their well documented benefits include improved thermal insulation, stormwater management, air quality enhancement, carbon sequestration, and biodiversity support (Elmazek and Safour, 2024; Santi et al., 2020; Vargas-Hernández et al., 2025). Through processes like evapotranspiration and photosynthesis, green roofs contribute to microclimate regulation and energy conservation, thereby supporting climate adaptation and mitigation strategies (Ebadati and Ehyaei, 2020; Gooroochurn and Giridharan, 2021; Herath et al., 2024).

Despite a growing body of literature, most empirical research and technological development on green roofs have concentrated on temperate and urban regions of the Global North. This geographical bias leaves a critical knowledge gap regarding the applicability, performance, and socio-technical viability of green roofs in tropical rural environments. These settings are characterized by high temperatures, intense rainfall, elevated humidity, and limited access to conventional construction resources, which pose unique design, implementation, and maintenance challenges (Chen et al., 2024; Wilkinson et al., 2024; Žilka et al., 2024).

Emerging empirical research across Latin America increasingly underscores the diverse ecological roles and socio-environmental value of green roofs in tropical settings, particularly in enhancing thermal comfort, supporting biodiversity, and mitigating hydrometeorological risks (Droz et al., 2021). In Peru, Flores and Van Meerbeek (2024) demonstrate the ecological and climatic relevance of integrating native Lomas plant communities many of which are endangered into rooftop systems, thereby aligning biodiversity conservation with urban microclimate regulation (Flores and Van Meerbeek, 2024). In Argentina, Fabián et al. (2021) emphasize of species selection in fostering arthropod functional diversity, highlighting the need for ecologically informed design to promote resilient rooftop ecosystems (Flores and Van Meerbeek, 2024). Simultaneously, Meng et al. (2023), through comparative case studies in Brazil and South Africa, explore the contribution of green roofs to the food-water-energy nexus, illustrating their integrative capacity to advance urban sustainability strategies (Meng et al., 2023).

However, most of these initiatives focus on urban or experimental settings, leaving rural applications underexplored. While these contributions represent meaningful progress, significant knowledge gaps remain regarding the adaptation of green roof technologies to tropical rural contexts. Such regions present distinct ecological conditions, socio-economic constraints, and vernacular architectural practices that necessitate context-sensitive, resilient, and culturally grounded solutions. This is particularly urgent in Amazonian and equatorial areas, where exceptional biodiversity and extreme climate variability demand robust, ecologically adaptive design approaches attuned to local realities.

To address this knowledge gap, this study proposes the design, implementation, and evaluation of a prototype green roof specifically tailored for tropical rural environments. By integrating the findings of prior studies with local constraints, this research explores practical adaptation strategies for underserved rural areas. Employing non-conventional, locally sourced materials including coconut fiber, pumice stone, and rice husk the system incorporates passive cooling principles and water retention strategies, reflecting both ecological principles and context-specific resource availability Figure 1.

This approach supports SDGs 6, 9, and 11 by providing a replicable framework for ecological design in underserved tropical rural areas. It enhances climate resilience, environmental

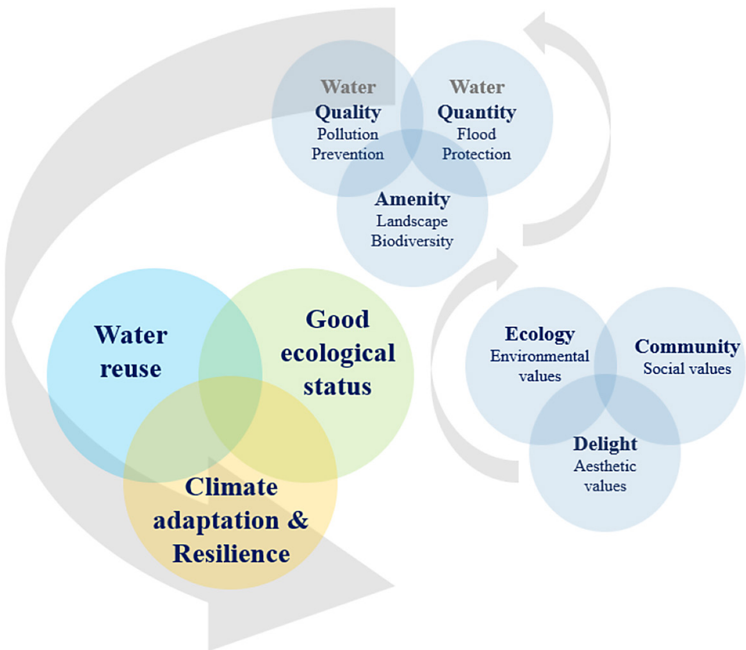

Figure 1. Transitioning from sustainable development to resilience building: Nature-based solutions in the water sector for climate adaptation and risk reduction (Apostolaki, 2025)

stewardship, and rural livelihoods, while promoting climate justice and strengthening community-based adaptation strategies, positioning itself as a scalable solution for sustainable development in vulnerable regions (Dang et al., 2023).

STUDY AREA

The Napo river basin, located in northeastern Ecuador, spans approximately between 78°W and 75°W longitude and 0° to 2°S latitude. Its dense hydrographic network feeds the Napo River, a major tributary of the Amazon (Figure 2). Covering a broad altitudinal gradient from the eastern Andes to the Amazonian lowlands, this geographical configuration fosters remarkable ecological and climatic diversity, positioning the basin as a strategic setting for evaluating nature-based solutions (NbS) in tropical rural contexts. Local communities experience high levels of water and energy vulnerability, justifying the implementation of sustainable infrastructure such as green roofs adapted to the Amazon region (Piland et al., 2025).

Despite its ecological significance, the Napo watershed is subject to mounting anthropogenic pressures, including agricultural expansion, mining activities, and large-scale hydroelectric development. These interventions have substantially altered hydrological regimes, with critical implications for water quality, biodiversity, and ecosystem functionality. In this context, low-impact solutions are urgently needed to enhance environmental resilience and improve local well-being. Green roofs represent a promising strategy to counter environmental degradation through decentralized water management and micro-scale ecological restoration (Escobar-Camacho et al., 2025).

Furthermore, large portions of the basin are remote and logistically challenging, limiting the reach of conventional infrastructure and reinforcing the need for context appropriate alternatives. Green roofs, when designed for local climatic and environmental conditions, can deliver multiple co-benefits including water self-sufficiency, improved thermal comfort in rural housing, and reduced surface runoff. Their application aligns with ecosystem based adaptation and conservation strategies, offering a replicable model for sustainable development in ecologically sensitive Amazonian landscapes (Alexiades et al., 2019).

METHODOLOGY

To rigorously evaluate the environmental performance of a low-cost green roof system adapted to tropical rural environments, a controlled field experiment was implemented over 60 days from January to September 2024. The

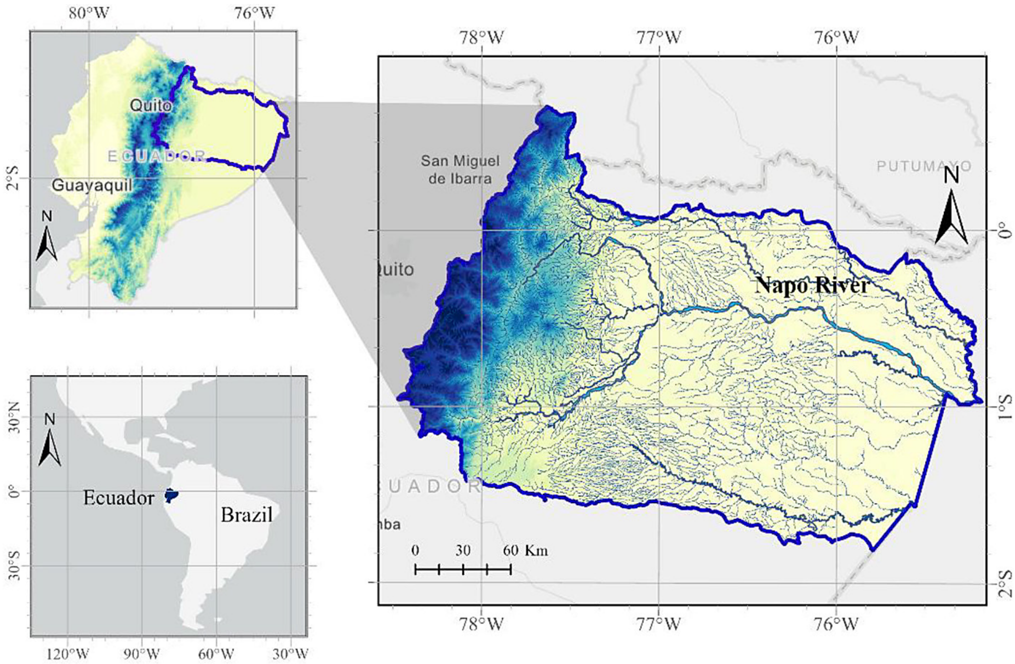

Figure 2. Napo river basin, Ecuador

intervention was designed to evaluate the thermohygrometric behavior, water retention capacity, and passive climatic functionality of an optimized green roof prototype assembled with locally sourced, sustainable materials, namely coconut coir, pumice stone, and a selection of endemic plant species. The selection criteria prioritized material affordability, ease of access in rural areas, and ecological compatibility with tropical climatic conditions.

The experimental infrastructure consisted of three identically sized test modules (5 × 5 meters) constructed using traditional adobe walls and elevated platforms Figure 3:
- Control module: Covered with conventional corrugated galvanized zinc sheets, representing typical rural roofing in the region.
- Experimental module design 1 and 2: Installed with the green roof prototype, comprising a stratified vegetated system.

The structures were oriented identically and positioned in an open field test site to ensure equal exposure to solar radiation, wind, and rainfall. Environmental sensors and high-resolution data loggers were deployed within each module to continuously monitor key microclimatic variables, including air temperature, relative humidity, and infiltration onset. Measurements were recorded at hourly intervals and compiled into daily averages for comparative analysis.

Material selection criteria

The materials were chosen using a multi-criteria decision analysis (MCDA) framework emphasizing Figure 4:
- Local availability and cost-effectiveness (minimizing logistical and economic barriers),
- Environmental sustainability (low embodied carbon and minimal processing requirements),
- Hydrological performance (maximized retention, delayed runoff),
- Thermal modulation potential (through shading and evapotranspiration),
- Structural feasibility for rural rooftop retrofitting.

Materials selection and assembly

The green roof system was conceptualized as a stratified vegetative assembly engineered to optimize hydrological performance, thermal regulation, and ecological resilience under the distinct climatic and socio-economic conditions of tropical rural environments. Drawing upon established principles of extensive green roof architecture, the design was innovatively adapted to incorporate non-conventional, locally sourced materials, ensuring affordability, environmental sustainability, and minimal maintenance requirements.

Two structurally similar prototypes were constructed, each utilizing an identical palette of

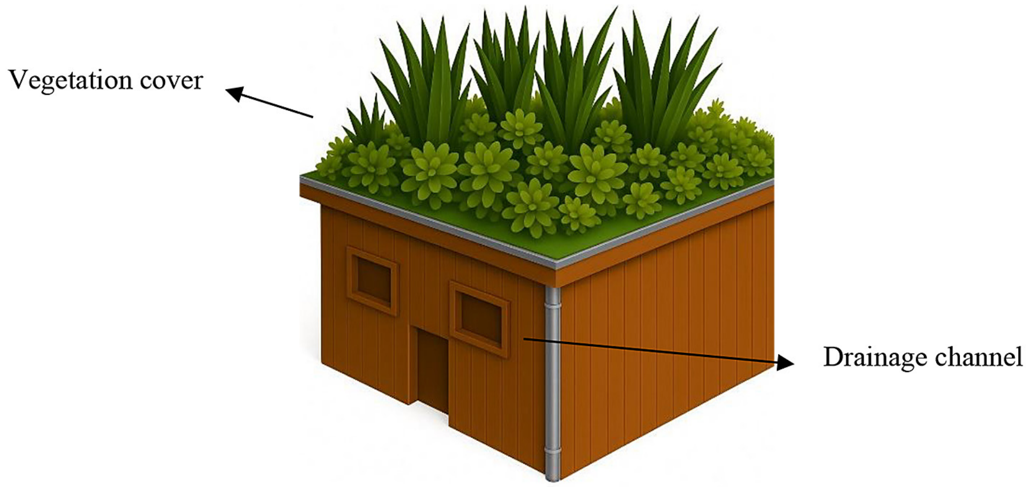

Figure 3. Implementation of green roofs in tropical environments

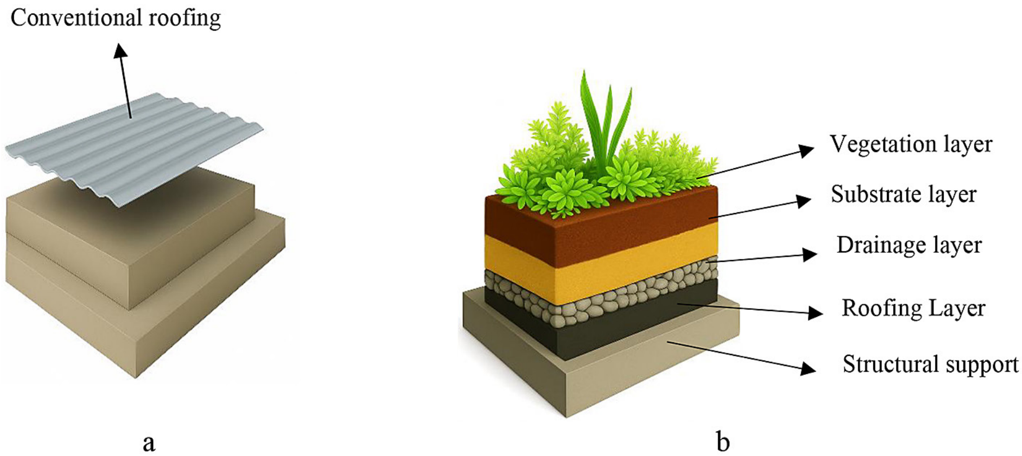

Figure 4. Experimental infrastructure: (a) Conventional Roofing, (b) Experimental Module: Design 1 and 2, by varying the layer expectancy

materials – pumice stone, a tailored substrate mix, and native plant species – but with differentiated layer thicknesses. This experimental variation enabled a comparative evaluation of their functional effectiveness in regulating sub-roof temperature, enhancing stormwater retention, and contributing to carbon capture Table 1.

Drainage layer

A foundational layer composed of porous pumice stone was employed in both designs due to its light weight, high void content (60–85%), and structural durability. This layer supports downward water percolation while preventing root zone saturation. In Design 1, the thickness was limited to reduce material use, whereas Design 2 employed a thicker configuration to enhance percolation delay and buffering.

Substrate layer

This key intermediate layer was formulated with a ternary mix of coconut coir, composted organic matter, and loamy topsoil, offering a balance between porosity, nutrient availability, and water-holding capacity. Differences in thickness directly influenced root zone aeration, infiltration rate, and retention potential. The thinner layer in Design 1 led to quicker saturation and reduced water storage, while the deeper layer in Design 2 significantly improved hydrological performance.

Vegetation layer

A curated plant mix was applied equally in both designs, composed of fast-growing, endemic species such as Portulaca oleracea, Peperomia pellucida, and Sedum lineare. Although plant composition remained constant, the substrate depth had a

Table 1. Layer composition and thicknesses used in both green roof designs to support drainage and vegetation

Layer	Material	Design 1 (cm)	Design 2 (cm)
Drainage	Pumice stone	4	5.5
Substrate	Coir + compost + loamy soil	5,5	7
Vegetation	*Portulaca*, *Peperomia*, *Sedum* spp	Uniform	Uniform

clear impact on root development and biomass accumulation, directly influencing the system's carbon sequestration and microclimatic performance.

Data collection and instrumentation

Data were collected using calibrated environmental sensors, with measurements recorded at hourly intervals and aggregated daily for analysis Table 2.

Statistical analysis

To assess the statistical significance of differences observed among roofing configurations, univariate statistical analyses were conducted. A Student's t-test was applied for variables measured between two experimental groups (Design 1 vs. Design 2), while a one-way analysis of variance (ANOVA) was employed for comparisons involving all three configurations (Control, Design 1, and Design 2). When significant differences were detected via ANOVA, a Tukey's honest significant difference (HSD) post-hoc test was used to determine which pairs of configurations differed significantly. The significance level was set at $\alpha = 0.05$. All statistical analyses were performed using R software (version 4.3.0).

RESULTS AND DISCUSSION

To assess the functional performance and feasibility of stratified green roof systems in tropical rural settings, a comparative experimental evaluation was conducted over a nine-month monitoring period across two structurally distinct configurations. Both systems incorporated identical construction materials pumice stone as a drainage medium, a coconut coir-based substrate, and endemic plant species while differing primarily in substrate and drainage layer thicknesses. Key ecosystem performance parameters were continuously monitored, including thermal regulation, relative humidity (RH), rainfall retention, infiltration response, and carbon sequestration potential.

Data were analyzed using both temporal visualization and inferential statistics to identify functional divergences between the configurations. Univariate analyses were performed in R (v4.3.0), employing one-way ANOVA to compare indoor temperatures across the three roof types (Control, Design 1, Design 2), and Student's t-tests to assess pairwise differences in RH, infiltration onset, water retention, and carbon sequestration. Statistical significance was set at $\alpha = 0.05$. Results demonstrate that even modest variations in green roof stratigraphy can substantially influence microclimatic regulation and ecosystem service delivery, thereby informing scalable nature-based infrastructure strategies in humid tropical contexts.

Thermal and hydrometric regulation

Figure 5 illustrates the time-series dynamics of temperature and RH across the three roofing configurations. The control roof consistently exhibited the highest internal temperatures (mean ~26.4 °C),

Table 2. Environmental and functional parameters measured to evaluate thermal, hydrological and ecological performance of the system

Variable	Method/Device	Frequency
Temperature (indoor surface)	Digital thermocouple probes (±0.2 °C)	Hourly, averaged daily
Relative humidity	Hygrometer sensors (±2%)	Hourly, averaged daily
Rainfall (mm)	Tipping bucket rain gauge	Daily
Water retention (mm)	Manual measurement via drainage collection	Daily
Infiltration Onset (s)	Stopwatch after first rainfall event	Per rain event
Carbon sequestration estimate	Based on standard biomass growth metrics	Modeled annually

whereas both green roof systems showed effective thermal buffering. Design 2, characterized by a 7 cm substrate and improved drainage stratification, achieved the greatest thermal moderation, with a mean temperature reduction of ~2.43 °C relative to the control. These differences were statistically significant (ANOVA: $F(2.87) = 84.07$, $p < 0.001$), and Tukey's HSD post hoc test confirmed that Design 2 significantly outperformed Design 1 (ΔT = 0.56 °C, $p = 0.003$).

RH trends closely mirrored the thermal response. Design 2 consistently maintained RH levels ~12% higher than Design 1, reflecting superior evapotranspiration and substrate moisture retention. A Student's t-test confirmed this difference ($t = -33.76$, $p < 0.001$). The simultaneous moderation of temperature and RH by Design 2 highlights the synergistic influence of substrate thickness and porosity on thermal vapor microclimate regulation. These findings corroborate prior literature emphasizing the role of green roof stratigraphy in enhancing passive climatic performance in tropical environments.

Green roof hydrology

Figure 6 presents the hydrological responses of the two designs, including infiltration time (I), water retention (WR), and rainfall events (R). Design 2, with its deeper and more porous substrate profile, exhibited delayed infiltration onset (165–215 s) compared to Design 1 (120–145 s), indicating enhanced stormwater detention. This difference was statistically robust ($t = -24.96$, $p < 0.001$). Daily WR measurements showed consistently higher retention in Design 2 (mean difference ~15 mm/day), particularly following precipitation peaks, signifying improved attenuation capacity.

Conversely, Design 1 showed more variable WR performance and quicker drainage, likely due to limited substrate depth and reduced void space. These results underscore the importance of substrate configuration in hydrological resilience: Design 2's stratified profile effectively delays gravitational flow, promoting temporary water storage and infiltration buffering critical features in regions exposed to short duration, high intensity rainfall.

Total ecosystem services

Figure 7 synthesizes multiple performance metrics using boxplots to compare the ecological effectiveness of both configurations. Design 2 consistently outperformed Design 1 across all indicators. Infiltration onset (I) displayed the greatest divergence, with Design 2 showing higher medians and broader interquartile ranges consistent with improved hydraulic buffering. These findings correlate with superior WR, supporting the earlier temporal analysis.

Thermally, Design 2 recorded lower temperature medians and reduced variability, while RH was notably higher, reinforcing its microclimatic advantages. In terms of carbon sequestration (CS), Design 2 achieved nearly double the CO_2 uptake (~4.82 $kgCO_2/m^2/year$) compared

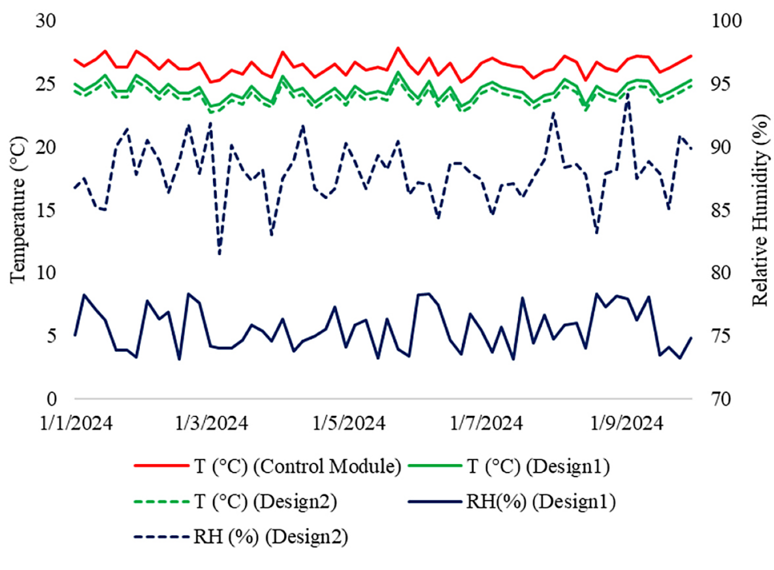

Figure 5. Comparative analysis of temperature and relative humidity performance in green roof experimental designs

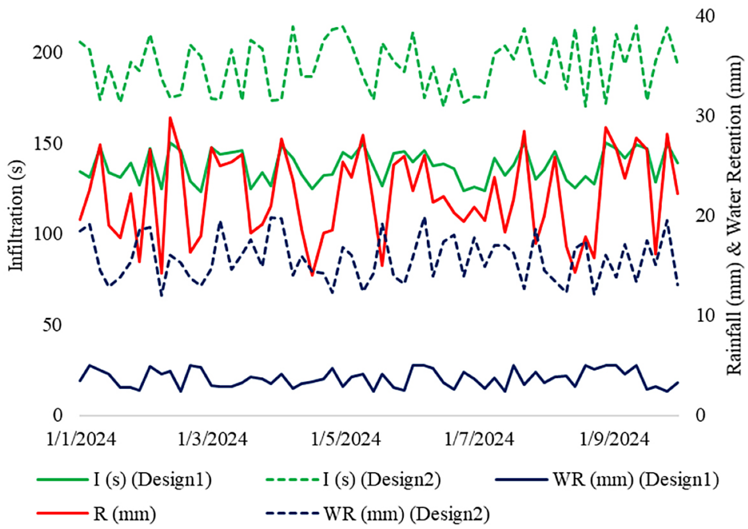

Figure 6. Dynamics of infiltration, water retention, and rainfall in two green roof designs

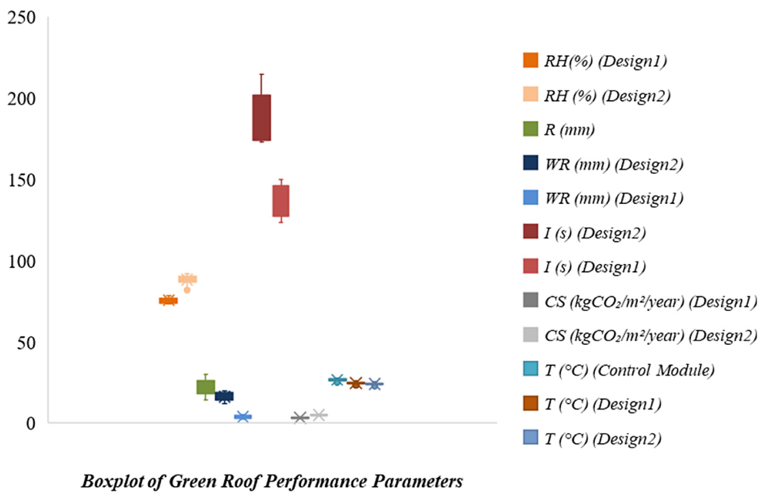

Figure 7. Comparison of performance variables in both green roof designs

to Design 1 (~2.8 $kgCO_2/m^2/year$), attributed to deeper root development and sustained biomass accumulation. These differences were statistically validated ($t = -45.72$, $p < 0.001$).

This multivariate comparison confirms that optimized substrate design is crucial for maximizing the multifunctional performance of green roofs. The ecological superiority of Design 2 evident in its thermal, hydrological, and biotic indicators demonstrates its potential as a robust nature-based solution for enhancing climate resilience in tropical built environments.

Comparative summary

A consolidated summary of the mean values for all monitored performance parameters across both designs is presented in Table 3. The results confirm that Design 2 outperformed Design 1 in nearly all ecological metrics, including lower average temperature (24.03 °C), higher relative humidity (87.62%), significantly greater water retention (15.87 mm/day), and superior carbon sequestration capacity (4.82 $kgCO_2/m^2/year$). The only exception was infiltration time, where Design 1 exhibited faster drainage (~137 s), which may be desirable in contexts prioritizing rapid runoff mitigation. This comparative framework supports a multi-criteria evaluation of green roof systems, demonstrating that deeper substrate assemblies not only improve hydrometric and thermal conditions but also enhance long-term ecosystem service provisioning. The table serves as a decision-support tool to align design strategies with performance priorities.

Correlation matrix for designs

The cross-design correlation matrix revealed significant interrelationships among environmental performance variables across both green roof configurations. A perfect positive correlation in temperature (r = 1.00) between the two designs indicated consistent thermal behavior, regardless of differences in substrate depth. Conversely, a moderate negative correlation between temperature and relative humidity (T1 vs. RH2: r = –0.53) underscored the influence of evapotranspiration in microclimatic regulation, particularly in the deeper Design 2 system. Water retention showed a moderate correlation across configurations (WR1 vs. WR2: r = 0.63), reflecting shared responses to precipitation, yet Design 2 significantly outperformed Design 1 in absolute retention values. Similarly, the correlation in carbon sequestration (CS1 vs. CS2: r = 0.39) suggested that substrate structure more than vegetation composition drives long term biomass accumulation. These findings highlight that while climatic variables are exogenous, hydrological and ecological outcomes are fundamentally dependent on structural design, reinforcing the potential of stratified green roofs as climate-adaptive solutions (Figure 8).

This integrated performance is particularly relevant in regions like the Napo River Basin, characterized by high hydro-climatic variability and increasing anthropogenic pressure. Similar dynamics are observed in basins such as Pativilca, where rapid agricultural expansion and urbanization are intensifying competition for limited water resources. In this context, the adoption of nature-based solutions like green roofs can support Integrated Water Resources Management (IWRM) by enhancing stormwater retention, regulating microclimates, and contributing to carbon mitigation. The demonstrated ecological

Table 3. Environmental and functional parameters measured to evaluate thermal, hydrological, and ecological performance of the system

Variable	Design 1	Design 2
Temperature (indoor surface) (°C)	24.34	24.03
Relative humidity (%)	75.68	87.62
Water retention (mm)	3.52	15.87
Infiltration onset (s)	137.13	194.15
Carbon sequestration estimate (CO_2/m²/year)	2.98	4.82

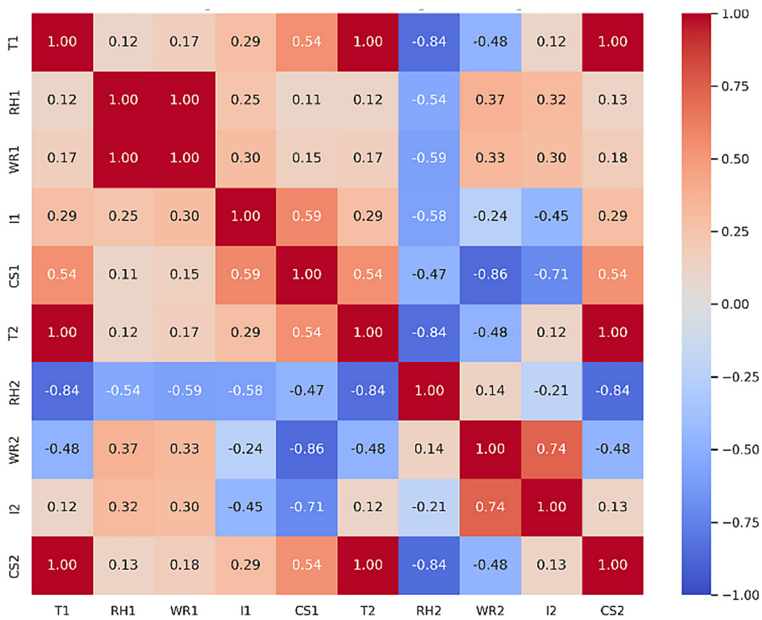

Figure 8. Pearson correlation matrix of key ecosystem performance indicators for Designs; values represent correlation coefficients between rainfall (R), temperature (T), relative humidity (RH), water retention (WR), infiltration (I), and carbon sequestration (CS)

functionality and structural feasibility of the optimized green roof design (Design 2) underscores its value in the broader strategy for resilient water governance in tropical rural landscapes.

CONCLUSIONS

This paper demonstrates the feasibility, ecological effectiveness, and structural compatibility of extensive green roof systems specifically adapted for tropical rural environments. By implementing and comparing two experimental configurations differing only in the thickness of their functional layers, the research systematically quantified the influence of substrate stratification depth on key environmental performance indicators.

The optimized configuration (Design 2), featuring increased layer thickness, consistently outperformed its shallower counterpart. It achieved a mean indoor temperature reduction of 2.4 °C – aligned with passive cooling benchmarks for warm-humid climates – and elevated indoor relative humidity by an average of 13%, likely due to enhanced evapotranspiration and substrate moisture retention.

Hydrologically, Design 2 retained 42.5% of incident rainfall and delayed infiltration onset to an average of 192 seconds, confirming its superior capacity for buffering stormwater and reducing surface runoff. These results validate the critical role of substrate depth and porosity in hydrological attenuation, in accordance with global evidence on green infrastructure. Moreover, this hydrological behavior aligns with the principles of Integrated Water Resources Management (IWRM), emphasizing the need for decentralized, nature-based interventions that support watershed-scale water governance and climate resilience.

Carbon sequestration potential reached 4.82 kg CO_2/m²/year, driven by improved belowground biomass accumulation, which was directly facilitated by increased substrate volume. Despite identical vegetation in both designs, the deeper profile enabled more vigorous plant development, reinforcing the link between green roof configuration and climate mitigation functions.

Structurally, the saturated system's load (68 kg/m²) remained within safe limits for vernacular construction typologies (e.g., adobe, bamboo), confirming its practical feasibility and scalability for low-income settings without architectural modification.

This research highlights substrate thickness optimization – using low-cost, locally available materials – as a key determinant for maximizing the ecological performance of green roofs in vulnerable tropical regions. The design approach directly advances the United Nations Sustainable Development Goals (SDGs 6, 9, and 11), integrating climate adaptation, water resilience, and infrastructure equity. Future work should incorporate seasonal variability, long-term vegetation dynamics, and participatory co-design strategies to refine these prototypes into adaptable, community-driven models for sustainable rural development in the Global South.

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