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DOI: **10.5937/greenb26071L**
Review paper

GREEN ROOFS AND GREEN FACADES AS COMPLEMENTARY NATURE-BASED SOLUTIONS FOR URBAN HEAT ISLAND MITIGATION

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Abstract

Rapid urbanization, climate change, and the growing frequency of extreme heat have intensified thermal conditions in cities worldwide. Among the most significant urban climate phenomena is the Urban heat island (UHI) effect, whereby urban areas experience higher temperatures than surrounding rural environments due to high-density built environment, low vegetation cover, anthropogenic heat emissions, and the presence of heat-retaining materials. This paper examines green roofs and green facades as complementary, climate-responsive nature-based strategies for reducing the UHI effect and improving urban environmental quality. The review focuses on their thermal performance, environmental co-benefits, and contribution to sustainable urban development. Evidence demonstrates that green roofs can reduce building cooling loads by up to 70% and lower indoor temperatures under specific climatic conditions, while green facades effectively cool vertical surfaces and street-level urban canyons. Together, these systems deliver synergistic environmental benefits, including improved air quality, carbon sequestration, stormwater retention, biodiversity support, and noise reduction. It is concluded that the integrated deployment of green roofs and green facades represents an effective and urgently needed measure for climate-resilient urban development, with significant potential for application in Serbian cities.

Key words: *Urban heat island, green roofs, green facades, urban climate resilience*

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1. INTRODUCTION

Urban areas are increasingly exposed to the combined effects of rapid urbanization and climate change. According to the United Nations, more than 55% of the world's population currently lives in urban areas and this proportion is expected to reach 68% by 2050 [1]. The progressive replacement of natural landscapes with buildings, roads, and other impervious surfaces affects the urban energy balance and constitutes a primary driver of the Urban heat island (UHI) effect, whereby urban temperatures are typically 2-5°C higher than those of surrounding rural areas [2]. This thermal imbalance is further intensified by climate change, as 2024 has been confirmed as the warmest year on record, with global mean temperatures approximately 1.55°C above pre-industrial levels [3]. Elevated urban temperatures negatively affect energy consumption, outdoor thermal comfort, public health, and overall environmental quality.

Recent climate projections indicate that heat waves will become more frequent and intense in many regions, including southeast Europe [3]. Cities therefore need adaptation strategies that reduce thermal stress while supporting sustainable urban development. In dense urban areas, expanding conventional green infrastructure is often limited by space constraints and competing land uses, which increases interest in building-integrated vegetation systems that use roofs and facades without requiring additional land [4].

Nature-based solutions are widely recognized for providing multiple environmental and social benefits beyond temperature reduction [4]. Green roofs and green facades are among the most applied building-integrated systems [4]. By using existing building surfaces, they increase urban greenery while contributing to cooling through shading, evapotranspiration, and improved thermal insulation, thereby reducing surface temperatures, cooling demand, and urban heat stress [5].

The aim of this paper is to synthesize current evidence on the thermal performance of green roofs and green facades, with a focus on their complementary mechanisms, potential synergistic effects when combined, and their role as scalable nature-based solutions for climate-resilient urban development.

2. RESEARCH METHODOLOGY

This study applies a structured narrative literature review to synthesize current knowledge on the contribution of green roofs and green facades to Urban Heat Island (UHI) mitigation. The review includes peer-reviewed journal articles, international reports, and selected case-study sources published primarily between 2008 and 2025, supplemented by the foundational study of Oke [2]. Sources were selected according to their relevance to four analytical criteria: (1) thermal performance, (2) environmental co-benefits, (3) energy-saving potential, and (4) applicability in dense urban environments. The evidence was first analysed separately for green roof and green facade typologies and then comparatively, with particular attention to their complementary effects and implementation potential in Serbian cities. Because locally

measured performance data remain limited, the applicability assessment relates evidence from Mediterranean and Central European climates to available climatic and morphological data for Niš [4] [8] [10].

3. THE URBAN HEAT ISLAND EFFECT

The UHI effect is driven by four primary physical mechanisms: the high thermal mass of urban materials that absorb solar radiation by day and release it at night; reduced evapotranspiration from limited vegetation cover; anthropogenic heat from transportation, industry, and air conditioning; and urban canyon geometry that traps radiation and restricts airflow [2]. The consequence is a self-reinforcing cycle: elevated temperatures increase cooling energy demand, which generates additional waste heat and greenhouse gas emissions, further accelerating warming. Studies across European cities indicate cooling energy demand rises 10-20% per degree Celsius of urban warming above the rural baseline [5].

Nature-based solutions directly interrupt this cycle by restoring evapotranspiration and shading processes to the built environment. Among these, building-integrated vegetation occupies a strategically important position – it can be deployed on existing structures without land-use transformation, making it particularly relevant for dense urban fabric where spatial constraints preclude other approaches [4].

4. GREEN ROOFS

4.1. Typology and components

Green roofs consist of vegetated layers installed above conventional roof structures. Their cooling effect is primarily achieved through evapotranspiration, shading of roof surfaces, and thermal insulation provided by the substrate layer. Green roofs are engineered systems comprising, from base to surface: a waterproofing membrane, root barrier, drainage layer, filter layer, growing substrate, and vegetation. Green roofs are generally classified as extensive, semi-intensive, or intensive systems according to substrate depth, vegetation type, maintenance requirements, and accessibility. Extensive roofs are typically inaccessible and require minimal maintenance, whereas intensive roofs are generally designed for regular human use and support a wider variety of vegetation. In addition, green roofs enhance urban environmental quality by mitigating the urban heat island effect and providing habitats that support biodiversity in densely built environments [5]. The components and typological differences between these green roof systems are presented in Figure 1.

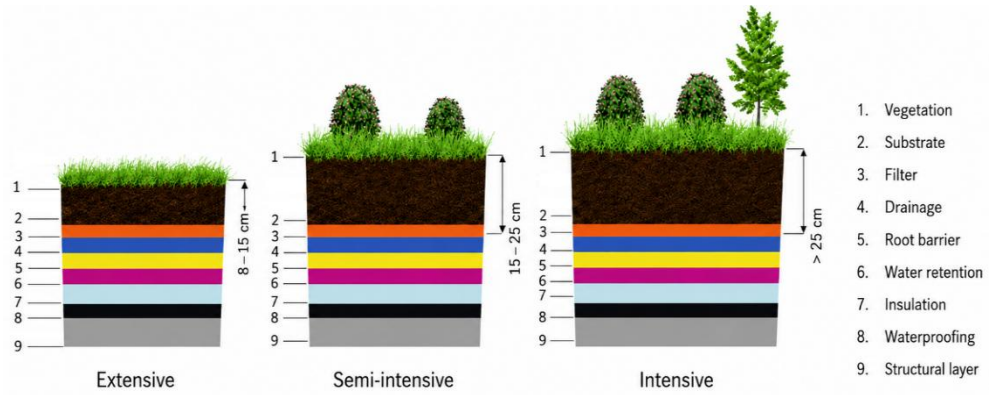


Figure 1 - Comparison of extensive, semi-intensive, and intensive green roof system layers [5]

4.2. Thermal mechanisms and quantified performance

The primary thermal mechanism of green roofs is evapotranspiration: plants and substrate release moisture that converts solar radiation into latent heat rather than sensible heat, directly cooling the roof surface and the air above it [5]. Shading by the vegetation layer intercepts radiation before it reaches the substrate, while the substrate itself provides thermal mass that delays heat transfer to the building interior. Research demonstrates that increasing the Leaf area index (LAI) from 0.5 to 3.5 reduces canopy air temperature oscillations from 11.6°C to 3.6°C, underscoring the importance of vegetation density [5].

The effectiveness of evapotranspiration depends on several factors, including plant species, leaf area index, substrate moisture content, climatic conditions, solar radiation, wind speed, and irrigation regime. Under prolonged drought conditions, evapotranspiration rates decrease considerably, reducing the cooling performance of green roofs. Therefore, appropriate plant selection and substrate design are essential for maximizing thermal efficiency [5].

In Mediterranean climatic conditions, such as those recorded in Athens, which share certain similarities with the warmer regions of Serbia, studies have reported annual energy savings of up to 37%, while extensive green roofs consumed 20% less energy than conventional black roofs under non-insulated conditions, and semi-intensive green roofs achieved reductions of 60–70% [6]. Across climates, green roofs can reduce building cooling loads by up to 70% and lower indoor temperatures by up to 15°C [5]. Beyond improvements in building energy performance, green roofs may also enhance the efficiency of photovoltaic systems when integrated with them, while simultaneously contributing to reductions in greenhouse gas emissions, highlighting their broader synergistic potential within urban energy systems [7].

5. GREEN FACADES

5.1. Typology and components

Green facades introduce vegetation to vertical building surfaces through climbing plants or modular living wall systems. Similar to green roofs, their cooling performance is based on shading and evapotranspiration. However, unlike green roofs, green facades directly influence the thermal environment at pedestrian level by reducing wall surface temperatures and improving microclimatic conditions within urban canyons [4]. The principal typologies and working principles of green facade systems are illustrated in Figure 2.

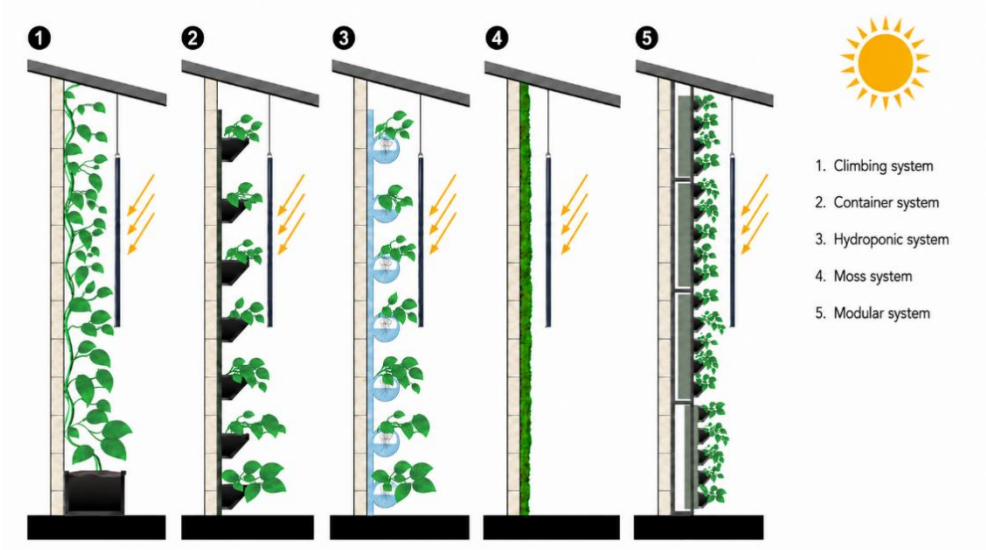


Figure 2 - Typology and working principles of green facade systems [7]

5.2. Thermal mechanisms and street-level cooling

Green facades reduce thermal gain on building walls through two complementary mechanisms [4] [8]. Shading by the vegetation layer intercepts radiation that would otherwise heat the wall surface; dark wall materials can reach 50-70°C on summer days, while green facades reduce these temperatures by 10-30°C. Evapotranspiration from plant surfaces cools the adjacent air layer, and the air gap in indirect systems provides additional convective cooling. These combined effects result in annual energy savings of 5-25% depending on facade orientation, wall construction, and climate [4] [8].

The critical distinction of green facades lies in their direct impact at pedestrian level. Reduced-scale experimental studies have been conducted to compare the microclimatic performance of street canyons with and without vegetated envelopes under summer conditions, showing relevant differences in thermal behavior. Their results showed that green facades reduced air temperature in the street canyon by up to 1.5°C, reduced the mean radiant temperature by up to 4°C on clear summer days, and increased relative humidity by 6-8% through evapotranspiration – directly improving outdoor thermal comfort [9]. Simulation studies across nine cities found

maximum canyon air temperature reductions of up to 26°C in hot and dry climates when facades were fully greened, with average reductions of approximately 12.8°C across all studied climates [8]. This pedestrian-level effect is the most important functional difference between green facades and green roofs.

Deciduous species offer an intrinsic seasonal adaptation: maximum shading and evaporative cooling in summer, followed by leaf fall that allows solar radiation to reach and warm the wall in winter – a passive response to seasonal energy needs that evergreen species cannot provide [4].

6. COMPARATIVE ANALYSIS AND INTEGRATED IMPLEMENTATION

The thermal and environmental performance of green roofs and green facades is complementary rather than competitive. Green roofs primarily benefit the building interior and the urban energy balance at roof level, whereas green facades act directly on the street environment, where thermal comfort is most immediately experienced by pedestrians. Together, they provide comprehensive thermal protection of the building envelope and contribute to cooling at both the building and urban scales simultaneously [4] [9].

Table 1. Comparative thermal performance of green roofs and green facades [4] [5] [8]

Performance indicator	Green roofs	Green facades
Primary surface	Horizontal roof	Vertical walls
Cooling load reduction	Up to 70%	Up to 50%
Indoor temp. reduction	Up to 15°C	3-8°C (top floors)
Street-level cooling	Indirect / limited	Direct and significant
Mean radiant temp. reduction	Limited	Up to 4°C [9]
Annual energy savings	10-60%	5-25%

Beyond comparing green roofs and green facades, performance differences within each system category should also be considered. Among green roof typologies, extensive, semi-intensive, and intensive systems differ primarily in substrate depth, structural load, maintenance requirements, vegetation diversity, and thermal performance. Extensive systems, characterized by shallower substrates and relatively low structural loads, are generally the most suitable option for retrofitting existing buildings. Semi-intensive systems represent an intermediate solution, providing greater vegetation density, moisture retention, and cooling potential while maintaining moderate structural and maintenance requirements. Intensive systems, with deeper substrates and more diverse vegetation, generally provide the greatest thermal mass, stormwater retention capacity, and ecological potential. However, they also require greater structural capacity, regular irrigation, and more intensive maintenance [5] [6]. These differences demonstrate a trade-off between environmental performance and technical requirements, meaning that the selection of an appropriate typology should depend on the structural capacity of the building, the intended use of the roof, and available maintenance resources.

A comparable internal differentiation applies to green facade systems. Direct greening systems, in which climbing plants are rooted at ground level, generally require limited structural modification and lower initial investment, but vegetation coverage develops gradually and depends on the growth characteristics and maximum height of the selected species. Indirect systems use supporting structures that separate vegetation from the building wall, thereby improving air circulation and reducing direct contact between plants and the facade surface. Modular living wall systems provide faster and more uniform vegetation coverage and enable greater control over plant distribution and irrigation, but they generally require higher initial investment, permanent irrigation infrastructure, and more intensive maintenance [4] [7]. Green facade typology should therefore be selected according to building height, orientation, irrigation availability, and maintenance capacity.

7. CASE STUDY: ACROS FUKUOKA, JAPAN

The ACROS Fukuoka Prefectural International Hall, designed by architect Emilio Ambasz and completed in 1995, is one of the most cited examples of building-integrated vegetation in a high-density urban context. Constructed on the last remaining open space in central Fukuoka – the Tenjin Central Park – the building was designed so that 15 stepped vegetated terraces on its south elevation would return to the city nearly the entire park area displaced by the structure [11] [12]. The design simultaneously applies the thermal mechanisms of green roofs (evapotranspiration, substrate insulation) and green facades (shading, surface cooling) across a single continuous envelope, demonstrating in built form the complementary action described earlier. The project demonstrates that, in densely built city centres, it is possible to reconcile economic interests, the need for civic infrastructure, and the preservation of public green space [11]. The stepped vegetated envelope of the ACROS Fukuoka building is shown in Figure 3.



Figure 3 - ACROS Fukuoka Prefectural International Hall with stepped vegetated terraces integrated into the building envelope [14]

In terms of measured performance, a thermal survey conducted in 2000 by Takenaka Corporation, Kyushu University, and the Nippon Institute of Technology recorded a surface temperature difference of up to 15°C between vegetated terraces

and exposed concrete surfaces on the same building, confirming significant UHI mitigation [13]. The planting expanded from 76 to 120 species and from 37,000 to over 50,000 plants through natural seed dispersal over approximately 25 years [12] [13], illustrating the long-term ecological development of intensive building-integrated vegetation systems. The case is particularly relevant to Serbian city centres where ground-level green space is scarce and flat-roofed building surfaces represent the primary available resource for nature-based interventions.

8. APPLICABILITY IN SERBIAN CITIES

The conditions in Serbian cities create both an intensified UHI problem and a strong technical case for building-integrated vegetation solutions. The city of Niš records an absolute maximum temperature of 44.2°C and an average of 49 tropical days per year, with building coverage ratios in the central zone reaching 68% and street canyon aspect ratios of 0-1.3 [10]. These morphological characteristics, which are the same parameters that intensify UHI formation, also create favorable conditions for green facade performance, as taller and narrower canyons amplify the cooling effect of vegetated surfaces.

The large stock of flat-roofed collective housing constructed between the 1950s and 1980s presents a technically accessible opportunity for extensive green roof deployment. The lightweight nature of extensive systems reduces structural reinforcement requirements compared to intensive alternatives. The structural load-bearing capacity of existing buildings should be assessed before retrofitting [10].

Policy instruments that have proven effective in western European cities include mandatory green roof installation on new public buildings, grant programs for retrofit projects, inclusion within municipal energy efficiency frameworks, and simplified permitting for facade greening. Pilot projects on schools, collective housing blocks, and municipal buildings in Belgrade, Niš and Novi Sad would generate locally relevant performance data while building professional capacity and public awareness, which are essential preconditions for scaling up implementation [10].

Similar pilot projects implemented in Mediterranean and Central European cities have demonstrated that locally adapted vegetation species and irrigation strategies significantly improve long-term thermal performance. These findings indicate that pilot projects in Serbia should prioritize native and drought-tolerant plant species adapted to regional climatic conditions [4] [8].

Despite their numerous environmental benefits, the implementation of green roofs and green facades remains constrained by several technical and economic challenges. Initial installation costs are generally higher than those of conventional roofing and facade systems, while existing buildings may require structural assessment to determine their load-bearing capacity before retrofit interventions. Long-term performance also depends on appropriate plant selection, regular maintenance, and irrigation, particularly in regions experiencing prolonged summer droughts. Although these systems require higher initial investment, their costs may be partly offset over the building life cycle through reduced energy consumption, extended roof service life,

improved stormwater management, and broader environmental benefits [5] [7]. Their long-term economic feasibility nevertheless depends on climatic conditions, system design, maintenance requirements, irrigation demand, and the scale of implementation.

Successful implementation in Serbia will require supportive legislation, technical guidelines, financial incentives, and integration into new construction and renovation projects.

9. CONCLUSION

Green roofs and green facades represent a technically developed and complementary pair of building-integrated strategies for urban heat island mitigation. Green roofs reduce building cooling loads by up to 70% and indoor temperatures by up to 15°C through evapotranspiration, shading, and thermal mass effects. Green facades cool vertical surfaces and street-level air in urban canyons – reducing air temperature by up to 1.5°C and mean radiant temperature by up to 4°C – providing pedestrian-level thermal comfort benefits that green roofs alone cannot achieve.

The primary conclusion of this review is that the integrated deployment of both systems produces effects that are synergistic rather than additive: green roofs reduce the heat load entering the urban system from above, while green facades reduce the heat exchanged between building walls and the street canyon below. Together they constitute a comprehensive building-scale response to UHI conditions.

In the Serbian context, hot summers, compact urban morphology, high building coverage ratios, and large stocks of flat-roofed buildings create conditions in which these systems are both most needed and most applicable. Integrating green roofs and green facades into building renovation programs and urban development policy, along with targeted financial instruments and locally calibrated pilot projects, represents a concrete and urgently relevant step toward climate-resilient, healthy, and sustainable urban environments. Future research should prioritise long-term monitoring in Southeast European climates and investigate integrated applications with photovoltaic systems, smart irrigation, and environmental monitoring under Serbian climatic conditions.

ACKNOWLEDGMENT

This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia through the institutional funding of the Innovation Center of the University of Niš (Contract No. 451-03-33/2026-03/200371).

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