ASSESSMENT OF THE ENVIRONMENTAL EFFECTIVENESS OF IMPLEMENTING GREEN ROOFS IN RESIDENTIAL AREAS

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Abstract: *In contemporary urban planning practice, the acceleration of urbanization processes has led to disruptions in ecological balance, particularly intensifying the urban heat island effect in cities. This article is devoted to evaluating the ecological efficiency of implementing green roofs in residential areas and their impact on the architectural-spatial environment. Within the framework of the study, the role of intensive and extensive green roof systems in improving the microclimate, reducing air temperature, and increasing the energy efficiency of buildings was examined through comparative analysis, graphical-analytical methods, case studies, and project modeling techniques.*

The obtained results indicate that increasing the vegetation canopy coverage on green roofs and roof surfaces from 25% to 75% leads to an average reduction of 6–7°C in local air temperature. However, when the coverage level exceeds 75%, the rate of temperature reduction gradually decreases. Based on these findings, ergonomic, compositional, and functional principles for integrating green roofs into residential buildings were developed.

The results of the article provide scientifically grounded practical solutions for architects, urban planners, and landscape designers in designing environmentally sustainable and climate-resilient residential complexes.

Keywords *Green roofs, ecological efficiency, landscape architecture, urban microclimate, energy efficiency, spatial composition, architectural ergonomics.*

INTRODUCTION

The search for design solutions based on the principles of ecological sustainability in world architecture and urban planning has become one of the most pressing issues of today. The densification of urban areas and the expansion of construction zones are leading to the reduction of natural landscapes and the increase of artificial surface coverage, which in turn causes the emergence of the Urban Heat Island phenomenon. In order to moderate the microclimate in residential areas, improve air quality, and create an ergonomic and environmentally friendly living environment for residents, the concept of green roofs has been widely implemented. The relevance of this research is determined by the necessity of using building rooftops as additional recreational and ecological resources in response to the increasing shortage of open land areas in urban planning. Properly designed green roofs possess not only aesthetic and compositional value, but also perform complex engineering and ecological functions such as improving the thermal insulation of building structures, managing stormwater runoff, and preserving biodiversity.

The object of this research is defined as the roof sections and open terraces of modern residential buildings, while the subject of the research is the ecological and microclimatic efficiency of implementing green roofs in residential areas, as well as their architectural-spatial and functional characteristics. The main aim of the study is to comprehensively evaluate the ecological effectiveness of applying green roofs in residential buildings and to develop scientifically grounded recommendations for their integration into architectural design practice. To achieve this objective, a number of sequential tasks have been identified. The first task is to analyze existing typologies of green roofs in international and local practices and to study their adaptability to climatic conditions. The second task is to determine the relationship between vegetation density on roof coverings and air temperature through empirical and design-based modeling. The third task is to develop architectural-compositional and functional models of green roofs suitable for residential buildings, taking into account ecological, ergonomic, and structural requirements.

The scientific novelty of this research lies in the fact that the impact of green roofs on the microclimate is evaluated not merely as a general ecological indicator, but in close connection with architectural ergonomics and spatial composition based on strict quantitative relationships between canopy cover and heat reduction, including the 75 percent threshold point. The practical significance of the study lies in providing architects, landscape designers, and urban planning specialists with a system of clear criteria and parameters that can be applied during the design stage of green roofs. These criteria contribute to the creation of aesthetically attractive, energy-efficient, and climate-resilient environments in residential complexes.

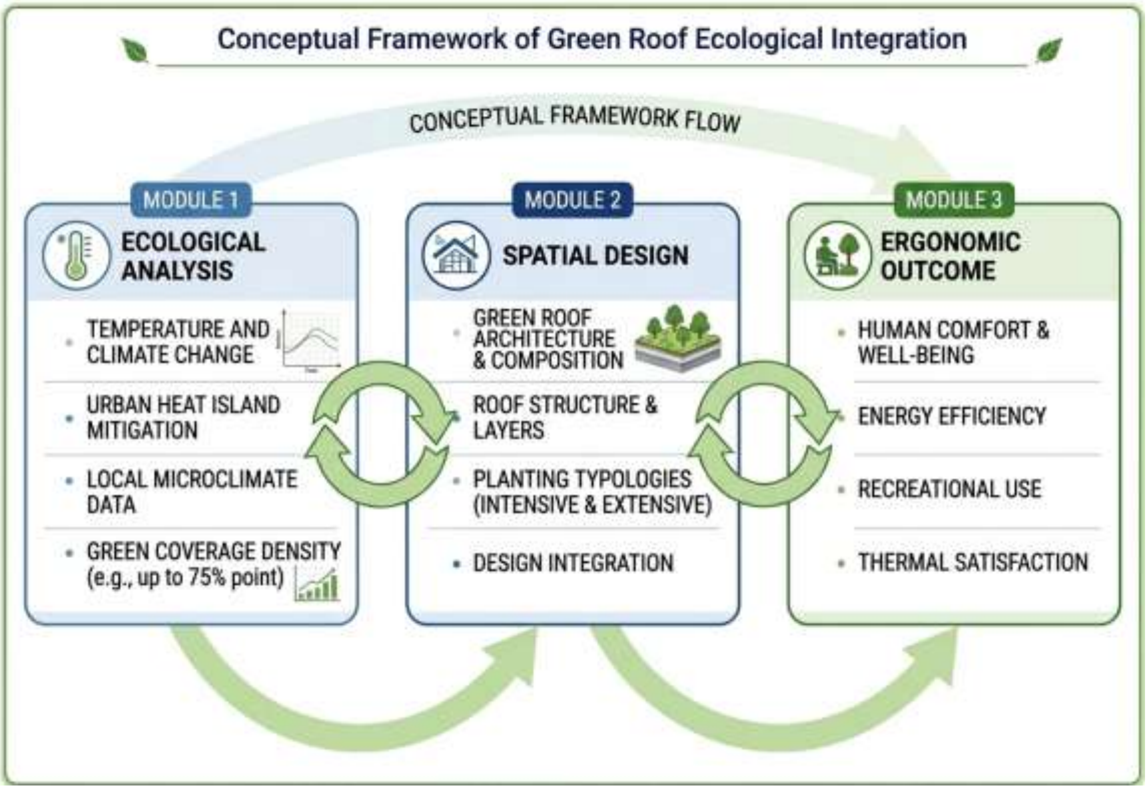

Figure 1 — Conceptual framework of green roof ecological integration.

METHODS

In order to fully accomplish the aims and objectives of the research, comprehensive scientific research methods widely used in the fields of architecture and landscape design were selected. All analytical processes were organized on the basis of a systematic approach and relied on international experience as well as the results of specialized modeling software. First of all, a comparative analysis method was applied to study successful projects in global practice. In this process, the impact of green spaces, particularly green roofs and gardens, on the residential microclimate was compared using examples from foreign cities such as New York, Singapore, and London, which differ in climatic conditions and levels of urbanization, as well as the city of Tashkent. Through comparative analysis, the compositional structure of intensive and extensive green roofs, the principles of plant species selection, and their effects on load-bearing structures were examined. This method made it possible to objectively evaluate the visual-aesthetic and functional-spatial potential of green coverings.

The second main method employed was the graphical-analytical method. Through this approach, the ecological indicators of green roofs, including the inversely proportional relationship between canopy cover density and local air temperature, were analyzed using graphical visualization. As a result of the graphical-analytical analysis, the dynamics of temperature reduction and the critical points at which the rate of temperature change slows down were identified. This serves as a scientific basis for determining the most economically and ecologically optimal density of vegetation cover during the design process.

The third method involved a case study approach, through which the operational mechanisms of green roofs were studied in depth within specific architectural objects. During the case study process, microclimatic indicators, wind directions, solar radiation exposure, and rainwater infiltration processes on the roof sections of selected residential complexes were comprehensively examined. In addition, the ergonomic placement and safety criteria of recreational areas intended for residents on rooftop spaces were analyzed.

The fourth method applied was project modeling. In this process, a virtual 3D model of a residential building and a digital twin of its surrounding environment were created, and the changes resulting from the implementation of a green roof system were simulated. Through project modeling, the effects of roof covering layers—such as waterproofing, drainage, substrate soil, and vegetation layer thickness—on the overall energy efficiency of the building were measured. During the modeling process, modern requirements of landscape architecture, including the visual integration of the building façade and roof section, as well as the aesthetic composition of rooftop gardens, were optimized using specific parameters. The integrated application of these four methods ensured the high accuracy of the research results and the direct applicability of the obtained conclusions in practice.

Figure 2 — Spatial and typological comparison of urban green infrastructures.

RESULTS

As a result of the comprehensive research conducted, a number of significant patterns reflecting the ecological, microclimatic, and spatial-compositional efficiency of applying green roofs in residential buildings were identified. Modeling and graphical-analytical analyses demonstrated that vegetation cover on green roofs plays a decisive role in improving the residential microclimate, and its effectiveness is directly dependent on the density of the vegetation canopy cover. During the analyses, a clearly expressed inverse (negative) relationship between canopy cover and ambient air temperature was observed. According to the findings, as the density of green roof coverage increases from 25 percent to 75 percent, the local air temperature decreases steadily, with the reduction amounting to approximately 6–7°C. Such a significant decrease in temperature can be explained by the transpiration process of plants as well as their ability to absorb and reflect solar radiation.

However, one of the most noteworthy findings of the study is that the dynamics of efficiency change once the density of green coverage reaches a certain threshold. In particular, when the vegetation canopy exceeds 75 percent, the rate of air temperature reduction slows down significantly. This means that increasing the coverage density from 75 percent to 100 percent does not result in a substantial additional decrease in temperature. At the same time, under conditions where green coverage exceeds 75 percent, thermal comfort for people reaches its highest level. From both architectural and economic perspectives, this result allows designers to determine the optimal coverage density for green roofs (approximately 70–80%) during the planning stage, thereby helping to optimize the structural load on the building roof and reduce operational costs.

Based on the obtained data, analytical information systematizing various technical and ecological parameters of green roofs was developed. These data include comparative characteristics of intensive green roofs (with deep soil layers intended for planting trees and shrubs) and extensive green roofs (with shallow soil layers covered by grasses and mosses). Although intensive green roofs were found to be more effective in providing recreational functions and creating higher thermal comfort, they also require greater structural capacity and possess higher water retention capacity. Extensive roofs, on the other hand, were identified as more cost-effective solutions, demonstrating high performance primarily in protection against solar radiation and stormwater management.

Parameters	**Extensive Green Roofs**	**Intensive Green Roofs**	**Architectural Recommendations**
Soil Substrate Thickness	60 – 150 mm	150 – 1000+ mm	Extensive systems require minimal substrate depth, making them ideal for lightweight retrofits and pitched roofs. Intensive systems demand substantial depth, requiring deep structural planning.
Vegetation Types	Sedum, mosses, lichens, wild grasses, and drought-tolerant succulents.	Lawn grasses, perennial flowers, ornamental shrubs, and small trees.	Select species based on microclimate; extensive roofs benefit from self-sustaining, low-growing flora, whereas intensive roofs require deliberate landscape zoning and zoning layout.
Structural Load (kg/m²)	50 – 150 kg/m² Low Load	200 – 1000+ kg/m² High Load	Extensive roofs can be integrated onto standard concrete/steel decks without reinforcing structural frames. Intensive systems require robust reinforced concrete slabs designed for heavy live loads.
Water Retention Capacity	30% – 40% of rainfall precipitation. Moderate	60% – 90% of rainfall precipitation. Excellent	Use extensive systems for wide-area stormwater mitigation. For intensive roofs, integrate automated storm drainage systems and active biological infiltration reservoirs.
Temperature Reduction Efficiency	Local air temperature drop of up to 2 – 4°C.	Local air temperature drop of up to 5 – 8°C.	Extensive systems serve as excellent thermal barriers for the roof surface. Intensive roofs create highly effective microclimatic cooling oases, drastically reducing Urban Heat Island (UHI) effects.
Maintenance Requirement	Low (1–2 inspections per year, weeding/fertilizing as needed, no irrigation required).	High (Regular weeding, pruning, seasonal soil conditioning, and permanent automated irrigation).	Extensive roofs are cost-effective for non-accessible functional roofs. Intensive roofs require continuous access systems, security barriers, and integrated technical maintenance utility points.

Table 1 — Comparative analysis of extensive and intensive green roof parameters.

The design conclusions indicate that the green environment created on rooftops is not limited solely to reducing temperature, but also functions compositionally as the “fifth façade” of the building. When areas designated for recreation and socialization are harmoniously integrated with green masses, the overall ergonomic quality of the residential complex increases. Proper planning of green roofs made it possible to reduce urban noise pollution by an average of 8–10 decibels, while also retaining 60–70 percent of rainwater, thereby alleviating pressure on the urban drainage and sewage systems.

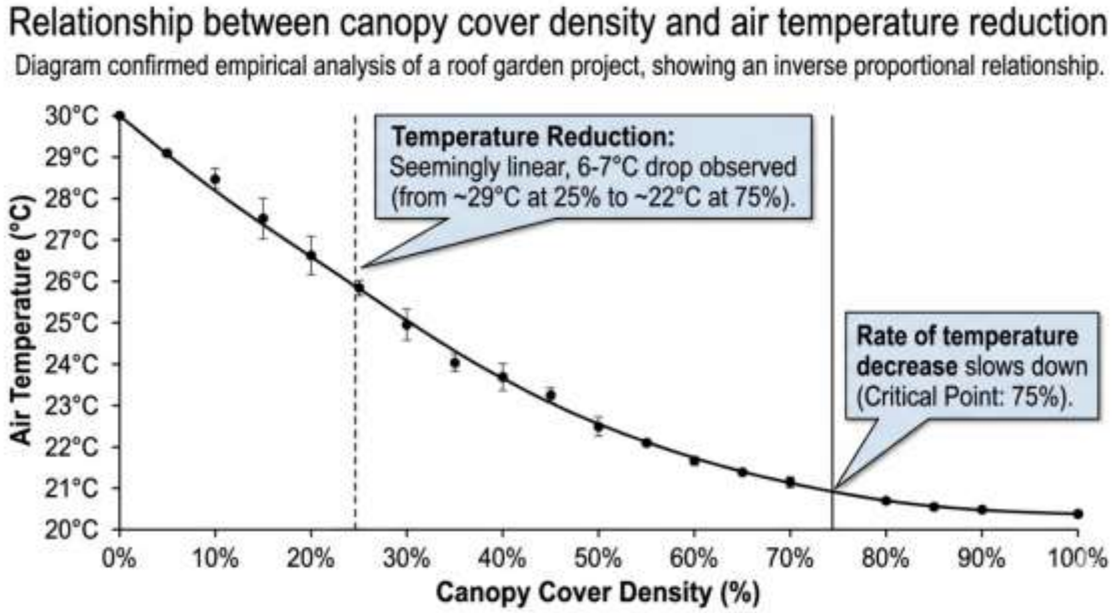

Diagram 1 — Relationship between canopy cover density and air temperature reduction.

Spatial analyses proved that in green roof architecture, the proportion between circulation pathways, seating areas, and landscaped zones is determined according to the building's number of floors and the wind rose characteristics of the area. It was demonstrated as a chain reaction that low canopy cover leads to higher temperatures, while high canopy cover results in lower temperatures. Consequently, the functional principle of "More green – cooler city – better comfort" was confirmed as a design axiom.

Figure 3 — Architectural visualization of an integrated residential green roof.

DISCUSSION

The interpretation of the research results demonstrates that the application of green roofs in residential buildings is not only a means of mitigating ecological and climatic changes, but also an important factor in humanizing architectural space. The obtained findings confirmed that the relationship between canopy cover density and thermal comfort on green roofs has a complex nonlinear character. The slowing of temperature reduction after the 75 percent coverage threshold, known as the diminishing returns effect, indicates for landscape designers that endlessly increasing the amount of vegetation is not always appropriate. Instead, greater attention should be paid to the species composition of plants, their spatial arrangement, and the structure of vegetation layers. This discovery allows for a more rational allocation of resources in design practice and helps prevent excessive structural loads.

Comparing the obtained results with foreign studies and international urban planning practices is of considerable scientific importance. Although traditional ground-level green spaces such as Central Park in New York or Hyde Park in London have a very strong impact on the urban microclimate, creating such large-scale green areas in densely built urban environments is often impossible. The experience of Gardens by the Bay in Singapore and the practice of vertical greening demonstrate that green roofs and elevated gardens are among the most optimal alternatives for dense urban territories. While studies conducted by foreign researchers have reported that intensive green roofs reduce temperatures by approximately 4–5°C, the modeled indicators under local hot climatic conditions showed slightly higher reductions of about 6–7°C. This situation can be explained by the broader potential effectiveness of green roofs in dry and hot climates such as those of Central Asia, where the influence of shading and evapotranspiration processes becomes stronger due to larger temperature amplitudes.

However, this study also identified certain limitations in the implementation of green roofs. First, introducing green roofs—particularly intensive types—onto existing older residential buildings presents major engineering and technical challenges. Their load-bearing capacity is generally not designed to support the weight of heavy wet soil and trees. Second, under dry climatic conditions, ensuring continuous irrigation and maintenance of vegetation requires considerable economic expenditure. Therefore, without integrating autonomous closed-loop irrigation systems that utilize rainwater harvesting and greywater recycling, the large-scale implementation of green roofs cannot provide sustainable results. In addition, because wind loads become significantly stronger at higher elevations, ensuring the aerodynamic safety of vegetation and landscape elements on tall buildings requires designers to develop more complex compositional solutions.

CONCLUSION

Based on this scientific research aimed at evaluating the ecological efficiency of implementing green roofs in residential areas, a number of important conclusions were formulated. In modern architecture, green roofs are not merely decorative elements, but active spatial-engineering systems that stabilize the urban microclimate, improve the energy efficiency of buildings, and provide a high level of thermal and visual comfort for residents. As identified during the study, the optimal vegetation coverage ratio is around 75 percent, at which point air temperature decreases by approximately 6–7°C and thermal comfort reaches its peak level. This pattern serves as a fundamental criterion in architectural design for functional zoning, plant selection, and structural load calculations.

Based on the research findings, the following practical recommendations are proposed for urban planning and architectural practice. During the design stage of newly constructed multi-story residential buildings, it is advisable to introduce a mandatory ecological standard requiring that at least 50–70 percent of rooftop areas consist of green spaces. In order to conserve water resources, extensive green roof systems should primarily utilize local drought-resistant (xerophytic) plant species adapted to dry climatic conditions. Recreational zones on green roofs should be designed as ergonomic environments equipped with safety parapets and additional sun-shading canopies, arranged according to residents' movement scenarios and usage patterns.

Future research directions should focus on investigating the economic and ecological efficiency of combining green roofs with various roofing materials, such as high-albedo "white roofs," as well as solar panel systems (biosolar roofs). In addition, developing methods for reconstructing the roofs of existing panel apartment buildings through the use of modern lightweight modular green systems remains one of the pressing challenges facing architectural science.

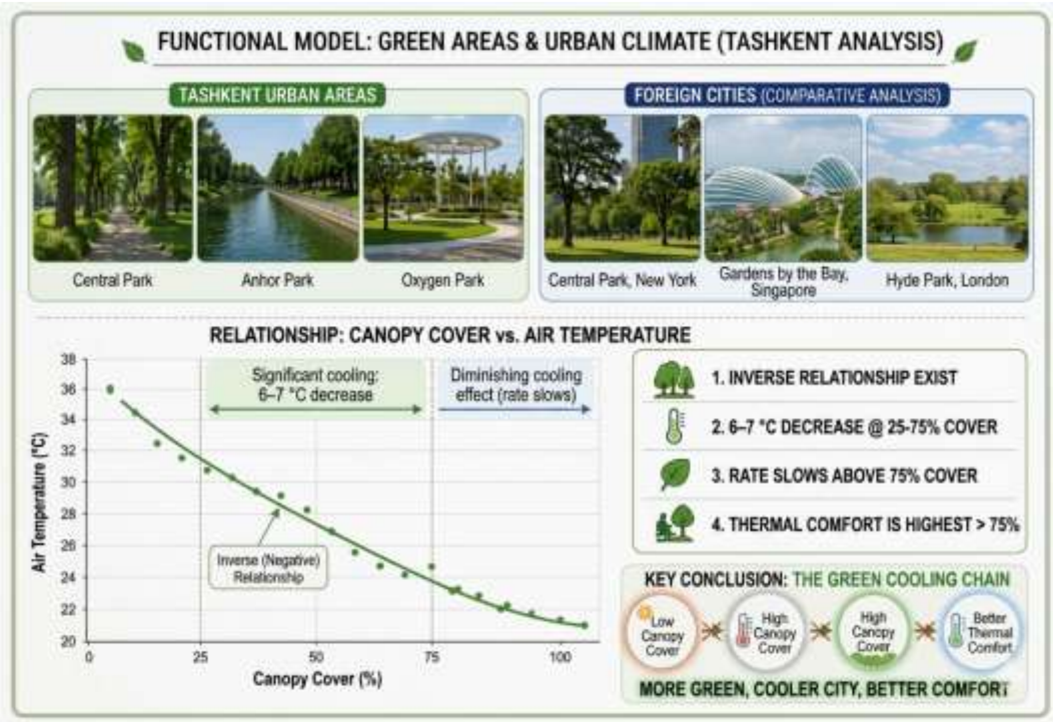

Figure 4 — Functional model: "More green – cooler city – better comfort"

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