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ROOFTOP GREENING TECHNOLOGY FOR BUILDINGS AND STRUCTURES: RESEARCH FINDINGS UNDER UZBEKISTAN CONDITIONS

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ABSTRACT. *This article presents the preliminary research findings on rooftop greening technologies for buildings and structures under the sharply continental climatic conditions of the Republic of Uzbekistan. Experimental sites were established based on extensive and semi-intensive green roof systems. The study analyzed the criteria for selecting experimental sites, the composition of lightweight substrates, and the comparative efficiency of different drainage materials.*

Optimal physical and agroecological properties of the substrate were determined, including a bulk density of 1,100-1,400 kg/m³, pH of 5.5-7.5, and an organic-to-mineral component ratio of 20-30%:70-80%. In addition, the water permeability of various drainage materials and their effects on structural load were evaluated. The findings have practical significance for the design of green roof systems adapted to local climatic and structural conditions.

Keywords: *green roof, greening, substrate, drainage system, environmental efficiency, energy efficiency, BIM, urbanization.*

ANNOTATSIYA*. Maqolada O‘zbekiston Respublikasining keskin kontinental iqlim sharoitida binolar va inshootlar tom qismini ko‘kalamzorlashtirish texnologiyasining dastlabki tadqiqot natijalari keltirilgan. Tajriba maydonlari ekstensiv va yarim intensiv yashil tom tizimlari asosida shakllantirilib, tajriba obyektlarini tanlash mezonlari, yengil vaznli substrat tarkibi hamda drenaj materiallarining qiyosiy samaradorligi tahlil qilingan. Substratning optimal fizik-agroekologik ko‘rsatkichlari (hajmiy zichlik 1100-1400 kg/m³, pH 5,5-7,5, organik/mineral komponentlar nisbati 20-30%:70-80%) aniqlangan, shuningdek turli drenaj materiallarining suv o‘tkazuvchanligi va konstruktiv yuklamaga ta’siri baholangan. Natijalar mahalliy sharoitga mos yashil tom tizimlarini loyihalashda amaliy ahamiyatga ega.*

Kalit so‘zlar: *yashil tom, ko‘kalamzorlashtirish, substrat, drenaj tizimi, ekologik samaradorlik, energiya samaradorligi, BIM, urbanizatsiya.*

INTRODUCTION

Today, urbanization is a continuing global trend, and by 2050, approximately 68% of the world's population is expected to live in urban areas. Between the 1970s and the 2000s, urban areas expanded by approximately 58,000 km², while this figure is projected to reach nearly 1.5 million km² by 2030. The rapid expansion and densification of cities have resulted in the loss of available vegetated areas for the construction of buildings, roads, and other infrastructure. Consequently, surface permeability has declined as natural surfaces have increasingly been replaced by impervious materials such as concrete and asphalt.

These changes adversely affect the urban climate, soil conditions, water resources, biodiversity, and human well-being. In response, cities are increasingly adopting green infrastructure and policy mechanisms to mitigate the adverse effects of urbanization and climate change. Building greening can generally be divided into two main categories: rooftop greening and vertical greening. Green roof systems typically comprise a growing medium, waterproofing layers, drainage systems, and vegetation layers.

Under the conditions of Uzbekistan, urban ecology and the expansion of green spaces are also becoming increasingly important. In recent years, a number of presidential decrees and resolutions aimed at improving urban greening, increasing energy efficiency, and ensuring environmental sustainability have been adopted in the country. These include the Strategy for the Socio-Economic Development of the Republic of Uzbekistan until 2030 and the regulatory document SHNQ 2.03.10-24, Roofs and Roof Coverings, which contains a dedicated section on green roofs. The latter was approved in early 2025 and entered into force on February 3, 2025, establishing requirements for the design, construction, and technical regulation of green roof systems.

Nevertheless, the concept of greening buildings and structures under the specific conditions of Uzbekistan remains insufficiently studied from a scientific perspective. Developing optimized greening strategies that account for local climatic conditions, plant species, substrate layers, and technological solutions represents an important scientific and practical challenge. Such research is essential for developing green roof systems that are both environmentally sustainable and technically suitable for the climatic and structural conditions of Uzbekistan.

STATE OF RESEARCH ON THE PROBLEM

Urbanization and the rapid expansion of urban areas are among the most extensively studied global issues, with numerous studies confirming their impacts on biodiversity, climate change, and human well-being (Seto et al., 2011; Grimm et al., 2008; IPCC, 2023). Urban green infrastructure, particularly green roofs, has been

widely investigated from both ecological and technical perspectives. Green roofs provide multiple ecosystem and building-related functions, including stormwater retention, building insulation, thermal regulation, and biodiversity enhancement (Oberndorfer et al., 2007; Perivoliotis et al., 2023; Wang et al., 2022).

Mentens et al. (2006) evaluated the hydrological performance of green roofs based on empirical observations and found that green roof systems can retain approximately 50–80% of precipitation. Berardi et al. (2014) demonstrated the role of green roofs in reducing cooling demand during summer and limiting heat loss during winter. Santamouris (2014) identified green roofs as an effective strategy for mitigating the urban heat island effect.

In a study by Qun Yu and Jiaqi Guo (2025), BIM technology was employed to conduct a multidimensional assessment of the outdoor environment of existing residential areas and to develop low-carbon renovation strategies. The results indicated that vegetation coverage could be increased to 57%, while building energy consumption and carbon emissions could be reduced by 28% and 35%, respectively. Abu Qadourah (2024) demonstrated that extensive green roof technology under Mediterranean climatic conditions could reduce a building's annual energy consumption by up to 12%. Abdalazeem et al. (2024) reported that, under hot semi-desert climatic conditions, optimization of green roof parameters reduced maximum indoor air temperature by approximately 7.8–10.75%.

Within the Russian scientific literature, Kireeva and co-authors have developed classifications and typologies of green roofs, while Benuzh and Mochalov demonstrated the potential for integrating green roof technologies into renovation processes in Moscow. However, research in Uzbekistan, Kazakhstan, and Belarus has largely remained at the level of general conceptual recommendations, while empirical field-based studies remain limited.

Therefore, the development of an empirically validated green roof model adapted to local climatic and structural conditions represents an important and distinctive scientific research priority. Such an approach can provide a scientific basis for selecting appropriate plant species, substrate compositions, drainage systems, and technological solutions for the implementation of green roofs under the specific environmental conditions of Uzbekistan.

RESEARCH METHODS AND STUDY CONDITIONS

The study aimed to comprehensively evaluate the environmental, microclimatic, and energy-efficiency performance of rooftop greening systems for buildings under the climatic conditions of Uzbekistan. The research was conducted using an integrated methodological framework combining field experiments, laboratory analyses, digital modeling, and economic-statistical approaches.

The study sites were selected with consideration of the dry continental climate of Uzbekistan. Rooftops of residential and public buildings were selected as experimental sites, and their structural characteristics, including load-bearing capacity, roof slope, and waterproofing condition, were assessed in accordance with applicable construction and regulatory standards. Green roof systems were designed as extensive systems with a substrate depth of 8–15 cm and semi-intensive systems with a substrate depth of 15–30 cm. Experimental plots were established using a randomized design, with each treatment replicated at least three times (Gomez & Gomez, 1984).

The drainage system was constructed as a multilayer assembly consisting of a waterproofing layer, drainage layer, filter layer, and growing substrate. Stormwater retention efficiency was determined using the gravimetric method and calculated according to the following equation:

$$R = (P - Q) / P \times 100\%$$

where R is the stormwater retention rate (%), P is the total precipitation amount (mm), and Q is the volume of water discharged through the drainage system (mm).

In selecting the plant assortment, priority was given to species adapted to local climatic conditions and tolerant of drought and high temperatures. Phenological observations were conducted according to the methodology of I.N. Beydeman (1974, 2008). During 2026–2028, the phenological phases, duration of the growing season, and seasonal changes of selected tree and shrub species were monitored. The ornamental characteristics of landscape plants were evaluated according to the Shtonda methodology.

The substrate consisted of mineral and organic components, including perlite, vermiculite, sand, and compost. Its physicochemical properties, including bulk density, water-holding capacity, and pH, were determined under laboratory conditions. The water-holding capacity of the substrate was calculated using the following equation:

$$W = (M_1 - M_0) / M_0 \times 100\%$$

where W is the water-holding capacity (%), M_1 is the mass of the substrate in the wet state, and M_0 is the mass of the substrate in the dry state.

The thermal performance of the green roofs was assessed using both experimental and computational methods. Temperatures at the roof surface and within the underlying interior space were continuously monitored using dedicated sensors. Heat flux was estimated using the equation:

$$Q = \Delta T / R$$

where Q is the heat flux (W/m^2), ΔT is the temperature difference between the interior and exterior environments (°C), and R is the thermal resistance of the roof assembly ($m^2 \cdot K/W$).

Three-dimensional parametric modeling of the roof and surrounding area was performed using Building Information Modeling (BIM). In addition, computational simulations of wind flow, thermal conditions, acoustic environment, and solar radiation were conducted using CFD and SVE approaches following the methodology proposed by Qun Yu. The economic efficiency of the green roof systems was evaluated using life-cycle cost (LCC) analysis and the payback period, calculated as:

Payback Period = I / S

where I is the initial investment cost, and S is the annual economic benefit.

The integrated methodological framework enabled simultaneous assessment of the ecological, hydrological, thermal, microclimatic, and economic performance of green roof systems and provided a basis for identifying technically and environmentally appropriate rooftop greening solutions for the conditions of Uzbekistan.

RESULTS AND DISCUSSION

Selection of Experimental Sites and Establishment of Experimental Plots

The results of the study conducted under the sharply continental climatic conditions of the Republic of Uzbekistan enabled the identification of suitable sites and optimal parameters for the implementation of green roof systems. The analysis demonstrated that the most suitable buildings for effective green roof installation are those with flat roofs having a slope of 0–5°, adequate load-bearing capacity, and full exposure to solar radiation. It was also found that installation costs can be substantially reduced on roofs with well-maintained waterproofing systems, whereas additional structural protection measures are required in areas exposed to high wind loads.

For extensive green roofs, a substrate depth of 8–12 cm was established as optimal. This depth was sufficient to support low-maintenance, drought-tolerant vegetation, predominantly Sedum species. For semi-intensive systems, the substrate depth was maintained within the range of 15–20 cm, which provided more favorable conditions for root-system development, greater biomass accumulation, and improved aesthetic quality of the green roof area.

During periods of intensive spring precipitation, the drainage and filter layers effectively removed excess water into the building's stormwater drainage system, while the substrate layer retained sufficient moisture for plant growth. Monitoring conducted in early summer showed that substrate moisture and temperature fluctuated considerably less than the corresponding external environmental conditions. This contributed to a plant survival rate exceeding 90%. Plant growth performance was higher in the semi-intensive systems than in the extensive systems.

The first-year results demonstrated that both extensive and semi-intensive green roof systems can be successfully established under the climatic conditions of

Uzbekistan. Extensive systems were characterized by lower installation and maintenance costs and greater operational simplicity, whereas semi-intensive systems demonstrated higher aesthetic and ecological performance.

Composition and Properties of Lightweight Substrate Layers

Analysis of the substrate system showed that maintaining a bulk density within the range of 1,100–1,400 kg/m³ minimized the structural load imposed on the roof while providing an optimal balance between water retention and root-zone aeration (Table 1).

Table 1. Optimal Parameters of the Physical and Agroecological Properties of the Substrate

Parameter	Optimal value
Bulk density	1,100–1,400 kg/m³
Water-holding capacity	High (stable capillary moisture retention)
Air permeability	Moderate to high
pH	5.5–7.5

The organic-to-mineral component ratio within the range of 20–30%:70–80% provided a balanced combination of the substrate's hydro-physical properties, ensuring a stable relationship between capillary moisture retention and the removal of excess water through gravitational drainage. The use of locally available materials, including expanded clay (LECA), perlite, and volcanic rock, not only improved the environmental safety and economic efficiency of the substrate but also enhanced its structural stability (Table 2).

Table 2. Optimal Composition and Physical Properties of the Substrate for Rooftop Greening

No.	Substrate component	Proportion (%)	Primary function	Effect on physical properties
1	Organic compost	20–30	Nutrient source for plants	Increases water-holding capacity
2	Expanded clay (LECA)	30–40	Formation of a lightweight structure	Reduces bulk density
3	Perlite	10–20	Maintaining aeration and moisture balance	Improves air permeability
4	Volcanic rock	10–20	Mineral stability and drainage	Increases mechanical strength
5	Sand (optional additive)	5–10	Structural stabilization	Regulates water flow

Observations demonstrated that a substrate depth of 8–12 cm for extensive systems and 15–20 cm for semi-intensive systems represents the most suitable range

under the climatic conditions of Uzbekistan. These substrate depths provide favorable conditions for normal plant development, adequate moisture storage, and improved resistance of the rooftop system to temperature fluctuations during hot summer days.

Results and Analysis of Drainage Material Selection

The experimental results confirmed that the drainage layer is one of the key components responsible for regulating the water regime of the entire green roof system. A comparative assessment of four drainage materials tested on the experimental plots-gravel, expanded clay (LECA), geocomposite drainage mats, and volcanic rock-enabled the identification of their respective advantages and limitations (Table 3).

Table 3. Comparative Analysis of Drainage Materials Used in Green Roof Systems

No.	Drainage material	Bulk density	Water permeability	Advantages	Disadvantages
1	Granular gravel	High (heavy)	Moderate to high	High stability, low cost, long service life	High weight; increases roof load
2	Expanded clay (LECA)	Low to moderate	High	Lightweight, good drainage, thermal insulation properties	Relatively low mechanical strength
3	Geocomposite drainage mats	Very low	Very high	Very lightweight, high hydraulic efficiency, rapid installation	Higher cost; dependence on imported materials
4	Volcanic rock	Moderate	Moderate	Natural material, stable, durable	Moderate weight; difficult to process

Although geocomposite drainage systems demonstrated the highest hydraulic performance during the trials, expanded clay (LECA) was identified as a balanced option in terms of both economic and environmental considerations. Comparative analyses indicated that the hydraulic conductivity coefficient of the drainage layer should be at least $\geq 10^{-3}$ m/s. This value served as an important technical criterion for rapidly removing excess water into the building's stormwater drainage system during periods of intense spring precipitation and for preventing water accumulation within the root-zone layer.

Granular materials such as gravel and expanded clay demonstrated reliable performance as conventional drainage solutions due to their mechanical stability and

natural properties. However, their relatively high density may impose additional static loads on the roof structure, which partially limits their application in older buildings or structures with restricted load-bearing capacity. Geocomposite drainage mats, in contrast, were distinguished by their low weight, high water permeability, and ease of installation. These characteristics are particularly advantageous for extensive green roof systems with shallow substrate layers, where they can substantially reduce the additional structural load imposed on the building.

During the observations, it was found that the drainage system could temporarily retain approximately 50–65% of precipitation and subsequently redistribute a portion of the retained water back into the substrate layer. This finding demonstrates that green roofs function not only as building components but also as an important element of urban stormwater management systems.

The main limitations and constraints identified during the study were as follows. Conventional drainage layers based on gravel and expanded clay impose additional loads on roof structures due to their relatively high self-weight. Expanded clay materials may undergo partial compaction and fragmentation when exposed to prolonged moisture and sustained mechanical pressure. Although geocomposite materials provide high hydraulic efficiency, their relatively high cost and dependence on imported products remain important limitations in the local market.

Based on these findings, the principles of “lightweightness–hydraulic conductivity–structural stability” were established as the primary optimization criteria. From a practical perspective, the combined use of expanded clay (LECA) and geocomposite drainage materials is recommended as the most appropriate solution, providing a balance between low structural load, effective water management, and adequate system stability.

CONCLUSIONS

Based on the preliminary research findings, the following conclusions were drawn:

Under the sharply continental climatic conditions of Uzbekistan, buildings with flat roofs having a slope of 0–5°, high load-bearing capacity, and good waterproofing are the most suitable sites for the implementation of green roof systems.

Both extensive green roof systems with a substrate depth of 8–12 cm and semi-intensive systems with a substrate depth of 15–20 cm can be successfully implemented under local conditions. The plant survival rate exceeded 90% in both systems.

A lightweight substrate with a bulk density of 1,100–1,400 kg/m³, pH of 5.5–7.5, and an organic-to-mineral component ratio of 20–30%:70–80% provides an appropriate water–air regime for normal plant development while reducing the static load imposed on the roof structure.

Among the drainage materials evaluated, the combined use of expanded clay (LECA) and geocomposite drainage mats is recommended as the most balanced solution in terms of weight, hydraulic performance, and economic feasibility. The drainage system demonstrated the capacity to temporarily retain 50–65% of precipitation.

The findings provide a scientific basis for the design and implementation of green roof technologies under the climatic and structural conditions of Uzbekistan. In the next stages of the research, further investigations will focus on the effects of green roofs on building thermal performance and energy consumption, digital modeling based on Building Information Modeling (BIM) technology, and comprehensive assessments of their economic and environmental efficiency.

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