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GREEN ROOFS AS A TOOL OF SUSTAINABLE DEVELOPMENT: ANALYSIS OF THE EXPERIENCE OF UKRAINE AND THE WORLD

Abstract. *The purpose of this article is to analyze international and Ukrainian experiences in the implementation of green roofs in construction, to highlight their environmental, economic, and social benefits, and to identify the prospects for integrating these technologies into contemporary urban environments. Special attention was given to the study of the impact of green roofs on improving the microclimate, reducing* CO_2 *emissions and increasing the energy efficiency of buildings, as well as evaluating the possibilities of adapting international practices in Ukraine.* ***Research methods.*** *This study employs the method of systems analysis, which helps to evaluate the impact of green roofs on the energy efficiency of buildings, the ecological status of cities and the comfort of the urban environment, and the empirical method, which is based on the observation or data analysis on the impact of green roofs for microclimate, conservation of water resources and building operational characteristics.* ***Research results.*** *The article highlights the key characteristics of green roofs as an element of ecological architecture that contributes to improving building energy efficiency, enhancing the urban microclimate, and reducing environmental impact. Architectural and planning solutions that can be applied to further the development of the sustainable urban planning concept are also summarized.* ***Conclusions***. *Green roofs are an effective tool for increasing energy efficiency of buildings, reducing the burden on urban infrastructure, and improving the environmental condition of cities. They help retain rainwater, protect the roof, and provide thermal and sound insulation. Both global and Ukrainian experience proves that their use is appropriate both in private and commercial construction, and advancements in technology allow for their adaptation to various climatic conditions and architectural contexts.*
Key words: *architecture, greening, green roofs, ecology, energy efficiency, urban infrastructure, sustainability, extensive green roofs, intensive green roofs.*

ЗЕЛЕНІ ДАХИ ЯК ІНСТРУМЕНТ СТАЛОГО РОЗВИТКУ: АНАЛІЗ ДОСВІДУ УКРАЇНИ ТА СВІТУ

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***Анотація. Метою** цієї **статті** є аналіз міжнародного та українського досвіду застосування зелених покрівель у будівництві, висвітлення їхніх екологічних, економічних та соціальних переваг, а також визначення перспектив впровадження цих технологій у сучасних міських умовах. Особливу увагу приділено дослідженню впливу зелених дахів на покращення мікроклімату, зменшення викидів CO_2 та підвищення енергоефективності будівель, а також оцінено можливості адаптації міжнародних практик в Україні. **Методи дослідження.** Нами використано метод системного аналізу, що допомагає оцінити вплив зелених дахів на енергоефективність будівель, екологічний стан міст і комфортність міського середовища та емпіричний метод, який базується на спостереженні або аналізі даних щодо впливу зелених дахів на мікроклімат, збереження водних ресурсів та експлуатаційні характеристики будівель. **Результати дослідження.** У статті висвітлені ключові характеристики зелених дахів як елемента екологічної архітектури, що сприяє підвищенню енергоефективності будівель, покращенню міського мікроклімату та зменшенню екологічного навантаження. Також узагальнено архітектурно-планувальні рішення, які можуть бути використані для подальшого розвитку концепції сталого містобудування. **Висновки**. Зелені дахи є ефективним інструментом підвищення енергоефективності будівель, зменшення навантаження на міську інфраструктуру та покращення екологічного стану міст. Вони сприяють утриманню дощової води, захищають покрівлю, забезпечують тепло- та звукоізоляцію. Світовий та український досвід засвідчує, що їхнє використання є доцільним як у приватному, так і в комерційному будівництві, а розвиток технологій дає змогу адаптувати їх до різних кліматичних умов та архітектурних контекстів.*
***Ключові слова:** архітектура, озеленення, зелені дахи, екологія, енергоефективність, міська інфраструктура, сталий розвиток, екстенсивна покрівля, інтенсивна покрівля.*

Statement of the problem. In modern megacities, the majority of the development consists of high-rise buildings that consume major amounts of electricity and cause significant emissions of CO_2 into the atmosphere. Due to the insufficient amount of vegetation in large cities, the concentration of carbon emissions often exceeds permissible environmental standards. Dense urban development limits the possibilities for placing green spaces on streets, making it reasonable to consider alternative solutions, particularly green roof landscaping. The implementation of green roof systems would contribute to improving the urban microclimate, increasing green area coverage, and reducing greenhouse gas emissions.

Analysis of Recent Research and Publications. The integration of green roofs in contemporary architecture has emerged as a crucial aspect of sustainable urban development, garnering considerable attention from both international and Ukrainian scholars. In international scientific literature, this subject is comprehensively explored in «Green Roof Systems: A Guide to the Planning, Design and Construction of Landscapes Over Structure» by Susan K. Weiler and Katrin Scholz-Barth [1], which analyzes the ecological, economic, and social benefits of such systems, as well as their contribution to combating climate change. Roger Chen, in his book «Green Architecture» [2], explores the practical aspects of implementing green roofs, providing examples of completed projects in various countries. Francis D. K. Ching and Ian M. Shapiro, in their book «Green Building Illustrated» [3], focus on the technical aspects, discussing both the advantages and potential disadvantages of green roofs, as well as the key elements of their design.

Analysis of International Experience demonstrates that the leading countries in the implementation of green roofs are Germany, Switzerland, Canada, Singapore, and Japan. For instance, in Germany, since the 1980s, government support

programmes have been in place to incentivise building owners to install eco-friendly roofs. In Singapore, green infrastructure is an integral part of the «City in a Garden» strategy, which promotes the active greening of roofs and fa3ades. In Canada, specifically in the city of Toronto, a special programme called the Green Roof Bylaw [4] mandates that developers incorporate green roofs into the design of new buildings.

Among Ukrainian authors, the issue of green roof implementation is addressed by O. Filonenko, Y. Avramenko, and V. Kidenko in their article «Green Roofs – Historical Experience and Modern Requirements» [5], which examines the historical development and evolution of the green roof concept. L. Hnatiuk and I. Nesteruk, in their article «Green Roofs in Modern Urban Landscaping» [6], analyse the potential for implementing such systems in densely built-up cities of Ukraine, particularly their impact on reducing high temperatures in such cities, improving environmental conditions, and enhancing the energy efficiency of buildings.

Despite the presence of individual projects, the Ukrainian experience currently lacks a systematic approach to the implementation of green roofs at the state level. In Ukraine, green roofs are more frequently encountered in commercial and premium residential construction, whereas in many European countries, they are standard practice even in low cost projects. However, considering international precedents, the introduction of government support programs, fiscal incentives, and ecological regulations could significantly galvanize the development of this sector in Ukraine.

Contemporary research also focuses on cutting-edge technologies for the creation of green roofs, such as the utilization of hydroponic systems, specialized substrates, intelligent irrigation systems, and the implementation of rainwater harvesting technologies. These approaches not only mitigate CO_2 emissions but also enhance the quality of life for urban dwellers, fostering a more comfortable and ecologically sound environment.

Exposition of the Main Material. Green roofs are building rooftops that are partially or entirely vegetated. In English, the term «green roofs» is used, reflecting the overarching trend of associating the color green with ecological initiatives. It is crucial to note that simply placing plants in pots, even if situated on a roof, does not constitute a fully-fledged green roof [7].

From a historical perspective, green roofs have ancient origins. In ancient Scandinavia, most buildings had roofs covered with soil and vegetation. Similar dwellings were found in Eastern European countries, where a roof with a layer of soil helped retain warmth in winter and provided protection from heat in summer [5]. These very principles laid the groundwork for modern green roof construction, which, in addition to thermal insulation properties, has acquired ecological and economic significance.

The widespread adoption of flat green roofs began in the late 19th and early 20th centuries. This process was significantly accelerated with the advent of reinforced concrete structures, which enabled the creation of more robust foundations for roof greening. Prominent examples of architectural edifices with green roofs include projects by Le Corbusier and Frank Lloyd Wright, who viewed such roofs as an integral component of the harmonious integration of architecture and nature.

Structure of Green Roofs. Contemporary technology for the creation of green roofs involves a multi-layered construction that ensures their efficiency and longevity. **Chart 1.** It illustrates the fundamental layers of a green roof, which include:

– *the structural base of the roof* (slab);

– *a thermal insulation layer* for maintaining the building's energy efficiency;

– *a waterproofing layer* that prevents water leakage;

– *an anti-root barrier* that impedes root penetration into the structure;

– *a drainage layer* that ensures the removal of excess water;

– *a filtering membrane* that retains soil but allows water to permeate into the drainage;

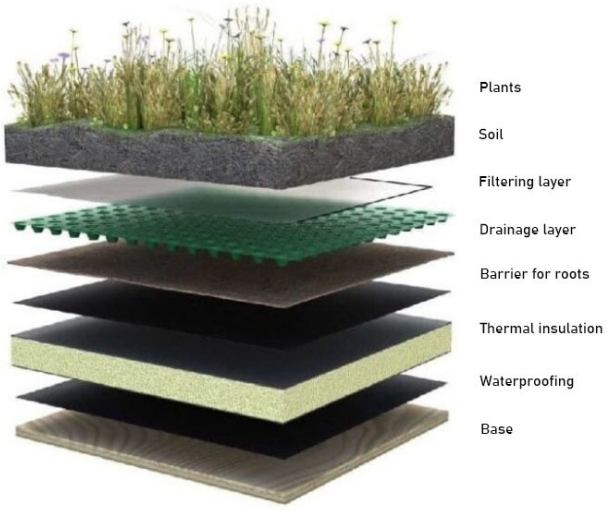

Chart 1. Scheme of the layers of a typical green roof. [8]

– *a soil substrate*, chosen in accordance with the type of vegetation;

– *a plant cover* that fulfils decorative, ecological, and insulation functions.

Key Advantages of Green Roofs. The application of green roofs offers a range of ecological, economic, and technical benefits:

– *reduced strain on sewage systems* (green roofs absorb rainwater, mitigating the risk of flooding and overloading storm drains);

– *improved rainwater quality* (natural filtration through soil layers reduces wastewater contamination);

– *enhanced energy efficiency* (due to thermal insulation properties, green roofs decrease heating costs in winter and air conditioning costs in summer);

– *sound insulation* (the plant layer absorbs noise, which is particularly relevant in metropolises);

– *roof protection* (a green roof prolongs the lifespan of the structure by shielding it from ultraviolet radiation, temperature fluctuations, and mechanical damage).

Types of Green Roofs. In global practice, two primary types of roof greening are distinguished: *extensive* and *intensive*. *Extensive greening* involves simpler roofs that require minimal maintenance. They serve protective and ecological functions, improving the building's thermal insulation. This type utilises undemanding plants, such as sedums, mosses, and grasses. Maintenance is kept to a minimum – it is sufficient to inspect the covering 1–2 times a year [7]. The Italian company MPM – Materiali Protettivi Milano, which specialises in the development of waterproofing, offers two types of liquid membranes for the Ukrainian consumer that can facilitate the placement of extensive greening on a concrete roof and a roof covered with a bituminous membrane [9]. In such cases, the roof layers are reduced to just 3–4: the roof base, a damp surface (for a concrete roof), a specific primer, and a liquid waterproofing membrane, onto which a thin layer of soil with turf is placed.

Chart 2. It illustrates one of the options for arranging an extensive roof. On the roof slab a waterproofing membrane is placed followed by insulation with a drainage system, and on top of that, a layer of soil for planting vegetation.

The Environmental Protection Agency Region 8 Headquarters Building in Denver, USA, serves as a representative example of the implementation of extensive green roofs worldwide. The project was designed by the architectural firm ZGF Architects and was completed in 2006 (fig. 1).

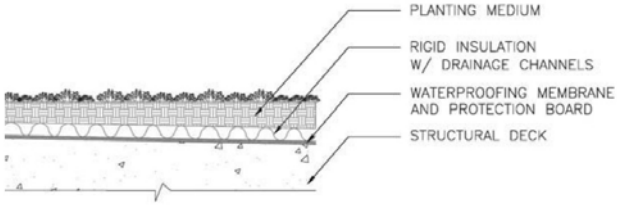

Chart 2. Insulation over the structural deck and waterproofing membrane with living green roof. [1, p. 156]

This is a twelve-storey building that is equipped with an extensive green roof, which is predominantly planted with mosses and perennial herbaceous plants. The roof structure allows collection and retention of up to 80% of rainwater, significantly reducing the load on the city's sewage system and providing substantial water resource savings.

Furthermore, a recreational area has been established on the roof, open to the public, creating a comfortable space for relaxation away from urban noise and air pollution [10]. Such green roofs are a common solution in the USA and are used in numerous buildings, including Cuyahoga County HQ (Ohio), Corporate HQ (Illinois), and Milwaukee Housing Authority (Wisconsin).

Another strong example of the implementation of extensive green roofs is The Green District in Stuttgart, Germany was designed by GENO-Haus and was completed in 1969 (fig. 2).

The green district in Stuttgart, Germany, was designed as an ecological response to the adverse effects of the neighbouring industrial area. The initiative to implement green roofs was spearheaded by GENO-Haus, which has been actively realising the concept of a sustainable urban environment since 1969.

Almost all the buildings in the district are equipped with *extensive green roofs*, planted with mosses, lichens, perennial herbaceous and grass plants. As a result, these roofs are *capable of accumulating up to 70% of rainwater*, gradually distributing it into the city's system, which significantly reduces the load on the drainage system.

In addition to water regulation, the green plantings prevent buildings from overheating in the summer, which helps reduce air conditioning costs and create a more comfortable urban microclimate. The successful implementation of this project has made Stuttgart one of the pioneers in the use of green roofs in urban planning [11].

Intensive roof greening involves complex, multifunctional roofs that can include landscape elements: lawns, bushes, trees, ponds, terraces, and pathways. They require a more robust structure

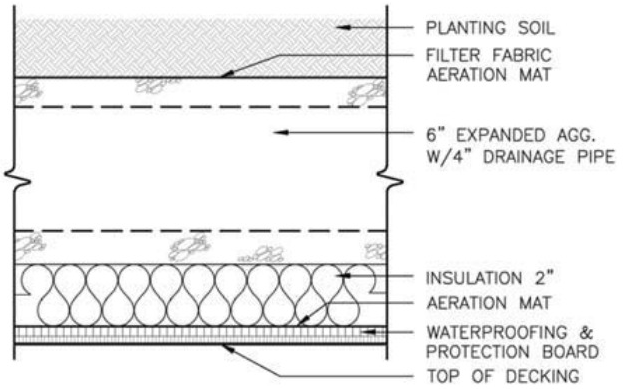

Chart 3. Green roof with drainage pipe in lightweight expanded drainage aggregate. [1, p. 159]

Fig. 1. The Environmental Protection Agency Region 8 Headquarters Building. Denver, USA. [2, p. 110]

and regular maintenance, similar to the upkeep of traditional gardens [7]. Roofs with intensive greening necessitate a thicker layer of soil and, consequently, a stronger structure. This type of green roof must be incorporated into the project and calculated in advance.

Chart 3. It illustrates an option for arranging an intensive roof with the application of a drainage pipe. On the roof slab, a waterproofing protective board is placed, followed by an aeration mat, 5 *cm* of insulation, a 15 *cm* layer of filler in which a 10 *cm* diameter drainage pipe is located, on top of which is an aeration mat and filter fabric, and on these is placed a layer of soil for planting vegetation.

One of the global examples of intensive green roof implementation is the Business Centre in Shenzhen, China. Designed by ZHUBO DESIGN, the building was completed in 2013 and comprises 25 storeys (fig. 3).

This contemporary 25-storey building is located in a densely built-up area of the city. Thanks to its architectural concept, it compensates for the lack of green spaces within the quarter.

The project includes access to green terraces on almost every floor, creating a comfortable space for office workers to relax. The cascading arrangement of greenery positively impacts the aesthetics of the district, making the building visually integrated into the urban environment.

This project utilises an *intensive green roof*, which involves planting not only herbaceous plants but also trees and shrubs. The most suitable species for such roofs are *juniper, ferns, ornamental grasses, apple trees, heather, quince, lilac, and conifers,* which ensure the stability of the landscape solution and a harmonious appearance throughout the year [13].

An example of green roof implementation in Ukraine is the White Lines Residential Complex

Fig. 2. Green District in Stuttgart. Germany. [12]

Fig. 3. Business Centre in Shenzhen. China. [14]

Fig. 4. Visualisation from the «White Lines» Residential Complex project. Kyiv [15]

in Kyiv. Designed by ARCHIMATIKA, the construction of the complex began in 2021 (fig. 4).

Three 24-storey residential buildings are connected by a stylobate section, which is three storeys high. It houses a shopping centre, which is separated from the residential premises. An *intensive green roof* is arranged on the roof of the stylobate section. It also features a children's playground, sports fields, and benches for residents to relax. The landscaping incorporates lawn grass, ornamental grasses, deciduous trees, and shrubs. The total area of the park on the roof is 1 hectare [15].

The green roof provides shelter for visitors from the scorching sun in summer and, due to natural thermal insulation, *reduces excessive heating and cooling of the stylobate building* and adjacent residential buildings. This allows for a reduction in the use of air conditioners in summer and heating in winter, decreases electricity consumption, and restores the ecological balance of the urban space.

Conclusions and prospects for utilising research results. Green roofs are an integral element of sustainable urban development, combining aesthetics, energy efficiency, and ecological functionality. An analysis of international and Ukrainian experience demonstrates their ability to reduce thermal load, improve microclimate, and optimise water drainage.

Global examples, particularly in the USA, Germany, and China, showcase the effectiveness of extensive and intensive roof greening. In Ukraine, this practice is only gaining momentum, but successful implementations, such as the «White Lines» and «UNIT.City» residential complexes, confirm its architectural and functional suitability.

The development of green roofs in the urban environment is an important step towards creating a harmonious space that meets modern requirements for environmental friendliness and comfort.

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