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Sustainable Construction in post-industrial Ursus district in Warsaw: Biologically Active Areas on Roofs and Underground Garages

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Abstract

Urbanization leads to the expansion of urban areas and increased population density, which has a negative impact on natural resources, including green spaces. To address these environmental challenges, various green measures and sustainable development practices offer environmental, economic and societal benefits. This article provides an overview of different types of green roofs, discusses their advantages and disadvantages, and outlines current legislation on biologically active areas in new residential developments. A residential project in the Ursus district of Warsaw was used as a case study to compare intensive and extensive green roofs. The project involved the installation of vegetation on the roof of an underground garage and later on the roof of the building, with detailed descriptions of the roof layers and vegetation used. One experiment examined seasonal variations in water runoff from green roofs. Three test sites simulated different seasons, with substrates in containers and vegetation watered twice daily. Results showed that spring, with temperatures around 15°C, provided optimal conditions for green roof establishment, while winter posed challenges due to frost. Both intensive and extensive green roofs have positive environmental, social and economic impacts, supporting the pillars of sustainable development. Examples of global green infrastructure further illustrate these benefits.

Keywords: biologically active area, green roof, intensive, extensive, sustainable construction

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1 Introduction

The expansion of urban populations is leading to an increase in built-up areas, frequently at the cost of green spaces. New housing developments, services and shops are being built. However, market research shows that green spaces within developments make properties more attractive to potential buyers (Kronenberg et al., 2020; García-Lamarca et al., 2022). In Poland, the roofs of apartment buildings in Saska Kepa were covered with sedum mats, which improved the aesthetics of the apartments and increased their price by 200 euros per square meter (Ociepa-Kubicka, 2015). However, legal standards restrict the extent of greenery that can be incorporated into converted land, prompting developers to explore strategies that reconcile extensive development with the incorporation of greenery. Green roofs represent a potential solution to this challenge.

In construction, a ceiling is a horizontal element that supports the roof and provides an upper boundary for the top floor (Gopagani et al., 2022). If a basement extends beyond the perimeter of the building, such as an underground garage, its floor can also be considered a ceiling. The ceiling's primary function is to safely transfer loads and serve as part of the building envelope, protecting against weather, water and temperature changes (Mousavi et al., 2021; Torero, 2022). It must be well insulated for thermal comfort and meet other criteria such as moisture, fire, and sound protection, which is achieved through a multilayered structure (Monczynski, 2017). In addition, the integration of vegetation into the roof can balance development needs with the creation of biologically active areas, merging building functions with green space preservation (Berg et al., 2022; Wang et al., 2023).

Residential construction in Poland is regulated by the Act of July 7, 1994, the Building Law and the Regulation of the Minister of Infrastructure of April 12, 2002 (Kaim and Kruzel, 2022). These regulations define biologically active areas as native soil covered with vegetation and surface water, including 50% of terraces and flat roofs used for lawns or flower beds (Gyurkovich et al., 2024; Michalik-Śnieżek et al., 2024). Multi-family residential lots are required to have at least 25% biologically active area, and single-family residential lots are required to have 30% biologically active area for playgrounds and recreational facilities. The Ursus Community Development Plan requires 25% biologically active area and a maximum lot coverage ratio of 0.4. Underground parking levels must be developed with green space or playgrounds. The ordinance of April 25, 2012, classifies the Ursus facility in the second geotechnical category, which includes structures in simple and complex soil conditions.

Classification of Green Roofs

Green roofs are engineered ecosystems that provide a nature-based solution to several environmental challenges, as highlighted in the comprehensive review of green roof literature (Mihalakakou et al., 2023). They help to conserve energy, reduce air pollution, control runoff, promote biodiversity, and provide aesthetic benefits. The passive cooling potential of green roofs through evapotranspiration has been studied, showing that even green roofs without vegetation can effectively cool buildings, contributing to the reduction of the urban heat island effect and stormwater management (Cascone and Rosso, 2023). In addition, green roofs serve as green stormwater infrastructure by capturing and retaining rainfall for evaporation and transpiration, with considerations for water quality improvement and maintenance practices to ensure their effectiveness and sustainability (Twohig et al., 2022).

Green roofs can be classified by type of insulation, type of vegetation, degree of slope, and whether they are system or non-system. Classic insulated roofs have insulation below the waterproofing layer, providing optimal insulation, but do not support green traffic roofs due to load sensitivity, while inverted roofs have insulation above the waterproofing layer, improving durability and temperature regulation. Extensive roofs, with 6-20 cm substrate layers, support shallow-rooted plants, are cost-effective and require less maintenance, while intensive roofs, with 15-150 cm substrate layers, support larger vegetation and recreational features, but are more costly and require more maintenance (Ociepa-Kubicka, 2015). Roof slopes are classified as flat, sloping, or steep, with steeper slopes requiring stability adjustments to prevent substrate drying from water runoff. System roofs, designed by manufacturers with warranties, include all necessary components and technology but are more expensive, while non-system roofs, designed by contractors using components from various suppliers, are less expensive but less secure (Drozd, 2015).

Advantages and Challenges of Vegetation on Ceilings

Every solution, including green roofs, has both advantages and disadvantages. However, the latter are more numerous. The benefits of green roofs can be considered from a variety of perspectives, including natural, technical, economic and spatial.

The implementation of biologically active surfaces on urban ceilings has the potential to enhance the overall quality of the built environment (Shashwat et al., 2023). Vegetation acts as a filtration system, removing particulate matter, including dust, soot, and smoke, from the atmosphere and depositing it into the soil via precipitation (Vigevani et al., 2023). It has been demonstrated that green roofs have the potential to absorb between 10 and 20% of harmful gases and dust on an annual basis (Kania et al., 2013). A 100 m² roof has the potential to filter up to 18 kg of dust annually, which is equivalent to the emissions of 15 cars (Monczynski, 2018). Furthermore, green roofs influence the water balance and quality (Liu et al., 2021). The capacity for water retention is contingent upon several factors, including the specific type of vegetation, the slope of the roof, the thickness of the substrate, and the intensity of rainfall. The installation of green roofs and other green infrastructure in residential areas has been demonstrated to reduce the risk of flooding and the burden on storm drains (Monczynski, 2018). The phenomenon of capillary pull provides energy to plants, thereby maintaining the integrity of the drainage layer (Drozd, 2015). Moreover, vegetation serves to diminish the concentration of nitrogen and heavy metals in precipitation, thereby capturing pollutants (Kania et al., 2013). The implementation of green roofs has been demonstrated to mitigate the phenomenon of the "urban heat island," which is characterized by elevated temperatures and the formation of smog (Wang and Sodoudi, 2022). The albedo effect, evapotranspiration, and shading contribute to the overall cooling effect of green roofs. However, during the summer months, traditional roofs can reach temperatures of 80 to 100 degrees Celsius (Drozd, 2018). On a summer day, a vegetated roof exhibits a temperature reduction of 19°C relative to a typical roof, with a further 8°C reduction at night. In urban areas, an increase in the biologically active area by 5% has been demonstrated to reduce the average summer temperature by 2.2°C and the concentration of smog by 10% (Kania et al., 2013). The temperature of green roofs can reach 25 to 40°C, which has an impact on the temperature of the rooms situated below them. On average, the temperature declines by 2°C during the day and increases by 0.3°C at night (Maczynski, 2018).

The installation of green roofs has been demonstrated to promote biodiversity in urban areas by creating habitats for animals and plants (Wooster et al., 2022). Birds have been observed soaring as high as the 19th floor, while butterflies have been documented flying up to the 20th floor (Velazquez, 2005; Wang et al., 2022). The return of endangered species of birds, spiders, and other invertebrates in cities has been facilitated by green roofs (Kania et al., 2013).

From a technical and economic standpoint, it is noteworthy that the incorporation of an additional insulation layer enhances the thermal insulation properties of green roofs, thereby reducing the costs associated with heating and air conditioning (Drozd, 2018). A 20-cm layer of soil substrate with a plant cover of 20 to 40 cm has been demonstrated to exhibit thermal insulation properties comparable to those of 15 cm of mineral wool. This finding indicates that heating costs are reduced, and that construction necessitates less heating equipment (Kania et al., 2013).

Green roofs have been demonstrated to reduce energy consumption by 10 to 30 percent in comparison to traditional roofs (Ociepa-Kubicka, 2015; Bevilacqua, 2021). The presence of vegetation on the roof serves to enhance the durability of the insulation materials, thereby protecting them from the effects of mechanical damage and weathering. Furthermore, inverted roof technology safeguards the waterproofing layer from fluctuations in temperature, ultraviolet radiation, and frost (Maczynski, 2018). Most of the waste generated during repairs can be mitigated using durable roofing materials (Kania et al., 2013). Additionally, green roofs are less susceptible to wind-related damage and possess enhanced fire resistance (Hopkins and Goodwin, 2011). A layer of soil substrate has been demonstrated to reduce sound by 40 decibels at a thickness of 12 cm and by 46 decibels at a thickness of 20 cm (Drozd, 2015).

In terms of the social and aesthetic implications of green roofs, they facilitate the maintenance and recuperation of biologically active zones (Zhang and He, 2021). An increasing number of buildings are being constructed in urban areas, with the majority of these developments occurring at the expense of green spaces. Despite the challenges posed by urban expansion, which has led to a reduction in the proportion of biologically active and green areas, it is difficult to envisage a scenario in which this process can be halted. In addition to enhancing the visual appeal of urban areas and expanding the proportion of biologically active zones, green roofs and walls have been shown to have a beneficial impact on residents, reducing the sense of being overwhelmed by the presence of tall buildings (Kania et al., 2013; Manso et al., 2021; Jim et al., 2022). Furthermore, green spaces on rooftops and garage ceilings can also serve as recreational areas (Teotónio et al., 2020).

In addition to the numerous advantages, green roofs present certain challenges (Cristiano et al., 2021; Zhang and He, 2021). Among the challenges associated with green roofs are higher design and construction costs compared to conventional roofs (Teotónio et al., 2020; Teotónio et al., 2021; Scolaro and Ghisi, 2022). The weight of these structures is significantly greater, resulting in higher reinforcement costs (Tokarska & Osyczka, 2011; Scolaro and Ghisi, 2022). Additionally, condensation and water vapor accumulation can impact the effectiveness of thermal insulation. Furthermore, green roofs require more maintenance and effort to maintain optimal condition (Ociepa-Kubicka, 2015; Koroxenidis and Theodosiou, 2021; Zhang and He, 2021).

The objective of this study was to analyze green roof technologies through a comparative analysis of extensive and intensive green roof systems applied in the construction of a residential development in the Ursus district of Warsaw. The research aimed to identify the optimal season for implementing green roofs on buildings. The study included three main areas: (i) Area's past and technical characterization: This section provides an overview of the context in which the post-industrial area under study has developed. This included detailed descriptions of the geological, hydrogeological and geotechnical conditions of the site, providing a thorough understanding of the basic environment for the green roofs; (ii) Project Characteristics: A comprehensive presentation of the project plan was provided, highlighting the biologically active areas and the specific green roof technologies employed. The study detailed the biologically active area on the ceiling above the underground parking garage, which used an intensive green roof system, and the biologically active area on the roof of the multifamily residential building, which used an extensive green roof system. Descriptions included the layer compositions and types of vegetation used. The primary objective was to determine the effect of ambient temperature on the substrate during different seasons and to evaluate the thermal performance and ecological benefits of each green roof type. (iii) Conclusions: The objective is to present existing green roof solutions in different contexts and to establish the substrate as an integral part of green roof construction, thereby enabling its use in a wide range of applications on a global scale.

The results of this study provide valuable insights into the practical application and seasonal performance of green roof technologies in urban residential developments, with implications for optimizing their design and implementation in similar post-industrial environments.

2 Material and methods

Study site description

The Ursus district was known for the Ursus Mechanical Plant, which produced tractors. The plant included a sewage treatment plant, a road, and a production hall with a forge. The wastewater treatment plant and the hall were located on land designated for development (Stępień, 2018). The wastewater treatment plant was in operationl until 2012. In 2015-2016, the above-ground parts of the facilities were dismantled, and in 2017, the foundations, undegraound infrastructure, and paved surfaces were removed, which resulted in the levelling of the site. The production hall was demolished in 2015. Prior to construction, the site underwent a remediation process. The previous vegetation included small-leaved linden, black pine, intermediate hawthorn, and mountain ash.

The construction site was classified as belonging to the second geotechnical category. Prior to construction, a series of geological surveys were conducted, the hydrogeological conditions were determined, and a geotechnical design was prepared. The project area is situated on the Warsaw Plain (Lechnio & Malinowska, 2018). A total of five geotechnical layers were identified within the subsoil of the plot, with a simplified distribution illustrated in Figure 1 (Stępień, 2018).

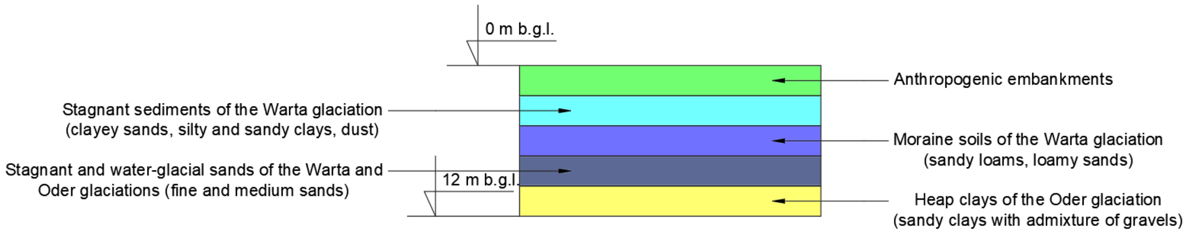

Figure 1. *Simplified layout of geotechnical layers of the discussed site.*

The waters of this level are susceptible to contamination due to the absence of a continuous isolation layer and the historical context of the area. It is anticipated that no contaminants will enter the groundwater during the project or subsequent operation. The dewatering process for the elevator shafts and separator has been completed, resulting in a temporary reduction in the water table using needle filters.

Given the industrial nature of the site, it was necessary to implement measures to control surface pollution. The Ursus plant ceased operations in 2006, and by 2017, the buildings had been demolished. Soil samples were collected in three distinct phases. The sampling periods were July-October 2017, January 2018, and February 2018 (Stępień 2018). In accordance with the development plan, the site is designated for multi-family residential development with accompanying services, categorizing it as Group I in accordance with the Regulation of the Minister of Environment dated September 1, 2016 (Journal of Laws 2016, item 1395).

The potential contaminants include metals and metalloids (e.g., arsenic, barium, chromium, zinc, tin, cadmium, cobalt, copper, molybdenum, nickel, lead, and mercury), gasoline and oils, and aromatic hydrocarbons and polycyclic aromatic hydrocarbons (PAHs). From July to October 2017, six test holes were drilled to a depth of 6.5 meters, and in February 2018, an additional five holes were drilled to a depth of one meter. The samples were then compared with the permissible values for the first group of soils (Stępień, 2018). Samples collected at depths of up to 0.25 meters below ground level exhibited concentrations exceeding the permissible threshold in an area spanning 3165 square meters. Conversely, samples obtained from depths exceeding 0.25 meters demonstrated no instances of exceedance (Stępień, 2018).

The soil was deemed to be contaminated, a designation that applied solely to the near-surface layer. The soil was designated as a waste material with the code 17 05 04 (Journal of Laws 2014, item 1923). The remediation was conducted via an ex-situ method, entailing the removal of the contaminated soil and its subsequent disposal. The Regional Directorate for Environmental Protection in Warsaw has confirmed the completion of the remediation process.

The project entails the construction of four seven-story buildings, to be completed in two phases. The initial phase of the project was completed between June 2019 and July 2021. The commencement of construction of the second stage was initiated in October 2020, with an anticipated conclusion in September 2022. Each phase of the project entailed the construction of a complex comprising two multi-family residential buildings with associated amenities, a shared underground garage, and the requisite infrastructure, including roads, parking facilities, and landscaping. In the initial phase of the project, 125 residential units and nine commercial spaces were constructed. In the second stage, 90 apartments and 7 commercial units are planned. The projected height of the buildings is 23.30 meters, which is in accordance with the local zoning plan. Furthermore, the condition of the building area is also met. The built-up area index is calculated using the following formula (1):

$$\frac{Pz_{fillings}}{Pz} \quad (1)$$

Where:

$Pz_{fillings}$– this is defined as the total area of all buildings situated on the plot;

Pz – the area of this plot.

Regarding the developments, the ratio of development area is as follows: 1st stage (2):

$$\frac{1745.27}{4940.89} = 0.35\ [-] \quad (2)$$

2nd stage (3):

$$\frac{1262.64}{3597.73} = 0.35\ [-] \quad (3)$$

The conditions set forth in the Local Land Use Plan have been met, as the development area ratio for the analyzed sites should be lower than 0.4, as indicated in the Plan.

Impact of temperature on the used substrate

The construction process frequently occurs at disparate times of the year, necessitating flexibility in planning work, including the establishment of green roofs. The implementation of outdoor work, including green roofs, can be significantly affected by atmospheric conditions such as temperature. To investigate the impact of temperature on the substrate, a series of tests were conducted at three distinct temperature settings, namely 5, 15, and 25 degrees Celsius. The substrate was placed in containers with geotextile fabric in lieu of a bottom and watered twice daily (20 ml of water each time), with the volume of water drained being measured. The initial step was to ascertain the characteristics of the extensive substrate utilized in the investigation. The moisture content and grain size of the substrate were analyzed using a 1-liter sample. In accordance with the established protocol, three portions of substrate, each with a volume of 1 liter, were prepared for the experiment. To measure a liter volume of substrate, the following apparatus was utilized: a liter container, a lint container, a sieve on a stand, a spatula, a weight, and a balance (Figure 2).

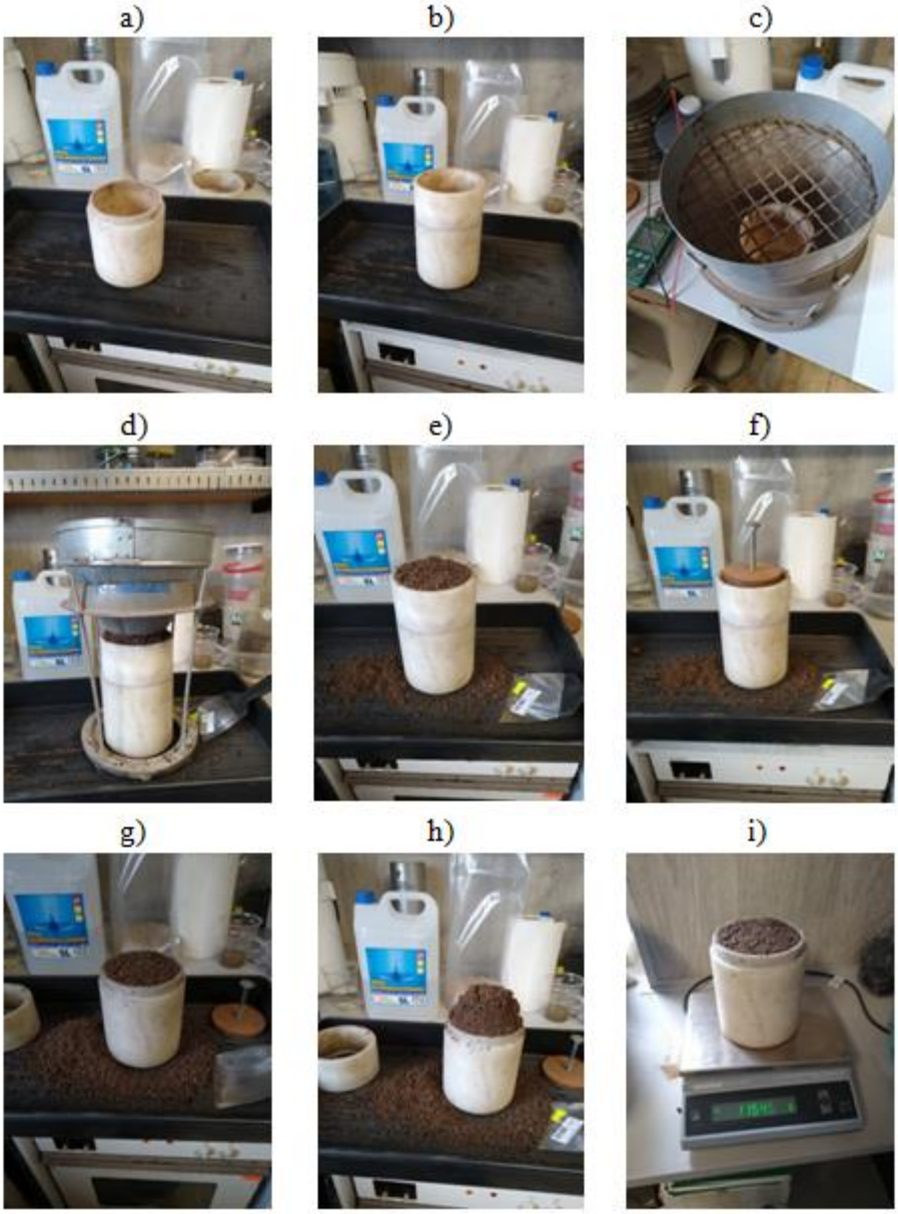

Figure 2. *Preparation of a liter sample of substrate for the experiment (a-i).*

An extension was attached to the 1-liter container (Figure 2a) to increase its volume (Figure 2b). A sieve was then placed over the container on stands to allow the substrate to fall freely (Figure 2c). The substrate was poured through the screen until the volume of substrate exceeded the volume of the container, forming a top layer (Figure 2d). The excess substrate was then removed with a spatula, ensuring that it was level with the edge of the container (Figure 2e). A weight was then placed on the substrate to displace the air (Figure 2f). The extension was then carefully removed, ensuring that the container was not disturbed (Figure 2g). A spatula was then used to level the substrate to achieve a flat surface (Figure 2h). The prepared sample was then weighed (Figure 2i).

3 Results

Biologically active zone located above the underground garage

In the instance of the biologically active zone situated above the subterranean garage, the objective was to satisfy the stipulations set forth in the Local Development Plan and the Ordinance pertaining to the ratio of biologically active area on the premises. To this end, green areas were incorporated into the design. In the initial phase, the ceiling above the subterranean garage was adorned with verdant foliage. The floor slab over the garage, situated outside the outline of the buildings, was designed as an inverted floor slab incorporating vegetative layers (Figure 4).

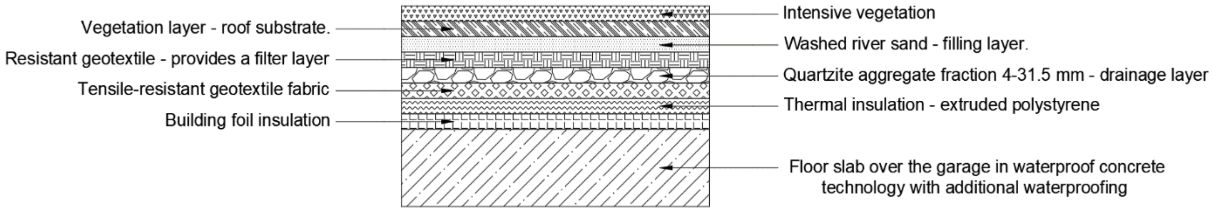

Figure 4. *Description of the layers above the underground garage and their arrangement.*

The foundation for the green area, and concurrently the substructure of the subterranean parking facility, is a reinforced concrete slab utilizing waterproof concrete (white tub) technology. The objective of this technology is to guarantee the structural integrity of the entire element, to provide protection against potential leakage and spillage (Bajorek, 2015). The floor slab has been treated with a waterproofing agent. In the case of a ceiling constructed from waterproof concrete, this constitutes an additional layer that serves to protect against the ingress of moisture and water. Furthermore, the layer incorporates drainage facilities designed to channel water from the ceiling. Thermal insulation, in the form of extruded polystyrene, is then applied to the foil. The specific polystyrene boards utilized are contingent upon the geographical location. These boards are manufactured in a variety of forms and possess varying degrees of resistance. The initial type of insulation utilized is expanded polystyrene (EPS) boards, which are also referred to as polystyrene. The subsequent type is extruded polystyrene (XPS) (Sawicki, 2005). In areas designated for vegetated pavement, EPS 200 is utilized, while XPS 500 is employed for sidewalks and XPS 700 for roads. It is imperative that the thermal insulation exhibit resistance to both mechanical loads and moisture. To mitigate the cooling effect of rainwater on the roof, a preliminary separating layer of nonwoven fabric is positioned over the thermal insulation. The subsequent layer is a drainage layer comprising quartz aggregate. The objective of this layer is twofold: firstly, to facilitate the rapid and effective drainage of surplus water during periods of heavy precipitation; secondly, to provide a means of storing this water, thereby protecting the underlying soil layers from the effects of drying out. However, it is important to note that this layer should not act as a barrier to plant roots (Kania et al., 2013). A further layer of geotextile is positioned on top of the drainage layer; this acts as a filter. The function of this layer is to separate the vegetation layer and the drainage layer, thereby preventing the accumulation of silt within the drainage layer. It is imperative that this layer not impede the phenomenon of water infiltration (Monczynski, 2017). The primary characteristics of this layer are its high permeability for water and plant roots, coupled with a notable resistance to decay. The subsequent layer is a 10 cm layer of river sand, which serves the function of a filler layer. These elements collectively comprise the technological layers of the inverted roof. The final layer is the primary vegetation layer, which comprises a 40 to 50 cm layer of intensive roof substrate. The substrate is a combination of organic and mineral components, with the proportions of each carefully calibrated to achieve the desired outcome (Karczmarczyk et al., 2012). The soil substrate provides an optimal environment for plant development and growth. The thickness of this layer, which constitutes the substrate, is selected according to the type of vegetation utilized on the soil floor, with consideration given to the thickness of the root layer of the selected vegetation. It is assumed that in the case of trees and shrubs, the thickness of the vegetation layer for intensive greening must be a minimum of 10% of the height of the plant (Kania et al., 2013). It is permissible for the substrate to settle to 15% of its original height. The methodology for the installation of the substrate dictates that it should be laid in layers and lightly rolled during the process. Moreover, the layer must possess adequate porosity and water-holding capacity. This is particularly crucial when employing greenery on ceilings, as the judicious selection of these parameters enables the creation of a lightweight layer with optimal retention capacity (Karczmarczyk et al., 2012). The function of the vegetative layer is to facilitate the effective drainage of excess water into the drainage layer or to store it on a periodic basis. This layer must also be capable of storing nutrients essential for optimal plant development. The following aspects are of particular significance with regard to this component of the green roof: weight, as this method of ceiling management entails an additional, permanent load on the overall structure; structure, which should be of an appropriate grain size to facilitate the drainage of excess water and the retention of air within the pores; and composition, which is of paramount importance from the perspective of vegetation, given that this layer maintains the closest, constant, and direct contact with the plants and exerts a profound influence on the functioning of vital processes within the plant kingdom (Kania et al. 2013). The plants are planted directly into the substrate. The vegetation planted on the ceiling above the underground garage resembles that of a garden, comprising trees, shrubs, and perennials (Figure 5).

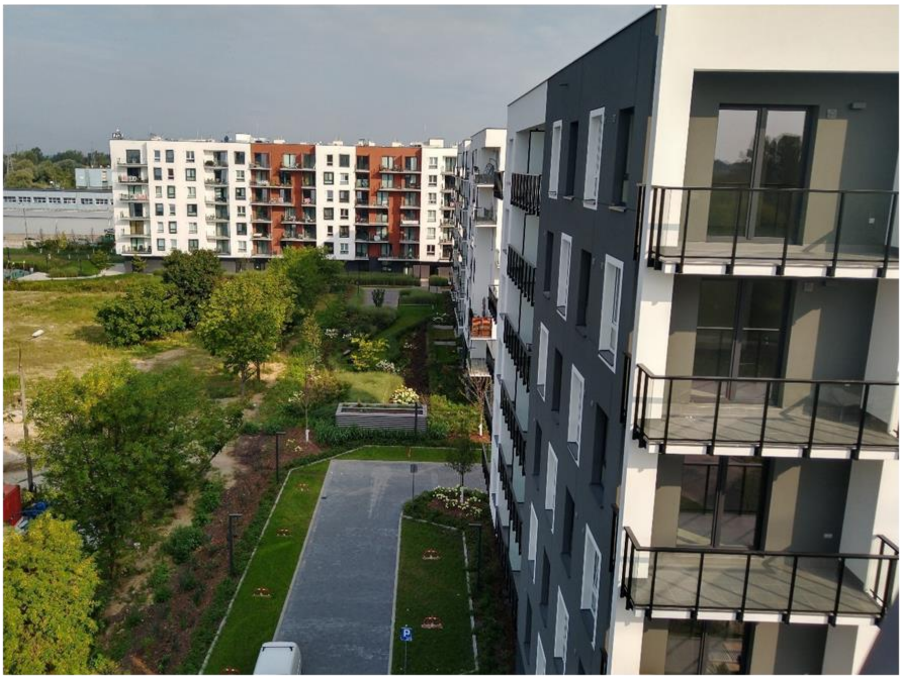

Figure 5. *Vegetation on the ceiling above the underground garage (Strzeszewska, 2023).*

The trees planted on the garage ceiling have a reduced soil layer, necessitating careful sizing to ensure optimal growth. A hole is created in the substrate, with a minimum width of 60 cm greater than the dimensions of the root ball. A welded steel grating is then laid on the layer of sand. Its purpose is to stabilize the surface under the tree and, in conjunction with the anchoring system and steel cables, to maintain adequate stabilization of the tree, thus preventing tipping and tilting under the influence of strong winds. The components collectively constitute a systematic underground anchoring kit. Subsequently, a compacted mineral substrate is positioned directly beneath the roots. It is essential to ensure that the substrate is properly prepared to prevent the potential for sinking trees while facilitating the effective drainage of rainwater from beneath the root ball into the soil profile. In the aforementioned project, trees such as Acer platanoides 'Farlake's Green' (common maple), Gleditsia triacanthos 'Skyline' (gleditsia triacanthos 'Skyline'), and Carya x lavallei (Lavalle's hawthorn) were utilized. Furthermore, approximately 650 shrubs were planted on the ceiling, including: Additionally, the planting scheme incorporated a variety of other species, including Forsythia 'Lynwood' (Forsythia), Hydrangea paniculata 'Unique' (Hydrangea), Spiraea salicifolia 'Alba' (Willowleaf Tavera), and over 3,700 perennials, such as: Echinops bannaticus 'Blue Glow' (Bannatine scallop) and Miscanthus sinensis 'Morning Light' (Chinese miscanthus) were also planted.

Biologically active area on the roof of a multi-family residential building

In the case of the second stage of the project, to meet the requirements of the Local Development Plan and due to the smaller size of the plot, landscaped greenery was designed both over the ceiling above the underground garage and on the roof of both buildings. This was done to comply with the regulations set forth in the Local Development Plan, which stipulate that landscaped greenery must be incorporated into the design of any new construction in the area. Furthermore, the facades of the buildings feature additional vegetation in the form of climbing plants. The reinforced concrete floor is the primary structural element, as it was constructed using a combination of concrete and reinforcing steel. The steel bars serve as supplementary reinforcement in tensile zones and can be either smooth or ribbed. The incorporation of reinforcement serves to enhance the load-bearing capacity of the structure. The waterproofing layer is composed of a heat-sealed bitumen membrane. The material is distinguished by its water resistance, compressive strength, and resilience to humic acids and other compounds present in the vegetation layer. It is essential that the material be resistant to a variety of chemical substances, including fertilizers, as well as fungi and mold. A detailed illustration of the roof layers and their configuration in a multifamily building is provided in Figure 6.

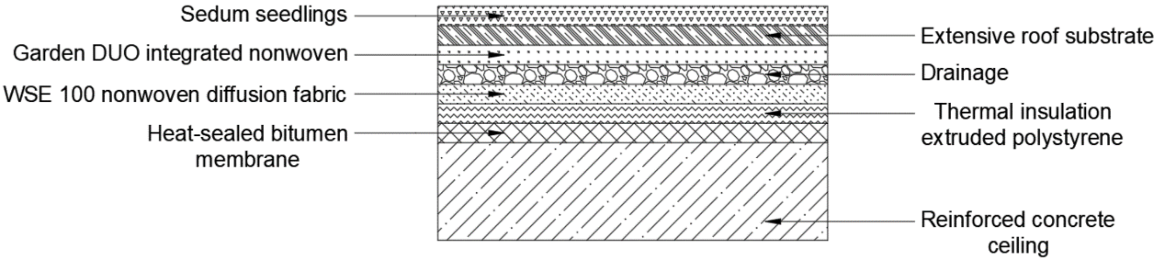

Figure 6. *Description of the layers on the roof of a multifamily building and their arrangement.*

The bituminous paper (Figure 7 a)) is overlaid with thermal insulation (Figure 7 b)), which is composed of XPS 300 extruded polystyrene.

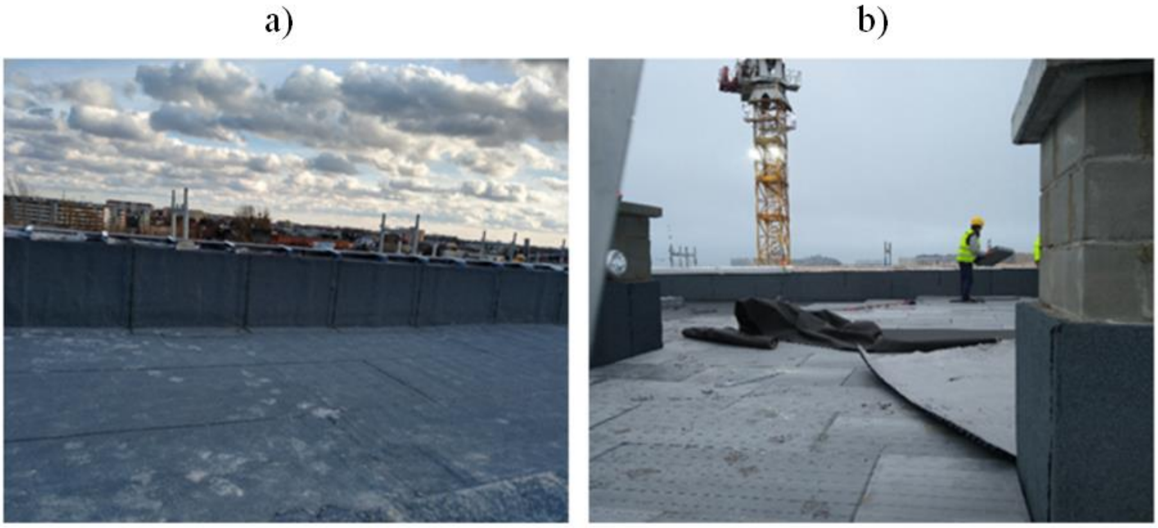

Figure 7. *a) A layer of bitumen felt on the roof; b) . Thermal insulation on the roof (Strzeszewska, 2023).*

The subsequent layers constitute the system layers of the green roof. The initial layer is a diffusion fleece, which serves as a separation membrane composed of a mesh of polypropylene fibers. Its function is to separate chemically incompatible layers or a drainage layer from a filter layer. Subsequently, a drainage layer with integrated nonwoven fabric (Figure 8 a)) is installed, comprising a combination of retention and drainage layers. This is followed by the addition of HDPE and TEX geotextile filter fabric (Figure 8 b)). The HDPE has extrusions 20 mm in height, which permit the accumulation of water, and perforations that direct excess water to the roof drain. The nonwoven fabric serves to prevent the perforations from becoming clogged and preventing the flushing of fine particles out of the vegetative layer.

a) b)

Figure 8. *a) Drainage with integrated non-woven fabric - retention layer; b) Drainage with integrated fleece - drainage laye (Strzeszewska, 2023).*

A layer of extensive roof substrate, measuring 10 cm in thickness, is applied directly on top of the nonwoven fabric (Figure 9). This is a mineral-organic soil substrate, specifically designed for extensive green roofs. The mixture consists of the following components: washed sand, washed gravel, lime grit, ash aggregate or expanded clay, peat, and compost.

a) b)

Figure 9. *a) Spreading the roof substrate layer; b) Layer of roof substrate (Strzeszewska, 2023).*

The project was designed in a manner that facilitated the creation of an extensive green roof, wherein sedum plants, measuring approximately 2.5 cm in height, were planted. These perennials have been selected for their resilience to challenging conditions, including water scarcity and mineral deficiencies. Sedums have been demonstrated to have a beneficial impact on air quality. The plants' developed root system obviates the need for irrigation (Figure 10). Nevertheless, it is crucial to remove unwanted vegetation from newly constructed roofs during their initial period of establishment.

a)

b)

Figure 10. *a) The sedums used; b) Roof with planted sedums (Strzeszewska, 2023).*

Results of the Impact of Temperature on Substrate

The experimental setup aimed to assess the impact of temperature on substrate properties under conditions simulating different seasons: summer, spring, and winter.

The procedure was repeated five times, and the results are presented in Table 1. The precise weight of each sample accurately reflected the volume of one liter of substrate, thereby providing the density of the sample.

Sample number	Density (g/l)
1	1151,4
2	1146,4
3	1147,6
4	1154,5
5	1139,3

Table 1. *Results of density measurement of substrate samples.*

Subsequently, the quantity of sifted material was determined by means of a weighing procedure, the results of which are presented in Table 2.

Sample ID	Grain Diameter (mm)	Mass (g)
1	<0,06	68,1
2	0,06	94,9
3	0,2	435,3
4	0,6	128,8

5	1	89,8
6	2	61,1
7	4	36,4
8	6	13
9	10	7,6
10	12	1,7
11	16	0

Table 2. *Results from the sieve analysis performed.*

The results of the substrate grain size test, as presented in Table 2, are shown in graphical form on the grain size curve, represented in red (Figure 11). The gray color indicates the optimal granulometric composition for extensive cultivation, as outlined in the FFL 2008 guidelines.

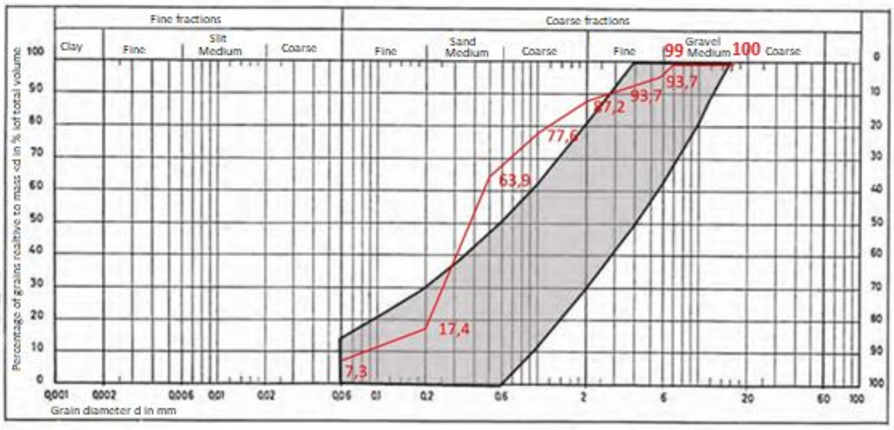

Figure 11. *Grain size curve of the tested substrate plotted on the area for extensive substrate according to FLL guidelines.*

Prior to the commencement of the experiment, the designated measuring stations were duly prepared. Each station comprised a substrate sample area, a thermometer, a water container, and a water container. Each of the three samples was placed in a plastic tube with a geotextile fabric on the bottom, which allowed for the drainage of water. The tubes were positioned in a funnel on stands with a water container placed underneath for convenient removal. Additionally, a thermometer and water container were positioned on the stand to ensure that the water temperature remained consistent with that of the substrate. The stands were situated in three distinct locations, each representing a different temperature range. The first sample was placed at a summer temperature of 25-30°C. Under these conditions, transpiration is intense and plants often have to give up more water than they take in in a given day in order to survive. The second sample was placed at a spring temperature of 15-20°C. These are ideal conditions for plant growth, as both roots and above-ground parts of the plant develop. The third sample was placed outdoors at a winter temperature of 1-5°C. Under these conditions, mainly the root system develops, with a possible slight growth increment, which is particularly noticeable in conifers (Maclvor et al., 2024; Fang et al., 2024).

Once the requisite preparations had been completed and the samples had been duly installed, the testing phase could commence. On the initial day of the experiment, to create the necessary water passages in the soil, all three samples were irrigated at one-hour intervals with 20ml of water using a syringe, in order to imitate the effects of a fine rain. Subsequently, the volume of water that had drained away was determined prior to the next watering. The results are presented in Table 3.

Time	Volume drained (ml)		
	1. Summer approx. 25°C	2. Spring approx. 16 °C	3. Winter approx. 2°C
11:00	0	0	0
12:00	0	0	0
13:00	0	0	0
14:00	0	0	0
15:00	0	0	0
16:00	6,60	0	0
17:00	13,50	16,00	0
18:00	15,00	18,50	4,00
19:00	19,20	19,25	10,00
20:00	19,00	19,75	18,50

Table 3. *Results from the „zero" day of the study.*

Subsequently, each sample was irrigated on two occasions per day for a period of 32 days, with 20 ml of water applied at ambient temperature, 12 hours apart (at 6:30 am and 6:30 pm). Subsequently, the volume of water drained was assessed after approximately 30 minutes. The results are presented in Tables 4, 5, and 6.

Day of experiment	Time	Temperature (°C)	Volume drained (ml)
1.	06:30	25	10,00
	18:30	24	9,00
2.	06:30	26	8,00
	18:30	28	8,00
3.	06:30	30	8,00
	18:30	27	8,00
4.	06:30	28	11,00
	18:30	28	8,50
5.	06:30	25	9,00
	18:30	28	6,20
6.	06:30	28	7,50
	18:30	28	9,00
7.	06:30	32	5,60
	18:30	26	9,00
8.	06:30	26	7,00
	18:30	25	8,50
9.	06:30	28	8,00
	18:30	25	7,80
10.	06:30	31	6,00
	18:30	28	7,00
11.	06:30	29	6,00
	18:30	28	7,50

12.	06:30	30	6,90
	18:30	25	7,00
13.	06:30	27	7,00
	18:30	31	5,90
14.	06:30	32	7,50
	18:30	30	6,50
15.	06:30	32	5,30
	18:30	27	4,00
16.	06:30	29	4,50
	18:30	31	4,80
17.	06:30	27	4,00
	18:30	30	5,50
18.	06:30	27	3,00
	18:30	27	5,00
19.	06:30	26	4,00
	18:30	25	14,50
20.	06:30	25	4,50
	18:30	27	9,00
21.	06:30	27	2,00
	18:30	31	5,00
22.	06:30	30	3,00
	18:30	31	1,80
23.	06:30	25	4,00
	18:30	22	4,00
24.	06:30	24	5,00
	18:30	26	6,00
25.	06:30	26	4,00
	18:30	29	2,50
26.	06:30	27	3,80
	18:30	25	3,80
27.	06:30	30	3,20
	18:30	26	3,00
28.	06:30	27	2,00
	18:30	26	5,80
29.	06:30	27	2,00
	18:30	29	3,50
30.	06:30	28	3,00
	18:30	23	2,00
31.	06:30	26	2,50
	18:30	25	4,50
32.	06:30	25	4,00
	18:30	22	1,50

Table 4. *Results of the summer position experience.*

The initial measurement site was operated under conditions approximating those of the summer season, with an average temperature of 27.31°C. Of the 64 temperature measurements taken, 28 were above the average temperature, representing 44% of the total measurements. The mean volume of water drained per watering was 5.71 ml, with a range of 5.35 ml in the morning and 6.07 ml in the afternoon. The greatest quantity of water was observed to drain on day 19 (14.5 ml at 25°C), while the least was observed on day 32 (1.5 ml at 22°C). The median outflow was 5.55 ml. A total of 1,280 ml of water was administered, of which 365.40 ml was subsequently drained, representing 29% of the total administered volume. The results are illustrated in Figure 12, which depicts the most readings between 25 and 30 degrees Celsius and 3 to 9 milliliters of outflow, with the greatest accumulation of points in a rectangle with similar side lengths.

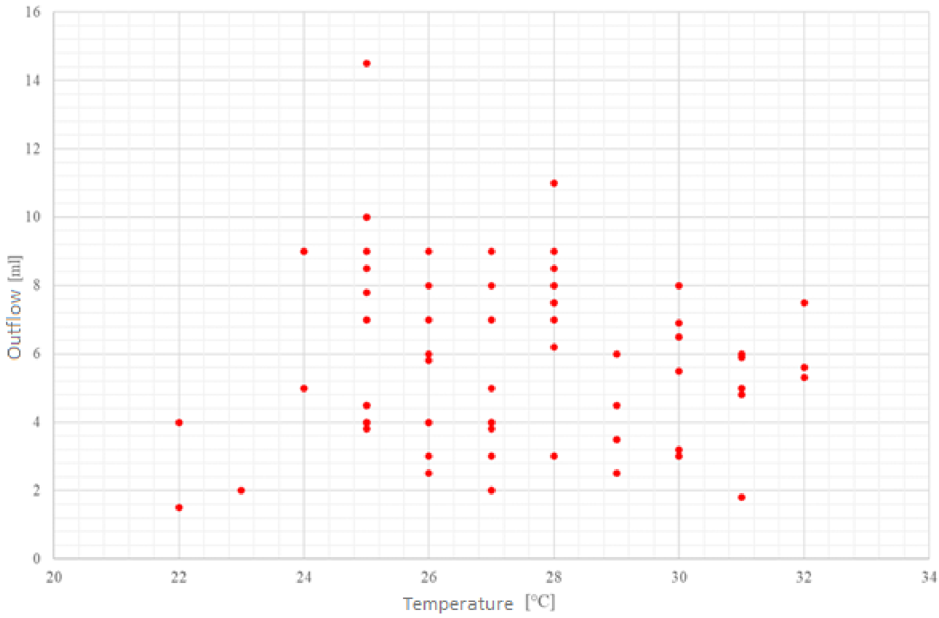

Figure 12. *Diagram of the outflowing water depending on the temperature at the summer position.*

Day of experiment	Time	Temperature (°C)	Volume drained (ml)
1.	06:30	14	14,25
	18:30	15	11,00
2.	06:30	15	14,50
	18:30	16	15,00
3.	06:30	16	15,00
	18:30	16	9,00
4.	06:30	17	15,00
	18:30	17	15,00
5.	06:30	16	14,00
	18:30	17	14,20
6.	06:30	17	14,00
	18:30	17	14,90
7.	06:30	17	14,60
	18:30	18	14,90
8.	06:30	18	14,50
	18:30	16	16,00

9.	06:30	17	14,00
	18:30	18	13,30
10.	06:30	17	14,50
	18:30	17	15,00
11.	06:30	17	13,20
	18:30	17	15,00
12.	06:30	17	14,50
	18:30	17	14,00
13.	06:30	17	11,70
	18:30	17	14,00
14.	06:30	16	13,00
	18:30	17	14,50
15.	06:30	15	12,80
	18:30	15	10,50
16.	06:30	15	13,50
	18:30	16	10,60
17.	06:30	16	13,80
	18:30	15	5,20
18.	06:30	15	15,00
	18:30	16	14,00
19.	06:30	16	13,50
	18:30	15	12,50
20.	06:30	14	15,20
	18:30	12,5	14,00
21.	06:30	13	13,00
	18:30	12	7,00
22.	06:30	12	16,50
	18:30	14	12,00
23.	06:30	13	13,00
	18:30	14	14,80
24.	06:30	13	14,80
	18:30	14	11,50
25.	06:30	12	14,00
	18:30	12	12,60
26.	06:30	12	14,60
	18:30	13	13,50
27.	06:30	11	13,80
	18:30	13	14,00
28.	06:30	14	11,50
	18:30	15,5	5,00
29.	06:30	15	15,00
	18:30	15	13,50
30.	06:30	12	13,00

	18:30	15	10,20
31.	06:30	14	13,00
	18:30	16	12,80
32.	06:30	16	14,00
	18:30	15	11,00

Table 5. *Results of the experiment at the spring site.*

At the second site, which corresponded to spring conditions, the mean temperature was 15.19°C. The temperature measurements were distributed in a manner that reflected a 50% probability of occurrence above and below the average. The mean volume of water exuded was 13.24 ml, representing 66% of the total volume applied in each instance. The mean water outflow in the morning was 13.96 ml, while the mean outflow in the evening was 12.52 ml. The greatest quantity of water was drained on the twenty-second day (16.5 ml at 12°C), while the least was drained on the twenty-eighth day (5 ml at 15.5°C). The median outflow was 14 ml. Of the 1,280 milliliters of water administered, 847.25 milliliters, or 66 percent, were lost through drainage. The results are presented in Figure 13, wherein the data points are arranged in an elongated rectangle.

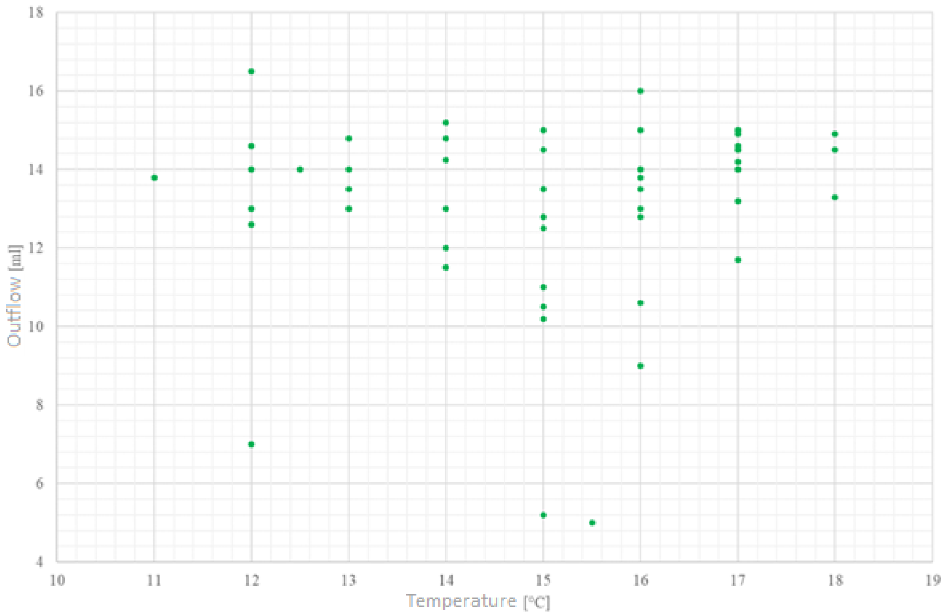

Figure 13. *Plot of water runoff versus temperature at the spring site.*

Day of experiment	Time	Temperature (°C)	Volume drained (ml)
1.	06:30	-3	19,50
	18:30	3	15,00
2.	06:30	0	15,00
	18:30	4	15,00
3.	06:30	1	13,00
	18:30	8	14,90
4.	06:30	6	13,50
	18:30	4	16,50
5.	06:30	4	17,00
	18:30	4	13,50

6.	06:30	6	15,00
	18:30	4	10,00
7.	06:30	3	18,00
	18:30	3	16,00
8.	06:30	3	19,00
	18:30	3	19,00
9.	06:30	5	14,50
	18:30	2	12,70
10.	06:30	2	12,90
	18:30	5	18,00
11.	06:30	1	19,10
	18:30	6	10,00
12.	06:30	4	11,30
	18:30	5	13,00
13.	06:30	5	9,20
	18:30	4	22,30
14.	06:30	1	11,50
	18:30	2	20,00
15.	06:30	-2	14,00
	18:30	0	16,00
16.	06:30	-3	12,00
	18:30	0	20,30
17.	06:30	-4	16,50
	18:30	0	17,80
18.	06:30	-4	14,00
	18:30	1	18,00
19.	06:30	1	17,00
	18:30	1	14,00
20.	06:30	1	16,60
	18:30	0	10,00
21.	06:30	0	17,60
	18:30	0	11,00
22.	06:30	-1	16,60
	18:30	1,5	16,00
23.	06:30	-2	14,50
	18:30	3	14,50
24.	06:30	4	17,00
	18:30	2	16,00
25.	06:30	-4	14,80
	18:30	-2	15,60
26.	06:30	-4	2,00*
	18:30	2	18,00
27.	06:30	-5	18,00*

	18:30	2	20,00
28.	06:30	-2	23,80
	18:30	3	13,00
29.	06:30	0	14,00
	18:30	4	8,00
30.	06:30	-1,5	8,50
	18:30	6	12,00
31.	06:30	3	17,00
	18:30	6	13,00
32.	06:30	0	16,50
	18:30	2	8,00

Table 6. *The results of the experiment on the winter stand.*

The third site exhibited conditions characteristic of the winter season, with an average temperature of 1.61°C. The data revealed that temperatures below the average were recorded on 30 occasions, representing 47% of the total measurements. The mean volume of water drained was 14.94 ml, representing 75% of the administered volume. The mean volume of water drained following the morning irrigation was 14.97 ml, while the mean volume drained following the evening irrigation was 14.91 ml. The greatest quantity of water was drained on the 28th day, with a total of 23.80 ml drained at a temperature of -2°C, which represents 119% of the administered water. On two occasions (on the 26th and 27th days), a layer of ice was observed on the surface of the substrate, which impeded the flow of water. The temperature at the time was -4 and -5°C, respectively. A total of 1,280 ml of water was injected, with 956 ml (75%) subsequently drained. The results are presented in Figure 14, which illustrates a wide dispersion and irregular distribution of points.

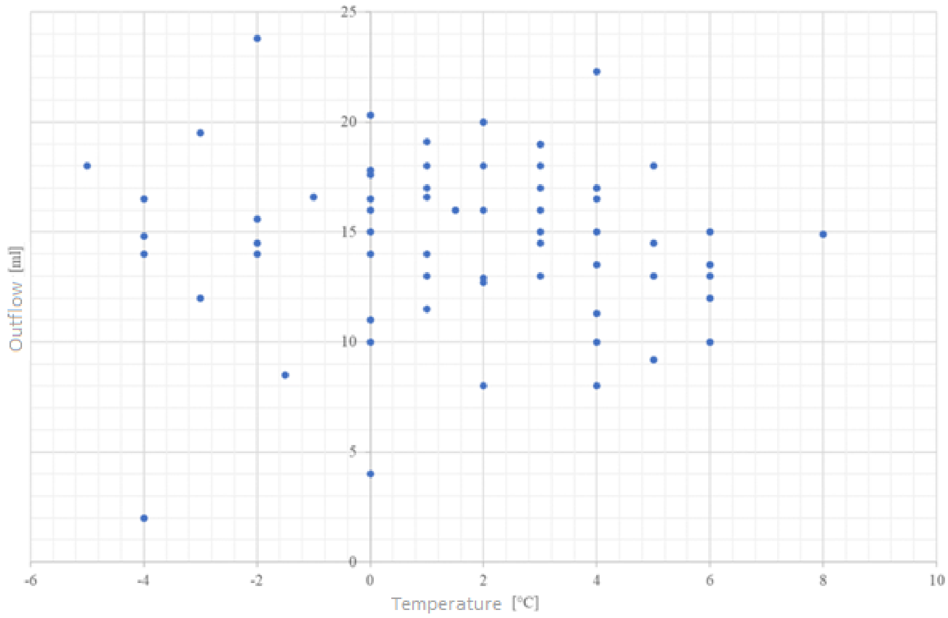

Figure 14. *Plot of water runoff versus temperature at the spring site.*

Figure 15 illustrates a comparison of water runoff during the experiment at three sites with disparate temperatures. The lowest volume of water was observed in the summer stand, where the rate of drainage exhibited a notable decline, as illustrated by the trend line (from 9 ml to 2.5 ml). At the other sites, the amount of outflowing water is also observed to decrease, although the differences are not as significant. The smallest discrepancy was observed at the winter site, despite the greatest fluctuation in water volume over the 32-day period.

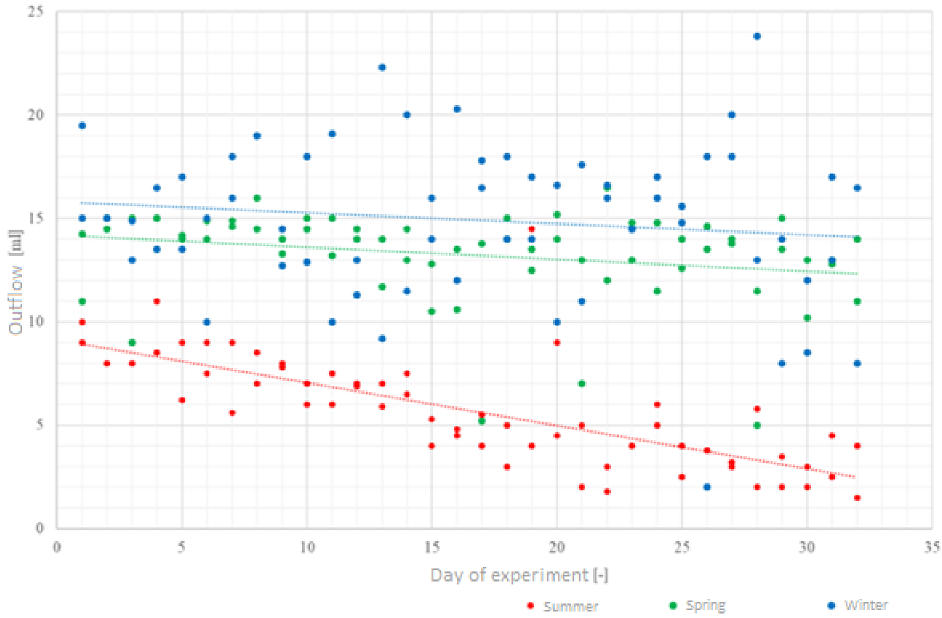

Figure 15. *Comparison of runoff water results over 32 days at three sites.*

4 Discussion

In today's world, construction is carried out with the environment in mind, and nature itself plays a central role in the survival and well-being of humanity (Algarni et al., 2022; Cappello et al., 2022; Tabatabaee et al., 2022). Therefore, it is of paramount importance to ensure a non-invasive integration between the environment and society. This approach not only preserves the balance between these two fundamental elements, but also has a positive impact on the economic dimension. The benefits of green roofs outweigh their drawbacks, and the earliest known examples were constructed as early as the 6th century BC (Šenfeldr et al., 2020). The Hanging Gardens of Babylon, built by Semiramis and considered one of the seven wonders of the ancient world, are an early example of a green roof (Abdulahaad, 2020; Hollin, 2023). In the present era, many countries are implementing policies that encourage investors to incorporate greenery on the roofs and walls of new construction projects (Liberalesso et al., 2020; Manso et al., 2021). The construction industry has a significant impact on natural resources, highlighting the importance of sustainable investments and environmentally conscious practices. There are numerous examples of the implementation of green roofs around the world, extending beyond Europe (Bevilacqua, 2021; Manso et al., 2021; Zhang and He, 2021; Jim et al., 2022).

The first example is located in the Polish capital, Warsaw. The Green Roof of the Warsaw University Library, inaugurated in 2002, is one of the most famous rooftop gardens in Poland. The public facility includes a rooftop garden of more than one hectare and a lower garden of an additional 1.5 hectares (Drozd, 2019; Strumiłło, 2021). The roof garden contains a variety of flora, including perennials, deciduous and coniferous shrubs, small trees, and climbers (Voronkova and Podlasek, 2024). The garden is divided into different colored sections (Bąk and Królikowska, 2016). Both the lower garden and the roof have been equipped with landscaping elements, including benches and trash receptacles, to make the area more accessible and welcoming to visitors. In addition, vertical greening systems were used on the library building, with plants climbing up the facade due to the presence of support structures mounted on the facade, both inside and outside the building (Chmura and Kobierska-Maciuszko, 1997).

Another example of a green roof in Warsaw is the roof over the Copernicus Science Center, which was opened to residents in 2014 (Strumiłło, 2021). The garden's layout and pathways evoke the Vistula River and its adjacent riverine areas. Due to the abundance of sunlight, the vegetation could not be typical of a riverside environment. To create a green roof that would thrive in a dry environment, plants that are adapted to such conditions were selected. These included the Carolinian yucca, sedums, carnations, and dwarf pine (Bąk and Królikowska, 2016).

As one of the first cities in North America to implement a green roof program, Chicago took significant steps to mitigate the urban heat island effect and improve stormwater infiltration (Hulicka, 2015; Sharma et al., 2016; McConnell et al., 2022). The regulations encouraged investors to create green roofs by allowing them to receive subsidies if the coverage covered at least 50 % of the site (Hulicka, 2015). The program resulted in the creation of Millennium Park, which is considered the largest green roof in the world and a success by various experts (Groos and Dages, 2008; McConnell et al., 2022). The park opened on July 16, 2004 and covers 24.5 acres (Paprzyca, 2018).

Millennium Park was built on the site of a former landfill and railroad (Postance, 2009). The project, which began in 1998, included the construction of an underground parking garage with a green roof and recreational facilities. The railroad was reconstructed in a way that did not interfere with surrounding development, combining the interests of the public with those of green development. The park uses renewable energy sources, including solar panels to power lighting and passive solar heating (Groos and Dages, 2008). Millennium Park offers a plethora of attractions, including the Jay Pritzker Pavilion, BP Bridge, Cloud Gate, Lurie Garden, and Crown Fountain (Paprzyca, 2018). The area is also home to a number of hotels, restaurants, and a theater, which together make it the de facto center of the city and the second most visited attraction in Chicago. It serves as an example of successful environmental revitalization and urban development (Groos and Dages, 2008).

Also of note is Toronto, which in 2009 became the first city in North America outside the United States to implement a green roof ordinance. According to the regulations, all new buildings larger than 200 square meters are required to have a green roof that covers at least 20% of the total roof area (Hulicka, 2015). An example of the implementation of a green roof in Toronto is the construction of a luxury condominium building. The building is a multi-family residence with a green roof on three levels, accessible to all condominium residents. The 1,300-square-meter green roof is enclosed on all sides and includes a variety of features such as a bridge, waterfall, trees, flowers and a pond. The concept was first developed in the 1980s during the renovation of a 1920s building with the goal of creating an urban oasis (Peck and Callaghan, 1999).

The establishment of green roofs is optimally suited to the spring season, as the atmospheric conditions during this period are conducive to the growth of vegetation. During this period, plants are largely self-sufficient, as natural conditions are conducive to their growth and adaptation. In comparison to the summer season, when the intense transpiration of plants increases the necessity for irrigation, the conditions in spring are more stable. During periods of high summer temperatures, the leaves of plants undergo intensive evaporation, which increases the need for additional irrigation. Additionally, the moisture present in the plants has a cooling effect, which may not promote optimal growth. During the winter season, the situation is reversed: low temperatures can negatively affect the substrates, which can freeze. This phenomenon hinders their proper functioning, leading to problems with plant establishment. Frozen substrate limits the ability of flora to take root and inhibits the overall growth and adaptation of greenery. (Chen et al. 2024; Chabada et al. 2024)

The creation of biologically active zones above subterranean garages is a complex engineering and landscaping challenge aimed at meeting regulatory requirements and enhancing urban greenery (Volchko et al., 2020; Mihai et al., 2021). The results of this project, focused on both a multi-family residential building and an underground garage, underscore the significance of multi-layered, integrated designs that prioritize structural integrity, effective drainage, thermal insulation, and optimal plant growth conditions.

The foundation of the green area, composed of a reinforced concrete slab with waterproof concrete technology, ensures durability and protection against leaks (Zhang and He, 2021). This is critical in maintaining the integrity of the structure, especially considering the additional load imposed by the green layers. The use of waterproofing agents and drainage facilities further enhances the resistance to moisture ingress (Simões et al., 2020), which is vital for preventing damage to both the garage and the vegetation above.

The application of thermal insulation, such as XPS, varies based on the area of use—EPS 200 for vegetated pavement, XPS 500 for sidewalks, and XPS 700 for roads. This differentiation ensures that the insulation is appropriately resistant to mechanical loads and moisture. Additionally, the drainage layer, composed of quartz aggregate and geotextile, plays a dual role in draining excess water and storing it to prevent the soil from drying out. This design ensures that the vegetative layer remains healthy and that the structural elements are protected from water damage.

The final vegetative layer, comprising a mix of organic and mineral components, is meticulously designed to provide an optimal environment for plant growth. The careful calibration of soil thickness based on plant type (e.g., a minimum of 10 % of the plant height for trees and shrubs) ensures that plants have adequate rooting space and nutrients. The selection of species such as Acer platanoides 'Farlake's Green' and various shrubs and perennials further demonstrates the project's attention to biodiverzity, and aesthetic appeal.

The experimental setup to assess the impact of temperature on substrate properties revealed key insights into water retention and drainage efficiency under different seasonal conditions. The results indicate that temperature variations significantly influence the substrate's ability to retain and drain water. For instance, higher temperatures (approximating summer conditions) resulted in a greater volume of drained water, highlighting the substrate's capacity to handle increased water flow during warmer periods.

The experiment showed that in summer-like conditions (average temperature of 27.31 °C), the substrate drained 29 % of the total administered water, while in spring-like conditions (average temperature of 15-20 °C), the drainage was more efficient. This suggests that the substrate's composition and the multi-layered design effectively manage water during different seasons.

5 Conclusions

The transformation of the Ursus District from an industrial site to a residential neighborhood showcased careful planning, remediation, and innovative green roof technologies for sustainable development. Compliance with local regulations and an emphasis on green infrastructure set a precedent for future urban projects. Critical remediation included the removal of contaminated soil to ensure the safety of future residents. Geological surveys and geotechnical designs identified five distinct geotechnical layers to ensure structural integrity. Divided into two phases, the project included four seven-story buildings with residential units, commercial space, underground parking, and necessary infrastructure, all in compliance with local zoning regulations. Extensive and intensive green roofs provided environmental benefits and code compliance. The study of temperature effects on substrate properties revealed significant effects on water drainage and retention, with higher temperatures reducing retention through evaporation and lower temperatures increasing retention and drainage. The results indicate the need for seasonal adaptation in green roof maintenance, with increased watering in summer and attention to drainage in winter. The project integrated green roofs on rooftops and over underground parking, with carefully selected vegetation to ensure long-term growth. The design included layers of waterproofing, insulation, drainage, and vegetation to support robust plant life and structural integrity, highlighting the importance of seasonally adaptive green roof strategies.

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