# Integration of Green Roofs and Facades as a Climate Change Adaptation Strategy: Environmental, Energy, and Microclimatic Aspects

Michal Kraus[1,2*)], Ingrid Juhasova Senitkova[3)], Jaroslav Zak[4)], Ales Kankovsky[5)]

[1*)] Department of Civil Engineering, Faculty of Technology, Institute of Technology and Business, Okruzni 517/10, 370 01 Ceske Budejovice, Czech Republic, info@krausmichal.cz; 0000-0001-5734-1488
[2*)] Department of Building Construction, Faculty of Civil Engineering, VSB—Technical University of Ostrava, Ludvika Podeste 1875/17, 708 00 Ostrava, Czech Republic, info@krausmichal.cz; 0000-0001-5734-1488
[3)] Department of Civil Engineering, Faculty of Technology, Institute of Technology and Business, Okruzni 517/10, 370 01 Ceske Budejovice, Czech Republic, senitkova@mail.vstecb.cz; 0000-0003-3178-383X
[4)] Department of Civil Engineering, Faculty of Technology, Institute of Technology and Business, Okruzni 517/10, 370 01 Ceske Budejovice, Czech Republic, zak@mail.vstecb.cz; 0000-0002-0973-1219
[5)] Department of Civil Engineering, Faculty of Technology, Institute of Technology and Business, Okruzni 517/10, 370 01 Ceske Budejovice, Czech Republic, kankovsky@mail.vstecb.cz; 0000-0002-8601-8898

https://doi.org/10.29227/IM-2025-02-02-093
Submission date: *2025-04-13* | Review date: *2025-05-13*

## *Abstract*

*The study examines the integration of green roofs and facades as an effective strategy for mitigating the adverse effects of climate change in urban environments. Urban areas face growing challenges due to the urban heat island effect, increased stormwater runoff, deteriorating air quality, and rising energy consumption. Green roofs and facades offer a sustainable solution by enhancing building performance and improving the surrounding microclimate through the natural benefits of vegetation. The research evaluates the technical and environmental advantages of vegetative roof and facade systems using detailed case studies and simulation models. Key findings demonstrate that green roofs and facades improve thermal insulation by reducing heat transfer through the building envelope, leading to lower indoor temperatures in summer and reduced heat loss in winter, which decreases the need for heating and cooling and results in lower energy consumption and greenhouse gas emissions. These systems also mitigate the urban heat island effect by absorbing solar radiation and cooling the surrounding air through evapotranspiration. Improved stormwater management is another benefit, as green roofs retain rainwater and slow runoff, reducing pressure on drainage systems and lowering the risk of flooding. Enhanced air quality is achieved through the capture of particulate matter and the absorption of pollutants such as carbon dioxide ($CO_2$) and nitrogen oxides ($NO_x$). The study identifies key design parameters influencing performance, including substrate composition, plant selection, irrigation methods, and structural load capacity. A comparative analysis of extensive and intensive green roofs shows that extensive roofs, with shallow substrates and low-maintenance plants, offer adaptability and low maintenance but lower insulation, while intensive roofs, with deeper substrates and diverse plantings, provide higher insulation and greater biodiversity but require more upkeep. Green facades, especially those using hydroponic modular systems, have proven effective in reducing noise and air pollution while improving the building's microclimate. The study concludes that integrating green roofs and facades represents a scalable and sustainable solution for enhancing urban resilience to climate change, offering significant environmental, economic, and social benefits.*

**Keywords:** *Green roofs, green facades, climate change adaptation, urban resilience, thermal performance*

## 1. Introduction

Climate change ranks among the most serious global challenges of the present era, affecting various of scientific disciplines – from climatology and ecology to economics and social sciences. The processes leading to climate change have been intensively studied, particularly since the mid-20th century, and are comprehensively described in the regular assessment reports of the Intergovernmental Panel on Climate Change (IPCC) [1,2].

As a result of intense human (anthropogenic) activity, the average global surface temperature of the Earth has increased by approximately 1°C compared to pre-industrial levels (with a probability range of 0.8–1.2°C). The most used reference period for defining pre-industrial temperatures is between 1850 and 1900. The rate of warming since the beginning of the 21st century has reached approximately 0.2°C per decade [3,4]. This increase in temperature is primarily attributed to the rise in the concentration of greenhouse gases in the atmosphere, particularly carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). Their concentrations have risen significantly since the Industrial Revolution, mainly due to the burning of fossil fuels, intensive agriculture, deforestation, and changes in land use patterns. However, it is essential to emphasize that climate change is not influenced exclusively by anthropogenic activities. The historical evolution of the Earth's climate exhibits significant variability driven by natural factors. These natural drivers include changes in solar activity, volcanic activity, Earth's orbital parameters (known as Milankovitch cycles), and natural ocean currents and atmospheric circulation fluctuations. These factors operate on different temporal scales and have, in the past, led to the alternating occurrence of glacial and interglacial periods [5].

Nevertheless, according to the scientific consensus summarized in the IPCC reports, the current rate and extent of global warming cannot be satisfactorily explained by the influence of natural factors alone. Long-term observations, paleoclimatic studies, and climate models clearly demonstrate that human activity is unequivocally the primary driving mechanism behind the current global climate change. Anthropogenic greenhouse gas emissions are amplifying the greenhouse effect, disrupting the Earth's energy balance and accelerating the

warming of both the atmosphere and the oceans.

The significant rise in global temperature is already triggering profound changes in natural ecosystems. These include shifts in climate zones, alterations in the phenological cycles of plants and animals, and an increased frequency of extreme weather events such as heatwaves, droughts, heavy precipitation events, and tropical cyclones. Furthermore, global warming is driving ocean acidification and accelerating the loss of glaciers and sea ice. These impacts are leading to a decline in biodiversity, the degradation of ecosystem services, and the destabilization of food webs upon which a significant portion of the human population depends.

From the perspective of socio-economic systems, global warming represents a substantial threat to agriculture, the availability and quality of water resources, human health, infrastructure, and overall economic stability at both regional and global scales. Developing countries and small island states are particularly vulnerable to climate risks due to limited adaptive capacity and low economic resilience. Consequently, climate change is critical in assessing the feasibility of achieving the Sustainable Development Goals (SDGs) proclaimed by the United Nations under the 2030 Agenda [6, 7]. Climate change negatively affects not only environmental goals but also those related to poverty reduction, food security, access to drinking water, human health, and social equality.

Climate change's multidimensional nature and global scale make it one of the most significant challenges for the international community. Addressing this issue requires comprehensive scientific understanding, effective mitigation (reduction of greenhouse gas emissions), strategic adaptation to its impacts, and the development of appropriate legislative and policy measures. The primary legal framework in this area is the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement, which aims to limit global warming well below 2°C above pre-industrial levels while striving to limit the increase to 1.5°C. According to scientific evidence, achieving this target would significantly reduce the negative impacts of climate change on both natural and socio-economic systems [8].

The average air temperature in the Czech Republic in 2023 was recorded at 9.7 °C, representing an increase of 1.4 °C compared to the reference usual measured between 1991 and 2020. According to available data, 2023 was the warmest year on record since 1961. The highest air temperature measured during the year reached 38.6 °C, recorded in Plzen. The average number of tropical days (days with maximum temperatures above 30 °C) in 2023 was 13.2 days. Temperature increases were observed in all months except April and May. Notable warming was particularly evident during the winter months of December and January, as well as in the autumn months of September and October. In contrast, April was significantly cooler than average. These findings were published by the Czech Hydrometeorological Institute (2024).

### *1.1 Green Roofs and Facades as a Tool for Sustainable Urban Development*

Green infrastructure is a key element of modern urban planning, designed to create a strategically planned network of natural and semi-natural areas such as parks, tree-lined streets, wetlands, and green roofs and facades. Its primary goal is to deliver various ecosystem services, including stormwater retention and infiltration, temperature regulation, and biodiversity support. By harnessing the natural capacity of landscapes to absorb and retain rainwater, green infrastructure reduces pressure on urban drainage systems and promotes more efficient water management. It also plays a crucial role in improving air quality by capturing atmospheric carbon and mitigating the urban heat island effect, making cities more resilient to climate change. Beyond its environmental benefits, green infrastructure enhances the visual identity of urban areas, enriching the cultural and historical landscape while creating more attractive and inviting public spaces. It strengthens community bonds by providing shared green spaces and supports local economies by increasing property values, attracting businesses, and encouraging eco-tourism. The combination of ecological, economic, and social benefits makes green infrastructure an essential tool for sustainable urban development, contributing significantly to cities' overall stability and quality of life [9-11].

In the past, green roofs primarily served as protection against climatic conditions. Their existence has been documented as far back as 3,000 years ago, with their origin driven by practical considerations rather than aesthetic or ecological intentions. Green roofs, which enhance both aesthetics and energy efficiency, also play a significant role in reducing stormwater runoff. By their very nature, they provide a sustainable and environmentally friendly alternative within the framework of urban development. The functions of green roofs and facades can be broadly categorized into five key areas: aesthetics, ecology, economics, energy efficiency, and environmental benefits. Green roofs and facades are particularly vital in densely populated urban areas where green spaces are limited. Their advantages extend beyond building owners and users, positively influencing the surrounding environment as well.

One of the primary functions of green roofs and facades is the improvement of microclimates and the reduction of stormwater runoff. Unlike conventional roofs, which are typically composed of waterproofing membranes, vegetated roofs are capable of mitigating extreme temperatures, reducing airborne dust, and increasing ambient humidity through the process of evapotranspiration - a process involving the transfer of thermal energy associated with the phase change of water between liquid and vapor states. This dynamic exchange not only regulates surface temperatures but also contributes to the stabilization of local microclimates. This contributes to the natural hydrological cycle. Moreover, green roofs delay stormwater runoff, as a significant portion of rainwater is absorbed by the vegetation, reducing the demand for irrigation and alleviating the burden on urban drainage systems. In addition to these hydrological benefits, green roofs create new habitats for living organisms, thereby promoting urban biodiversity.

Vegetation also acts as a protective layer for the waterproofing membrane on green roofs. It shields the membrane from degradation caused by ultraviolet (UV) radiation and minimizes the risk of mechanical damage. Furthermore, it serves as a thermal buffer, reducing heat load on the building envelope. A key objective in designing green roofs and facades is to enhance the resilience of urban areas to the impacts of climate change by improving the adaptive capacity of built environments. Achieving this goal requires a commitment to sustainable development that preserves the existing quality of life for residents. In the context of climate change, sustainable development can be facilitated through effective water resource management combined with the expansion of vegetated surfaces. Evapotranspiration plays a crucial role in this process by contributing to the cooling of the surrounding environment.

Another advantage of green roofs and facades is the increased attractiveness and overall utility of buildings. Their integration into urban areas positively impacts both work and residential environments, while also enhancing the visual appeal of cities and urban settlements. When green roofs and facades cover at least 10 to 20% of urban rooftops, they can significantly contribute to the improvement of the urban microclimate. The number of green roofs has been steadily increasing, having tripled since 2016. According to a qualified estimate, there are approximately 2.5 to 3 million square meters of green roofs currently in the Czech Republic. This estimate is based on the volume of substrate supplied specifically for vegetated roofing systems. In terms of quantity, extensive green roofs significantly outnumber intensive systems, primarily due to their lower structural demands, maintenance requirements, and implementation costs.

## 2. Case study

This case study focuses on addressing the challenges associated with the integration of green roofs and facades, with an emphasis on the technical evaluation of their implementation. For comparison, a non-vegetative variant was also considered, which assumes the absence of any green elements on the roof or facade. In this variant, higher energy consumption is anticipated, particularly in terms of cooling and heating demands. Based on existing knowledge about the urban heat island phenomenon, it is evident that the absence of vegetative elements does not contribute to mitigating this effect or to the effective retention of rainwater.

This case study evaluates the influence of integrated vegetation systems on the roofs and facades of a public amenities building. The building is located in the city center of Ceske Budejovice (South Bohemia, Czech Republic). The property is situated in the western section of a developed and functionally diversified urban area. The roof is designed as a flat green roof. For comparative analysis, an alternative configuration incorporating a PVC waterproofing membrane as the final layer will be examined on the same roof structure. The roof system under investigation comprises several distinct functional areas. The total area of the vegetated roof surface amounts to 365.07 m² and is designed with a pre-cultivated sedum mat as the vegetation type. The parapet surface area measures 52.66 m². Additionally, a gravel-covered section of the roof occupies 50.32 m². For the vegetated portion, the Leaf Area Index (LAI) is specified as 1 m²/m², indicating a moderate level of foliage density. The total thickness of the roof structure is 470 mm (see Table 1)

Tab. 1. Green Roof Layer Composition (from Exterior to Interior)

| Layer Description | Thickness [mm] |
|---|---|
| Sedum vegetation mat | 40 |
| Extensive green roof substrate | 80 |
| Filter layer – Filtek 200 | 2 |
| Drainage layer – Dekdren T20 Garden | 20 |
| Waterproofing membrane – Dekplan 77 | 1.8 |
| Separation layer – Filtek 300 | 2.9 |
| Thermal insulation – Dekperimeter SD 150 | 120 |
| Adhesive – Insta-stik STD | |
| Thermal insulation – EPS 150 | 200 |
| Adhesive – Insta-stik STD | |
| SBS asphalt membrane – Glastek AL 40 Mineral | 4 |
| Primer coating – Dekprimer | |

The green roof will be compared with a conventional roof featuring a standard layer arrangement, as specified in Table 2. The total thickness of the roof structure is 330 mm.

Tab. 2. Composition of the Reference Roof without Vegetation (from Exterior to Interior)

| Layer Description | Thickness [mm] |
|---|---|
| Waterproofing membrane – Dekplan 76 | 1.5 |
| Separation layer – Filtek 300 | 2.9 |
| Thermal insulation – EPS 150 | 200 |
| Adhesive – Insta-stik STD | |
| Tapered thermal insulation – EPS 150 | 120 |
| Adhesive – Insta-stik STD | |
| SBS asphalt membrane – Glastek AL 40 Mineral | 4 |
| Primer coating – Dekprimer | |
| Waterproofing membrane – Dekplan 76 | 1.5 |
| Separation layer – Filtek 300 | 2.9 |
| Thermal insulation – EPS 150 | 200 |
| Adhesive – Insta-stik STD | |

As part of the building design, the vegetated facade was conceived as a prominent architectural element that offers both aesthetic value and practical environmental benefits. This feature was deliberately integrated into the concept as an adaptive strategy, aimed at mitigating surface overheating, reducing ambient noise levels, and improving air quality by capturing airborne particulate matter. The facade into which the vegetation is incorporated forms a distinct volume of the building. This section is single-storey and houses one of the two lecture halls, along with an accessible terrace located above it.

The vegetation attachment system selected for the facade is supplied by LIKO-S, a company specializing in hydroponic modular green wall solutions. This system was chosen for its adaptability to various facade geometries and architectural configurations. The vegetated facade system is designed to cover an area of 82.68 m², ensuring integration with both the architectural form and the environmental performance goals of the building. It utilizes drought-tolerant plant species selected for their resilience and low maintenance requirements, making them particularly suitable for hydroponic applications in urban environments. The modular design ensures adaptability to the architectural form and allows for efficient installation and maintenance. To environmental performance evaluation, the vertical garden was assigned a Leaf Area Index of 1 m²/m², indicating that the total leaf surface area is equivalent to the surface area of the facade (see Table 3).

The BioTile system represents an advanced solution for the integration of vegetation into building envelopes. This system operates on the principle of vegetative panels filled with hydrophilic mineral wool, which simultaneously serves as the growing medium. The hydrophilic mineral wool exhibits high water retention capacity while ensuring proper aeration of the root system, which is essential for healthy plant growth. A key feature of the system is the segmented structure of the panels, which enables uniform distribution of water and nutrients to each plant. This design significantly reduces the risk of uneven irrigation and localized plant stress.

The panels are designed as independent modules, which simplifies both the installation process and subsequent maintenance or adjustments. The modular configuration provides the flexibility to tailor the size and shape of the vegetated surfaces according to specific architectural requirements. Moreover, the modularity facilitates easy replacement of damaged sections without the need for intervention in

the structural system of the facade. This makes the BioTile system a highly adaptable and resilient solution for modern green building applications.

Tab. 3. Green Roof Layer Composition (from Exterior to Interior)

| Layer Description | Thickness [mm] |
|---|---|
| Final hydrophobic coating | |
| Reinforced concrete monolithic wall | 300 |
| Adhesive and leveling compound | 3 |
| Thermal insulation Isover Profi T | 150 |
| Adhesive and leveling compound with mesh | 8 |
| Primer coating | |
| Silicone-silicate render, 2 mm grain | 2 |
| Air gap | 100 |
| Support frame + air gap | 215 |
| Cement-bonded particleboard (Cetris) | 14 |
| Waterproofing membrane | 1.5 |
| Dimpled drainage membrane | 8 |
| Biotile modules | 62 |

As a reference, a conventional facade system is analyzed. The facade has a total surface area of 82.68 m² and features a silicone-silicate render as the exterior finish. The system is designed in a modular configuration, consistent with standard construction practices for contemporary building envelopes (see Table 4).

Tab. 4. Reference Facade Layer Composition (from Exterior to Interior)

| Layer Description | Thickness [mm] |
|---|---|
| Final hydrophobic surface coating | |
| Reinforced concrete monolithic wall | 300 |
| Adhesive and leveling compound | 3 |
| Thermal insulation – Isover Profi T | 150 |
| Adhesive and leveling compound with embedded mesh | 8 |
| Primer coating | |
| Silicone-silicate render, grain size 2 mm | 2 |

## 3. Results & Discussion

### *3.1 Environmental Impacts of a Green Roof System*

An essential parameter for evaluating the ecological benefits of vegetated roofs, particularly in the context of $CO_2$ sequestration, is the Leaf Area Index (LAI). This dimensionless index defines the ratio of total leaf surface area to the ground surface area covered by vegetation. A higher LAI indicates a greater photosynthetically active surface, which can substantially enhance environmental performance. In this study, a LAI value of 1 m²/m² was adopted, corresponding to an extensive green roof with sedum species reaching up to 8 cm in height. This means that each square meter of roof area provides an equivalent square meter of leaf area. Although this value is relatively modest and results in a limited $CO_2$ uptake, it serves as a conservative estimate. In practice, denser vegetation or sedum species exceeding 10 cm in height could significantly increase LAI and thus strengthen the sequestration potential of the roof.

The initial carbon footprint of the green roof was calculated based on a total roof area of 365 m², with an embodied carbon emission of 87,700 g $CO_2$ eq/m² according to DEKSOFT. This results in a total initial carbon footprint of 32.01 t $CO_2$ eq for the entire green roof system. This figure reflects the environmental cost associated with the production, transport, and installation of the roof components prior to their operational life. It provides a baseline for evaluating the long-term environmental return on investment when accounting for subsequent $CO_2$ sequestration and energy savings.

To estimate the total amount of $CO_2$ sequestered over the expected 50-year lifespan of the green roof, a mid-range carbon uptake value of 0.45 kg $CO_2$/m²/year was used, as reported by [12]. With a LAI of 1 and a total surface area of 365 m², the calculation yields a total carbon uptake of 8.21 tonnes of $CO_2$ over the operational life of the roof. This figure, while moderate, underscores the role that even low-maintenance, extensive green roofs can play in climate change mitigation. For context, this amount is equivalent to offsetting the emissions of a conventional passenger vehicle driving tens of thousands of kilometres, emphasizing the potential of vegetated roofs to reduce the carbon footprint of urban infrastructure.

In terms of operational emissions, the maintenance-related carbon output is minimal. Assuming an annual maintenance emission factor of 0.33 g $CO_2$/m² [13], the total emissions over the 50-year period amount to only 6.02 kg $CO_2$. This negligible value confirms that extensive green roofs do not impose significant additional environmental burdens during their service life, particularly when compared to their carbon sequestration and energy-saving capabilities.

Seyedabadi [12] reports that sedum-based systems can reduce building energy-related $CO_2$ emissions by 7.68 kg $CO_2$/m²/year. When combined with direct sequestration by plants, the total annual reduction reaches 7.82 kg $CO_2$/m²/year. Over 50 years, this corresponds to a cumulative reduction of 142.7 t $CO_2$. This demonstrates the multifaceted ecological benefit of green roofs, as they simultaneously act as carbon sinks and thermal buffers, reducing the demand on building systems and mitigating the urban heat island effect.

When integrating all components of the life cycle analysis, the green roof system achieves a net negative carbon footprint. The total impact is calculated as follows: 32.01 t $CO_2$ eq (initial emissions) + 0.006 t $CO_2$ (maintenance emissions) − 8.21 t $CO_2$ (sequestration) − 142.7 t $CO_2$ (energy-related reduction), resulting in a net balance of −112.88 t $CO_2$ eq over 50 years. This clearly illustrates the effectiveness of green roofs in reducing greenhouse gas emissions and underscores their value as a viable strategy for sustainable urban development and climate resilience.

### *3.2 Environmental Impacts of the Reference Roof System*

The environmental assessment of the reference non-vegetated roof system includes the quantification of carbon emissions associated with its construction and maintenance throughout its anticipated 50-year service life. The initial carbon footprint was calculated for a total roof area of 365 m², ensuring direct comparability with the green roof variant. Based on data from DEKSOFT, the embodied carbon associated with the reference roof construction amounts to 62,100 g $CO_2$ eq/m², which yields a total of 22.67 tonnes $CO_2$ eq for the entire surface. This calculation was intentionally applied to the same surface area to enable accurate and consistent comparative analysis between different roof configurations.

In addition to the initial construction emissions, maintenance-related emissions were also considered, specifically those arising from the replacement of the waterproofing membrane. Due to the limited durability of conventional PVC-based waterproofing systems, it is assumed that the membrane will need to be replaced once within the 50-year period. According to DEKSOFT, the carbon footprint associated with the production and installation of new membrane material is 4.09 kg $CO_2$/m². Applying this to the effective roof area of 365 m² results in additional emissions of 1.49 tonnes $CO_2$ eq.

Combining the embodied emissions from initial construction with those from membrane replacement, the total life-cycle carbon footprint of the reference non-vegetated roof amounts to 24.16 tonnes $CO_2$ eq. This figure establishes a baseline for evaluating the relative environmental performance of alternative roofing solutions, particularly those incorporating vegetative systems designed to mitigate climate-related impacts.

### *3.3 Environmental Impacts of a Green Facade System*

A detailed life cycle carbon footprint analysis was conducted to evaluate the environmental performance of the vertical garden system integrated into the building facade. The calculation was based on a facade area of 82.68 m², which ensured direct comparability with other building components and enabled accurate interpretation of environmental benefits.

The initial embodied carbon associated with the insulation layer was calculated as 30,700 g $CO_2$ eq/m², while the vegetated facade system accounted for an additional 24,150 g $CO_2$ eq/m². The combined embodied carbon for both systems over the entire facade area amounts to 4.53 tones $2CO_2$ eq. This includes the production, transportation, and installation of all relevant components.

Over a projected lifespan of 50 years, the vegetated facade can also sequester carbon dioxide through plant biomass. Based on a mean annual $CO_2$ uptake rate of 0.45 kg $CO_2$/m²/year [12], the total carbon sequestration potential is estimated at 1.86 tones $CO_2$ for the whole system. This value reflects a conservative estimate for drought-tolerant species such as Sedum, which were selected for their adaptability and low maintenance requirements.

Maintenance-related emissions were also considered in the analysis. Drawing on values from [13], who studied modular vegetated roofing systems with comparable characteristics, the annual emissions associated with irrigation were calculated as 25.2 g $CO_2$/m²/year. Over the 50-year lifespan, this corresponds to 2.56 tones of $CO_2$, which were included in the total emission balance. Other maintenance-related emissions, such as substrate renewal or structural repair, are assumed to be embedded in the embodied footprint of the facade system itself and were therefore excluded from this category.

In addition to sequestration, the system significantly contributes to energy-related emission reductions by improving the building's thermal performance. The use of vegetated systems such as Sedum walls can result in a reduction of 7.82 kg $CO_2$/m²/year in building operational emissions [12]. Applying this value across the facade area and design life results in a total savings of 32.3 tones $CO_2$ over 50 years.

When all components are considered, including embodied emissions, maintenance, carbon uptake, and energy savings, the vertical garden system achieves a net negative carbon balance of −27.07 tones $CO_2$ eq over its life cycle. This calculation, based on the same facade area used in all comparative assessments, confirms the substantial environmental benefit of integrating modular vertical greenery into building design as a climate adaptation measure and a tool for reducing the built environment's carbon footprint.

### *3.4 Environmental Impacts of a Reference Facade System*

The calculation of $CO_2$ sequestration for the conventional facade begins with the assessment of its initial embodied carbon footprint. According to DEKSOFT, the embodied emissions associated with the facade construction amount to 30,700 g $CO_2$ eq/m². When applied to the total facade area of 82.67 m², this results in a cumulative initial carbon footprint of 2.54 tonnes $CO_2$ equivalent. Since the conventional facade does not provide any carbon sequestration or energy-related emission reductions, the total life-cycle carbon footprint remains unchanged at 2.54 t $CO_2$ eq over the considered 50-year service life.

## 4. Conclusion

Climate change has become an increasingly debated and tangible issue in contemporary discourse. Discussions on melting glaciers, global warming, urban heat islands, and local climate variations have intensified in both scientific and public spheres. However, the role of urban heat islands - specifically their overheating effects and the influence of construction practices - remains largely underappreciated despite their significant contribution to climate change.

Green roofs and facades are increasingly becoming essential components of sustainable architecture, contributing to the mitigation of urbanization's negative environmental impacts. As a result of climate change, increasing urban density, and more frequent extreme weather events, significant changes are also occurring in both microclimatic conditions and hydrology.

Vegetation-based architectural elements play a significant role due to their inherent environmental benefits and contribute directly to the advancement of sustainable development. These systems enhance the retention of rainwater, thereby increasing the ecological value of buildings by promoting more efficient stormwater management and reducing the burden on urban drainage infrastructure. Compared to conventional building solutions, vegetated elements uniquely manage precipitation on-site, supporting resilience in urban water systems. Furthermore, they actively participate in carbon dioxide ($CO_2$) sequestration throughout the entire life cycle of the building.

In addition to their ecological advantages, vegetated systems provide measurable thermal insulation benefits. By reducing heat transfer through building envelopes, they lower the building's energy demand for heating and cooling, substantially reducing $CO_2$ emissions associated with energy consumption. This dual functionality—both as carbon sinks and thermal regulators—makes vegetation-based construction systems highly effective tools for climate change adaptation. As such, they are increasingly recognized as essential components of sustainable and resilient architectural design.

**References**


1. O. Edenhofer, C. Kilimann and K. Seyboth, "The intergovernmental panel on climate change (IPCC) – Scientific authority and map maker of climate policy alternatives", Encyclopedia of Energy, Natural Resource, and Environmental Economics (Second Edition) 1, 47-60 (2025).
2. A. Xepapadeas, "Uncertainty and climate change: The IPCC approach vs decision theory", Journal of Behavioral and Experimental Economics 109, 102188 (2024).
3. D. Li, X. Lu, I. Overeem, D.E. Walling, J. Syvitski, A.J. Kettner, B. Bookhagen, Z. Yinjun and T. Zhang, "Exceptional increases in fluvial sediment fluxes in a warmer and wetter high mountain Asia", Science 374, 599-603 (2021).
4. D. Li, I. Overeem, A.J. Kettner, Y. Zhou, X. Lu, "Air temperature regulates erodible landscape, water and sediment fluxes in the permafrost-dominated catchment on the Tibetan Plateau", Water Resour. Res. 57, e2020WR028193 (2021).
5. T. Yang, Y. Shen, L. Lu, J. Jin, Y. Zhang, L. Zeng, F. Jiang and Y. Zhao," Milankovitch cycles recorded by the Late Permian volcanic ash layers in southwestern China", Marine and Petroleum Geology 161, 106671 (2024).
6. United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development. 2015. Available online: https://sdgs.un.org/2030agenda
7. X. Li, L. Liu, Z. Zhang, W. Zhang, D. Liu and Y. Feng, "Gender Disparity in Perceived Urban Green Space and Subjective Health and Well-Being in China: Implications for Sustainable Urban Greening", Sustainability 12, 10538 (2020).
8. X. Fan, S. Shen, D. Wang and C. Zhou, "The Paris Agreement and firms' carbon information disclosure: Honesty or catering?", International Review of Economics & Finance 99, 103988 (2025).
9. M. Kraus, "Green construction as essential approach in sustainable design: Comprehensive review", International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM 19, issue 6.2, 465-570 (2019).
10. N. J. Paul, P. J. Irga and F. R. Torpz, "Active green wall plant health tolerance to diesel smoke exposure", Environmental Pollution 240, 448-456 (2018).
11. S.M Sheweka and N. M. Mohamad Arch, "Green Facades as a New Sustainable Approach Towards Climate Change", Energy Procedia 18, 507-520 (2012).
12. M. R. Seyedabadi, U. Eicker and S. Karimi, "Plant selection for green roofs and their impact on carbon sequestration and the building carbon footprint," Environmental Challenges 4, 100119 (2021).
13. T. Kuronuma, H. Watanabe, T. Ishihara, D. Kou, K. Toushina, M. Ando and S. Shindo, "$CO_2$ Payoff of Extensive Green Roofs with Different Vegetation Species", Sustainability 10, 2256 (2018).