Nature-based Solutions for the building system

Giulio Hasanaj, Chiara Catalano

Abstract: Nature-based Solutions (NbS) applied to the building system represent a key strategy to address urban environmental challenges while improving the quality of life and guiding the planning, design and sustainable management processes of future cities. NbS play a fundamental role in the climatic and environmental balance of urban areas and are an indispensable component of the ecological transition. The integration of NbS in roofs and walls offers multiple ecosystem benefits and are fundamental tools for increasing biodiversity, climate adaptation and ecological integration of the built environment, contributing to the transition towards more resilient and liveable cities. The chapter analyse and present NbS for the building system with a specific focus on roofs and walls. In the case of roofs, different types of green solutions are analysed: 1) extensive green roofs, which are light and low-maintenance; 2) intensive green roofs, characterised by a greater depth of substrate and more diverse vegetation; 3) semi-intensive roofs, which combine features of both; 4) biosolar roofs, which integrate vegetation and photovoltaic panels to maximise energy yield; 5) biodiverse green roofs, designed to host native species and promote urban habitats; and finally 6) blue-green roofs, which combine water tanks and typical green roof built-up improving the water management aspect. Regarding walls, the solutions analysed include 1) green facades which consist of climbing vegetation on supports; 2) green walls which integrate modular systems with plants rooted in artificial substrates; 3) planter green walls that are systems installed in containers integrated into the building façade. The mentioned building related NbS are synthesized in factsheets containing a) general description, b) technical and design parameters for the adequate implementation, and c) indicators for biodiversity enhancement, climate resilience, and health, well-being and air quality.

Keywords: Nature-based Solution, Urban biodiversity, Building System, Green roofs, Green walls.

The contribution of green roofs and green façades to urban biodiversity

Cities are today the places where we live (Mancuso 2023, p. 6). Urban areas are afflicted by the disruptive impacts of climate change (IPCC 2023), air, soil and water pollution (WHO 2024), and the progressive loss of biodiversity (IPBES 2019). Such phenomena are exacerbated by the degradation of green infrastructure, the loss of ecosystem services and urban expansion, which reduce soil naturalness and adaptive capacity, while increasing climatic, ecological and environmental vulnerability (WHO 2016; IPCC 2022).

«The way in which settlements and key infrastructure are planned, designed and maintained determines patterns of exposure, social and physical vulnerability, and resilience capacity (IPCC 2022, p. 1289)». In this regard, natural spaces – and particularly green and blue infrastructure – play a crucial role, as they influence the climatic and environmental balance of urban areas and are an essential component for halting biodiversity loss, mitigating climate change, and improving public health (EC 2013; EC 2021).

Nature-based Solutions (NbS), in particular, represent a key resource for guiding the planning, design and sustainable management of the cities of the future (UN-Habitat

Giulio Hasanaj, University of Florence, Italy, giulio.hasanaj@unifi.it, 0000-0003-0069-3292
Chiara Catalano, CNR - IRET, Research Institute on Terrestrial Ecosystems, Italy, chiara.catalano@cnr.it, 0000-0003-4582-3476

Referee List (DOI 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Giulio Hasanaj, Chiara Catalano, *Nature-based Solutions for the building system*, © Author(s), CC BY 4.0, DOI 10.36253/979-12-215-0966-3.19, in Roberto Bologna, Anna Lambertini, Luca Solari (edited by), *Nature and City. An Integrated Approach to Urban Biodiversity*, pp. 181-234, 2025, published by Firenze University Press, ISBN 979-12-215-0966-3, DOI 10.36253/979-12-215-0966-3

2022, p. XXII). NbS are recognised for their ability to pursue environmental, social and economic objectives simultaneously, acting as transformative levers for equitable and sustainable urban development (EC 2022; Xie et al. 2022).

However, the presence of natural spaces within urban areas remains limited compared to artificial surfaces. The proportion of green areas in European cities covers less than 16% of urbanised land, and only 3% of these spaces are publicly accessible (EEA 2021). In Italy, the availability of public green space is in some cases even more limited, with public green areas often accounting for less than 5% of the total municipal area (SNPA 2022).

The World Health Organization (WHO) recommends that cities should provide at least one accessible green space of 5,000 m^2 within 300 metres of residential areas (WHO 2016). Each citizen should have access to a minimum of 9 square metres of safe and functional urban green space, while the ideal amount of urban greenery is estimated at 50 square metres per person (Maryanti et al. 2016). Despite these recommendations, more than 60% of the urban population in Europe lives in areas with insufficient green spaces (Pereira Barboza et al. 2021).

NbS are receiving increasing attention for their potential to enhance the sustainability, resilience and biodiversity of urban environments, and are being implemented in many cities (Goodwin et al. 2023). However, their application is mostly concentrated at ground level or within urban open spaces (Almaaitah and Joksimovic 2022), while only a limited share concerns buildings. In several international contexts, green roofs and living walls have been tested, generating interest among citizens but often receiving limited attention within urban planning processes (Kandel et al. 2024).

Considering that the building stock constitutes a critical element in advancing both climate adaptation and the enhancement of urban biodiversity, it is essential to identify the NbS that can be effectively applied to buildings. Evaluating the key performance indicators emerging from existing evidence, defining the appropriate technical, construction and maintenance requirements, analysing the associated co-benefits, and recognising the principal knowledge gaps enable the consolidation of current understanding and inform future research on the implementation of NbS in urban environments (Kandel et al. 2024). Moreover, such an approach contributes to building a robust knowledge base to support the integration of NbS within architectural design and urban planning practices.

This contribution outlines NbS applied at the building scale included among the solutions of the urban domain of the NbS CataTool Decision Support System (DSS) (See Chapter *The NbS CataTool of the National Biodiversity Future Center*) and considered as key instruments for supporting the urban ecological transition. The work focuses particularly on green roofs and green walls, describing their various types — including extensive, intensive, semi-intensive, biosolar, biodiverse and blue-green roofs, as well as green façades, living walls, and planter walls — and presenting relevant scientific knowladge references for biodiversity, climate resilience, health and environmental quality.

By expanding the contents already present within the DSS, the work also provides a technological and typological analysis of these solutions. Each NbS is summarized in a technical data sheet that includes: a general description, design and construction parameters, maintenance requirements, and co-benefits in response to the challenges of biodiversity, resilience, health and wellbeing. This organisation makes it possible to translate scientific and technical knowledge into operational tools for designers, local authorities and policy makers.

Extensive green roof

Section A - General Description

Fig. 1 – Extensive green roof in Basel (Source: Catalano 2013).

Description

Extensive green roofs (EGR) are near-natural greened surfaces hosting mosses, succulents, forbs (including bulbs and tubers) and some grasses on an average 6-15 cm thick growing medium (Catalano et al. 2018; FLL 2018; Madre et al. 2013). Plant species able to grow on EGR with little maintenance and irrigation are stress tolerant, mostly annuals and low growing or creeping perennials capable of regenerating themselves and propagate easily (Madre et al. 2013; Thuring and Dunnett 2014). On such roofs, spontaneous colonization shall be favoured for resilient EGR over time (Vidaller et al. 2023) and not be considered a failure (Schrieke et al. 2021); also diverse plant assemblage perform better than monoculture (Tran et al. 2019). EGR represent most of the case studies due to the lower costs related to the installation and maintenance compared to the other kind of green roofs; they also possess the lower species richness due to the harsher conditions (higher drought, lower space for roots, stronger wind effect) and a more uniform structure (Madre et al. 2013). However, these conditions favour endangered and rare species typical of arid or very dry habitats, which tolerate or have adapted to harsh environmental conditions, thereby promoting pioneer vegetation (Pétremand et al. 2018). However, building height negatively influences arthropods biodiversity (Madre et al. 2013) while size is not necessarily linked to higher diversity (Mayrand and Clergeau 2018) thus even small EGR are a good mean to support biodiversity in dense urban areas.

Synonyms

Sedum roofs; mosses roofs; eco-roofs

Section B - Technical details

Implementation conditions

The construction of an extensive green roof is subject to a range of structural and climatic conditions. From a structural perspective, the load-bearing system must be designed to support an additional load varying between 60 and 150 kg/m² under water-saturated conditions, with higher values possible in specific configurations (ENEA 2024; ZinCo 2024). An extensive roof must include root-resistant certified waterproofing and a minimum slope of at least 1–2%, with appropriate drainage systems to prevent water stagnation that could damage the vegetation (FLL 2018; Peck and Kuhn 2003). On steeply sloping roofs, exceeding 25–30%, containment elements must be incorporated to prevent substrate slippage (Peck and Kuhn 2003).

Despite their limited substrate depth, extensive green roofs should ensure a minimum water retention capacity of 25 L/m² and achieve at least 95% vegetation cover within three years of installation (Eisenberg et al. 2022).

Local climatic conditions have a strong influence on design choices. In arid climates, for example, it is advisable to provide emergency irrigation systems that can be activated during periods of extreme drought (Eisenberg et al. 2022). In temperate and humid climates, by contrast, drainage management becomes particularly important, as the substrate can easily become saturated, thereby reducing the efficiency of its thermo-hygrometric functions (Elliott et al. 2016). In Mediterranean climates, it is recommended to use a soil layer thicker than 15 cm (composed mainly of fine-grained materials) to ensure optimal colonisation by plant species (Chenot et al. 2017).

Design features

The typical stratigraphy of an extensive green roof includes: 1) root-resistant waterproof membrane; 2) drainage layer made of gravel or plastic honeycomb panels; 3) geotextile filter fabric; 4) lightweight growing substrate with a predominantly mineral composition (such as lapillus, pumice and sand) and a limited organic component; 5) vegetation, usually consisting of non-woody plants (e.g. mosses, sedums, ground covers, hardy perennial herbs and grasses), although a wide variety of species can be employed (ENEA 2024; ZinCo 2024).

Plants suitable for extensive green roofs are low-growing and slow-developing species with rapid propagation, shallow root systems, or hardy perennials — including succulents — capable of surviving with minimal nutrient input and without additional irrigation (Eisenberg et al. 2022).

Extensive green roofs are often implemented on existing buildings, as they are generally lighter in weight, require less water and lower investment, and, with the appropriate technical supports, can also be installed on steeply sloping surfaces (Eisenberg et al. 2022).

Along the roof edges, gravel strips are typically incorporated, which, in addition to serving as firebreaks, improve perimeter drainage and facilitate access for inspection and maintenance (FLL 2018).

The extensive green roof represents a well-established technical solution which, with relatively simple design requirements (limited weight and minimal maintenance), offers multiple benefits: thermal and acoustic insulation (up to 8 dB), reduction of atmospheric pollutants, rainwater management, enhancement of biodiversity and mitigation of the urban microclimate. However, it is essential to comply with design criteria suited to the climatic and structural context, to follow an appropriate stratigraphy using suitable materials, and to ensure a minimum level of periodic maintenance (Berardi et al. 2014; ENEA 2024).

Maintenance

Once established, an extensive green roof requires only limited maintenance (generally one to two interventions per year) (ZinCo 2024; ENEA 2024). Routine maintenance includes the removal of unwanted vegetation (such as tree seedlings carried by the wind), the periodic cleaning of outlets and drainage systems from leaves and debris, and occasional applications of slow-release fertilisers to replenish nutrients within the substrate (FLL 2018; Eisenberg et al. 2022).

During the initial post-installation phase, greater attention is required, with regular irrigation until the vegetation is fully established and frequent inspections to promptly remove any emerging weeds (Peck and Kuhn 2003).

Irrigation is generally not required; however, although xerophilous species can tolerate prolonged periods without water, supplementary irrigation may become necessary under conditions of extreme drought (Woods-Ballard 2015). Pruning and mowing are not required (ZinCo 2024). These simple maintenance practices ensure a healthy and long-lasting vegetative cover, preventing the accumulation of dry biomass that could increase the risk of fire and compromise the ecosystem benefits of the extensive green roof (Climate-ADAPT 2020).

Section C - Societal challenges

Biodiversity enhancement

Integrating extensive green roofs in urban spatial planning strategies has great potential to increase the connectivity among green spaces (Braaker et al. 2014). Extensive green roofs community composition of high-mobility arthropod groups (bees and weevils) were mainly shaped by habitat connectivity, while low-mobility arthropod groups (carabids and spiders) were more influenced by local environmental conditions. For the first group of arthropods, green roof communities are connected by the frequent exchange of individuals among surrounding green roofs. On the other hand, low-mobility species communities on green roofs are more likely connected to ground sites than to other green roofs (Braaker et al. 2014).

Extensive green roofs are highly likely to provide habitat for a greater abundance and diversity of both plants and animals than conventional roofs which are spontaneously colonized (Williams et al. 2014). Even if other types of green roofs are more biodiverse, extensive green roofs, if they are left to spontaneous colonization, can act as refugia for species adapted to poor, sandy and dry environments (Muratet 2024).

Extensive green roofs can make a significant contribution to maintaining and enhancing the local diversity of species. A study conducted on eight extensive green roofs located in Hamburg revealed a remarkable species richness of arthropods. A positive correlation was observed between vegetation cover and species richness, highlighting that even relatively thin substrates, when appropriately vegetated, can support an ecologically diverse community. These findings suggest that the structure and complexity of vegetation are key factors influencing the establishment of different species, even in highly anthropized urban environments (Nevermann et al. 2025).

Extensive green roofs designed with the objective of conserving biodiversity, including those with shallow substrates typical of extensive systems, promote the presence of rare or uncommon plant species within urban environments. Floristic diversity can be enhanced through the targeted selection of plant species and by configuring the substrate to create differentiated microhabitats (Muratet 2024).

Climate Resilience

Extensive green roofs, characterised by lightweight substrates and species requiring low maintenance, represent an effective solution for mitigating climate change in urban environments. These Nature-based Solutions can capture atmospheric carbon through photosynthesis, contributing to the reduction of greenhouse gas (GHG) emissions and the improvement of air quality (Getter et al. 2009). Moreover, extensive green roofs enhance the energy efficiency of buildings due to their insulating properties, reducing the need for heating in winter and cooling in summer. In certain configurations (such as Biosolar green roof), integration with photovoltaic panels can also lead to increased energy production, as the more favourable microclimate created by the vegetation helps to improve solar panel performance (ENEA 2024).

An extensive green roof can enhance the performance of the building envelope by increasing thermal and acoustic insulation, mitigating surface temperature peaks, and improving indoor comfort. During the summer, the vegetation and substrate contribute to reducing surface temperatures by up to 25 °C compared with a conventional roof, resulting in energy savings for cooling (ENEA 2024). At the same time, the solution improves the sustainable management of stormwater, retaining on average between 50% and 90% of precipitation and delaying runoff, with positive effects on the urban drainage network (Berardi et al. 2014).

Health, Well-being and Air Quality

Living and working in a green environment has a positive effect on both mental and physical health, providing psychological relaxation and reducing stress (Hedblom et al. 2019). Health and wellbeing benefits can also be achieved without the physical use of green spaces, as a positive psychological effect may arise from the simple visual perception of greenery, even when such spaces are not directly accessible (WHO 2016). Therefore, green roofs and walls can serve as tools to promote citizens' health and wellbeing.

Although, by definition, an extensive green roof is not intended for intensive recreational use, many projects adopt a mixed solution to maximise health and wellbeing benefits. This configuration typically includes peripheral areas of a flat roof with extensive vegetation (offering visual appeal, as well as thermal and hydrological benefits) and a central walkable section (such as a paved deck or pergola), or vice versa. In such cases, particular care must be taken to separate the planted and pedestrian zones (through edging and dedicated drainage), and to provide localised irrigation for the green areas where these adjoin accessible spaces.

Intensive green roof

Section A - General Description

Fig. 2 – Intensive Green Roof at Manifattura Tabacchi in Florence (Source: Hasanaj 2025).

Description

Intensive green roofs (IGR) are highly engineered systems capable of supporting a wide variety of vegetation types, including trees, shrubs, perennial herbs, and lawns, within a growing medium typically ranging from 15 to 200 cm in depth (FLL 2018). These systems offer significant design flexibility and can be developed across large, contiguous roof surfaces, either on a single level or spanning multiple elevations. The main limitations are the structural load capacity of the building and associated construction and maintenance costs. Due to their substantial substrate depth and broad palette of plant species, IGRs can replicate the aesthetic and recreational functions of ground-level parks and gardens, providing valuable green spaces in dense urban settings. However, this complexity also entails high maintenance demands, including regular irrigation, fertilization, pruning, and weeding, making ongoing care essential for long-term functionality and ecological performance (Catalano et al. 2018).

Synonyms

Hanging gardens; soil based green roofs

Section B - Technical details

Implementation conditions

The implementation of an intensive green roof requires a suitably designed building structure capable of supporting the substantial loads arising from the saturated substrate, vegetation and any furnishing elements. The permanent load can range from 250 to over 1,000 kg/m^2, depending on the substrate depth and the type of vegetation used (FLL 2018; ENEA 2024). For existing buildings, a preliminary structural assessment is therefore essential, and, where necessary, reinforcement of structural elements should be undertaken.

Unlike extensive roofs, intensive green roofs are comparable to constructing a ground-level garden on a roof, making them suitable for accommodating a wide variety of vegetation, including trees and shrubs (ZinCo 2024; ENEA 2024).

The planning and design phase begins with an assessment of the building's structural condition, particularly the roof slab, to determine its load-bearing capacity. It is essential to carry out a feasibility analysis that includes a study and calculation of the slab's structural integrity in order to certify the maximum sustainable load. When calculating the overall static load, it is necessary to take into account the maximum weight that the structure may reach under full water saturation, as well as additional loads such as snow or those arising from maintenance activities (ENEA 2024).

From a technical perspective, the roof must be completely waterproofed using membranes that are resistant to root penetration (FLL 2018; Woods-Ballard 2015). It is also essential to provide an efficient drainage system and an automated irrigation system, as intensive vegetation requires a constant water supply, particularly during the summer months (METRO ADAPT 2019).

Local environmental conditions — such as solar exposure, wind intensity and urban microclimate — should guide the selection of the substrate and plant species, with a preference for native species that are resilient to water stress (Catalano et al. 2018; ENEA 2024). The detailed design and planning phase must also ensure ease of access for maintenance and safety (FLL 2018).

Other crucial aspects of implementation include the provision of a water supply connection on the roof to enable essential irrigation (ENEA 2024).

Design features

The functional stratigraphy of an intensive green roof consists of a sequence of technical layers, each with a specific role. The Italian standard UNI 11235:2015 outlines the elements that must always be included: 1) structural support; 2) root-resistant waterproofing; 3) mechanical protection layer; 4) drainage layer (gravel, plastic honeycomb elements, or modular drainage panels) that allows excess water to be discharged while retaining a portion useful for root absorption; 5) filter fabric to prevent the passage of fine particles; 6) growing substrate; 7) vegetation (FLL 2018; ENEA 2024; ZinCo 2024).

The root-resistant layer is always mandatory. If the existing waterproofing system does not fulfil this function, an additional membrane must be installed to protect the structure from root penetration (ENEA 2024).

The substrate depth is the defining feature of an intensive green roof and can range from 15 cm to 100 cm or more (FLL 2018). The water retention capacity of the substrate is typically between 50 and 150 litres per square metre, and it is essential that it remains biologically active and healthy to ensure optimal plant growth. The substrate is composed of lightweight, well-draining mixtures, generally consisting of pumice, expanded clay, and composted organic matter.

The drainage layer must ensure the rapid and effective removal of excess water and should be designed according to local climatic and hydraulic conditions (ENEA 2024).

The selection of plant species is extensive — including perennials, shrubs and trees — and must take into account the interaction between substrate depth, solar exposure, climate, water availability and the intended function (Catalano et al. 2018). In the case of shrubs and trees, the use of non-grafted plants grown in predominantly mineral substrates is recommended (FLL 2018).

The irrigation system (whether drip, sprinkler, or sub-irrigation) is an essential component to ensure the survival of vegetation during dry periods (Woods-Ballard 2015). Some systems incorporate integrated drainage modules that retain water and release it through capillary action, thereby improving water efficiency (Daku 2024; ZinCo 2024).

From a construction perspective, the intensive green roof is a dynamic system in which the proper dimensioning of each layer ensures durability, hydraulic performance and microclimatic comfort (Eisenberg et al. 2022). The design process must therefore integrate architectural, engineering, landscape and agronomic expertise within a multidisciplinary framework.

Maintenance

Maintenance represents a key determinant of the long-term functionality and performance of intensive green roofs. Such systems require management practices comparable to those of conventional gardens, including regular irrigation, pruning of shrubs and trees, mowing of lawns, fertilisation, and phytosanitary monitoring to control pests and diseases. Larger plant species have greater nutrient requirements, necessitating annual fertilisation in spring during the first three to five years, along with a basic chemical analysis of the substrate (pH, NPK) on an annual or biennial basis (ENEA 2024).

Routine maintenance also includes the periodic inspection of drainage systems, the removal of weeds, and the verification of the condition of waterproofing membranes. Extraordinary maintenance may involve the replacement of damaged substrate or vegetation, as well as the inspection and repair of the irrigation system (FLL 2018; ENEA 2024).

The level of maintenance required depends on the vegetative complexity and the intended use of the space. Accessible roofs featuring paved areas and trees may require up to 25–30 hours of maintenance per 100 m^2 annually (METRO ADAPT 2019). However, careful vegetation planning and the selection of native species can significantly reduce both water demand and maintenance needs (Catalano et al. 2018).

Finally, maintenance should be incorporated within a long-term management plan that includes seasonal inspections, performance reporting, and corrective actions (Woods-Ballard 2015). The maintenance cost of an intensive green roof can be up to ten times higher than that of an extensive one (ENEA 2024).

Section C - Societal challenges

Biodiversity enhancement

Intensive green roofs, due to their greater substrate depth and diversity of microhabitats, offer significant potential for enhancing urban biodiversity (Catalano et al. 2018).

They can host a wide range of plant species, supporting the presence of pollinating insects, birds and small invertebrates (Fernández-Cañero and González-Redondo 2010; ENEA 2024). However, the level of biodiversity is closely dependent on design choices: the selection of native species adapted to local climatic conditions increases ecological resilience and reduces maintenance requirements (Catalano et al. 2018; FLL 2018).

European guidelines emphasise the importance of viewing green roofs not merely as technological devices for water management or thermal insulation, but as seminatural ecosystems that contribute to the urban ecological network (Eisenberg et al. 2022; Kandel and Frantzeskaki 2024). The inclusion of heterogeneous elements - such as temporary wet areas, differentiated substrates, logs or stone features - can enhance habitat diversity and improve the overall ecological function (Woods-Ballard 2015). Conversely, an excessive degree of human intervention or an overly artificial vegetation layout may reduce the naturalness of the habitat (Catalano et al. 2018). In this sense, integrated design involving architects, ecologists and botanists is essential to balance aesthetics, functionality and biological sustainability in intensive green roofs.

Climate Resilience

Intensive green roofs mitigate high temperatures, addressing the phenomenon of urban heat islands. They act effectively on the improvement of the urban microclimate through the natural evapotranspiration effect of the vegetation, via low reflectivity and high absorption of solar radiation required for photosynthesis. The temperatures of green roofs can be 16-22°C lower than those of conventional roofs (EPA 2008). The widespread implementation of green roofs on between 80% and 90% of a city's rooftops can lead to a reduction in average air temperature ranging from 0.3 °C to 3 °C, depending on climatic conditions, vegetation type, and surface reflectance. This effect arises from plant transpiration and the increase in surface albedo, both of which decrease the amount of sensible heat flux released into the urban atmosphere (Santamouris 2014). Intensive green roofs can reduce a building's energy consumption. Thanks to their thermal mass layer, they insulate the building, allowing heating and cooling systems to work more efficiently, leading to a significant reduction in energy consumption (Oliveira Santos et al. 2024).

Intensive green roofs reduce the hydraulic load generated by extreme rainfall by collecting and retaining large volumes of water and delaying its entry into the sewer network, thereby preventing hydraulic overload. However, their hydrological performance depends on the season: in summer, evapotranspiration promotes water retention, whereas in winter the substrate often remains saturated, causing the vegetated roof to behave like an impermeable surface. Under extreme conditions, once the soil has reached saturation, effectiveness depends on the resilience of the urban drainage system and on the presence of complementary strategies. Intensive green roofs can retain between 41% and 75% of rainfall over a two-hour period (Liu et al. 2020). Approximately 44% of water from heavy rainfall events is retained within the roof structure (Kolasa-Więcek et al. 2021). Moreover, they contribute to water quality improvement through filtration, absorption and biodegradation processes, being effective in removing suspended solids and heavy metals (Woods-Ballard 2015).

Health, Well-being and Air Quality

The presence of low vegetation, grassy areas and trees covering building surfaces provides shaded spaces for users to rest. Urban green areas have a positive psychological effect. Intensive green roofs can be used for physical exercise, gardening and social interaction, all of which are positive factors for public health (Andreucci et al. 2019; Gehrels et al. 2016).

The use of intensive green roofs allows the creation of true outdoor social spaces on building rooftops, sheltered from the noise and vehicle traffic of urban streets. These spaces can include furniture elements such as benches, shelters, lampposts, etc., and can be used for recreational activities, including sports, leisure, relaxation, urban farming (related to the cultivation and production of food), or gardening (World Bank 2021).

Intensive green roofs provide areas for recreation and opportunities to enjoy outdoor living spaces, contribute to local food production and boost the local economy creating jobs in many sectors (Susca et al. 2011; Whittinghill and Rowe 2012).

Intensive green roofs are important sources of information about the environment. They can serve as classrooms for local schools, providing a space for observation and experimentation for students interested in nature, biology, and the environment (Hop and Hiemstra 2012).

Semi-intensive green roof

Section A - General description

Fig. 3 – Semi-intensive Green Roof of the Water Filtration Plant in Wollishofen, Zurich, Switzerland (Source: Chiara Catalano 2013).

Description

Semi-intensive green roofs are a hybrid solution between extensive and intensive green roof systems. They typically support shrubs, perennial herbs, and lawns, planted in a growing medium ranging from 12 to 100 cm in depth (Catalano et al. 2018). This type of green roof retains much of the biodiversity and multifunctionality potential of intensive systems while significantly reducing structural load, installation complexity, and maintenance costs. Unlike extensive green roofs, which are limited to low-growing, drought-tolerant vegetation due to shallow substrates, simple-intensive systems allow for a wider range of plant species and more diverse habitat structures. The spatial design and vegetation selection are like those used in traditional intensive roofs, enabling aesthetic, recreational, and ecological benefits. However, by optimizing substrate thickness and simplifying irrigation and drainage systems, simple-intensive roofs offer a cost-effective and flexible approach for enhancing urban green infrastructure.

Synonyms

Simple-intensive green roofs; light-intensive green roofs

Section B - Technical details

Implementation conditions

Semi-intensive green roofs (SIGR) are an intermediate stage between extensive and intensive green roofs, thought to be visited and used also for recreation purposes. The substrate thickness varies according to the plant growing form, that is from 12 cm up to 40 cm for grass or herbaceous plants and up to and 60 cm for perennials and shrubs, from

15 cm up to 50 cm for woody shrubs and perennials, and up to 100 cm for bushes (FLL 2018, Pérez and Coma 2018). In mediterranean climate, irrigation is needed mostly during prolonged periods of drought, or limited precipitations, generally during summer. During the other time of the year, while the deeper substrate allows greater water retention than extensive roofs, efficient drainage is still necessary to avoid waterlogging and to maintain root health. Compared to extensive green roofs, SIGR provides higher thermal resistance due to the higher substrate thickness but requires a higher loading capacity of the roof structure considering all the layers in saturated weight, the vegetation and the people visiting the roof, beside maintenance. Considering for example a thickness between 10-25 cm with herbs, grasses and shrubs, the weight at maximum water capacity ranges between 120-350 Kg/m2 (Pérez and Coma 2018).

Design features

The built up, as for the other green roofs types with exception of blue-green roofs, consists of the following layers above the roof structure (FLL 2018; Catalano et al. 2018): 1) root-resistant waterproofing; 2) mechanical protection layer; 3) drainage layer (gravel, plastic honeycomb elements, or modular drainage panels) that allows excess water to be discharged while retaining a portion useful for root absorption; 4) filter fabric to prevent the passage of fine particles; 5) growing substrate; 6) vegetation. In addition, due to fire safety and a better water management, gravel border is required along the perimeter and roof outlets. Regarding the plant species selection, it is possible to select different growth forms, from small herbaceous to perennial ground covers, but also bulbs, grasses and small shrubs, which require moderate maintenance (occasional pruning) and occasional irrigation (Vacek et al. 2017). For higher substrate up to 100 cm at punctual areas, it is possible to use woody plants (FLL 2018).

Maintenance

Semi-intensive roofs demand moderate but regular maintenance. This includes seasonal pruning for bushes and other woody species, periodic fertilization and weed removal for lawns, but also inspection of irrigation components. Though higher in maintenance compared with extensive roofs, this green roof system also provides the potential for a formal garden effect and/or potentially greater ecological benefits. As all green roofs plants can dry out in hot summers, thus objects that can generate sparks, glass (e.g. bottles) or cigarette ends must be avoided. However, the risk of spreading fire through wind is limited because the biomass is relatively small and the mineral substrate layer is reducing the potential inflammability risk. Exceptions are grass roofs because dry conditions increases the risk of fire propagation (i.e., if in summer the substrate is not moisturized by irrigation for example). Therefore, grass-dominated green roofs require targeted maintenance interventions (e. g., mowing and removal of aboveground biomass) to reduce fire hazard and prevent excessive accumulation of organic matter in the substrate, which can promote nutrient leaching and subsequent runoff water pollution.

Section C - Societal challenges

Biodiversity enhancement

Semi-intensive Green Roofs (SIGR) have a wide palette of plant and therefore can better support biodiversity both flora and fauna (including pedo-fauna); if maintenance is reduced to the minimum, for example for grass dominated vegetation one time late mowing, and the spontaneous colonisation is not arrested, except for invasive exotic plants, it can represents an enhanced natural form of vegetation, often self-sustaining and evolving. This typology can be considered a good mean of compensation, partially restoring the environmental footprint of the building by increasing biodiversity and restore water cycle. Over time, without or minimal irrigation, and allowing spontaneous species to colonise the roof, SIGR can mirror local surrounding communities (metapopulations) acting as stepping stones for natural habitats harnessing the enhanced soil-plant-insect relationships (Frisk and Hanslin 2025). In these conditions, species diversity of roofs communities is influenced positively by surrounding natural habitat proving their mutual beneficial relationship (Muratet et al. 2024). Additionally, the larger, the older and the deeper substrate, the higher the capacity of green roofs to support biodiversity due to a positive species/area ratio as in the case of the Wollishofen Water Filtration Plant in Zurich which hosts a great variety of species (including orchids) typical of semi-dry grasslands of temperate Europe (Landolt 2001). The way species are brought on roofs is relevant for species conservation, for example employing seeds or plants grown of the same ecotype by using the hay transfer method or hay seeds collected by vacuum or by hands, is increasing the potential biodiversity. Moreover, plant diversity is positively correlated with wildlife diversity but also CO_2 sequestration and stormwater capture and the resiliency to environmental stressors such as temperature, wind and water drought (Ndayambaje et al. 2024).

Climate Resilience and Water management

Green roofs contribute to the reduction of Urban Heat Island (UHI) effect cooling the air, but also reducing both roof temperature and ambient temperature compared to conventional roofs, thus reducing indoor cooling and heating needs. The vegetation layer (which can be simplified as foliage and ambient air) has a relevant impact on the mitigation of the UHI and it is characterized and influenced by many environmental parameters and thermal processes, such as: (1) solar radiation absorbed by the foliage; (2) long-wave radiation emitted by foliage into the ambient air and exchanged between the foliage and the air as well as the soil; (3) convective heat transfer phenomena occurring between the air and the foliage as well as between the soil surface and the ambient air of the canopy layer; (4) evapotranspiration and shading occurring in the foliage; and (5) convective heat transfer phenomena between the canopy and the ambient air (Mihalakakou et al. 2023). The substrate depth influences also the capacity of filtering stormwater with deeper substrate having higher water retention capacity thus a more effective means for water management purposes. Also plant diversity plays a role in both storing carbon and reducing carbon loss enhancing also the ability of the soil to absorb carbon (Speak et al. 2012). As all green roofs, one of the primary strengths is their ability to detain, retain, and slow the flow of stormwater, mitigating stress placed on sewers and water treatment facilities and local water cycles. Green roofs unlock the potential of the capture and reuse of untreated rainwater for irrigation and maintenance purposes, relieving pressure on freshwater systems.

Health, Well-being and Air Quality

Green roofs contribute significantly to CO_2 reduction and to the overall decrease of atmospheric pollution and greenhouse gas emissions. By moderating building temperatures, they help keep indoor environments at more stable levels (indoor temperature reduction up to 15°C), which in turn reduces the demand for air-conditioning (Mihalakakou et al. 2023). Lower energy consumption (cooling load reduction up to 70%) directly translates into a decrease in carbon dioxide emissions and other air-polluting criteria. Through this mechanism, green roof technology plays a relevant role in mitigating air pollution and limiting the release of greenhouse gases, thereby delivering both immediate and long-term benefits for the atmosphere and for human health. In addition, green roofs help prevent and reduce a wide range of air and pollutants (e.g., $PM_{2.5}$, PM_{10}, O_3, NO_2), enhancing environmental quality in densely populated urban areas. The carbon sequestration is performed by the plants and substrates and indirectly by energy savings due to the reduction of the building energy consumption both depending on the substrates' type and depth as well as the plant species richness and plant functional diversity (e.g. grasses, bushes, succulents), density and cover. To this regard, semi-intensive green roofs with grasses and forbs perform better than extensive green roofs with succulents. The thermal comfort associated with green roofs may also have indirect positive effects on those living or working inside the buildings they cover. Occupants of greener buildings often report higher levels of relaxation and well-being, which can be reflected in reduced absenteeism and improved workplace satisfaction. In this way, green roofs support not only environmental sustainability but also healthier, more comfortable, and more productive urban lifestyles. Beyond their environmental impact, SIGR also provides a variety of social and health-related benefits: visual and physical contact with natural greenery has been shown to offer a wide range of direct and indirect advantages for people, including improvements in both physical and mental health. Exposure to green space can support reductions in heart rate and blood pressure, alleviate respiratory health problems, and promote overall well-being. The presence of high-quality natural landscapes in urban areas can also influence how people feel, behave, and work. By lowering stress levels and counteracting feelings of sadness, additional greenery can improve mood and enhance productivity.

Biodiverse roof

Section A - General description

Fig. 4 – Biodiverse roof on a multi-level parking building in Manarola, Liguria, Italy (Source: Riccardo Guarino 2016).

Description

Biodiverse green roof (BGR) or 'brown roofs' were developed, respectively, in Switzerland and the United Kingdom to create urban areas with biodiversity conservation potential, by replicating near-natural habitats and host rare plants and animals, and relatively undisturbed (Baumann 2006; Brenneisen 2006; Dunnett 2015; Grant 2006). The genesis of biodiverse roofs took origin from long-term monitoring studies on extensive green roof where it was noticed that species establishment and succession was affected by the substrate kind and thickness, climatic conditions and of course time. For instance, on the traditional roofs constructed in Germany at the beginning of the 19th century and characterised by a coat of sand and gravel protecting the waterproof membrane, the first stadium (couple of years) was dominated by commensal species, while in the following 10 to 30 years, by meadows species in deeper substrate or shaded areas, or mosses and Crassulaceae species in shallow substrate and fully exposed areas (Thuring and Grant 2016). The fundamental design criterion for the construction of green roofs for biodiversity, consisted in creating micro-mosaic of different contiguous habitats capable to host different biological forms of plants and animals. The most relevant design characteristics distinguishing BGRs from conventional GRs are (Catalano et al. 2016a): 1) the creation of high spatial heterogeneity by varying substrate thickness and type, and adding extra features such as small temporary ponds, dead wood and other biodiversity shelters; 2) the selection of autochthonous plant species of the same ecotype or biogeographical region to foster local species dispersion also across cities (stepping-stones and metapopulation); the low maintenance and limited disturbance.

Synonyms

Brown roofs; ruderal green roofs; biotope roofs; soil-based green roofs

Section B - Technical details

Implementation conditions

When designing green roofs, it is necessary to correctly identify the permanent load, which must be assessed in relation to the materials comprising the individual layers and elements and, for safety reasons, to the fact that these elements may be completely saturated with water. Therefore, the values considered for static evaluation must be the densities under saturation conditions of all the individual layers or elements used in the built-up. An important factor to consider when designing any green roof is the dead load capacity (or weight) that the roof exerts onto a building. New buildings can be designed to ensure that they can withstand the weight of a green roof, while, when retrofitting onto an existing building the maximum load and carrying capacity of the roof structure mut be assessed by a structural engineer prior to installation. Generally, Biodiverse green roofs possessing the features of both extensive and simple-intensive roofs and a substrate which varies between 8 cm and 20 cm, therefore loads vary from about 100 Kg/m2 (typical of extensive green roofs) and about 400 Kg/m2 of semi-intensive green roofs. Biodiverse green roofs are based on shallow, low nutrient substrates (an average depth of 13 cm) and have low maintenance requirements; by varying substrate depth, the roof can support a greater diversity of plants and therefore biodiversity: mosses, succulents, herbaceous plants and grasses together with arthropods. Since the creation of habitat patches is one of the key design features, in retrofitting cases, the higher substrate thickness or heavier materials can be situated in correspondence of the pillars sustaining the roofs.

Design features

Similarly to all green roofs, the built up is the same as other conventional green roofs (FLL 2018; Catalano et al. 2018): 1) structural support; 2) root-resistant waterproofing; 3) mechanical protection layer; 4) drainage layer (gravel, plastic honeycomb elements, or modular drainage panels) that allows excess water to be discharged while retaining a portion useful for root absorption; 5) filter fabric to prevent the passage of fine particles; 6) growing substrate; 7) vegetation. Both irrigation and fertilisation are not required because resiliency and the low resources consumption is the requisite of all biodiverse green roof. The major difference to the other kind of green roofs is related to the substrate layer and therefore the vegetation. Keys design features are (Catalano et al. 2016a; 2018): (1) spatial heterogeneity, (2) use of autochthonous plant species of the same biogeographical region and (3) low maintenance and disturbance. As for the first point, fine-grained patchwork of different, contiguous habitats capable of hosting different biocoenoses can be obtained by varying the substrate thickness and kind, adding extra biodiversity-aiding structures such as stones, trunks, branches or other biodiversity shelters, and creating temporary ponds to offer water source for insects and birds while favouring the establishment of ephemeral hygrophilous biocenoses. As for the second point, the selection of plant species belonging of the same biogeographical region shall favour species already adapted to local conditions thus enhancing the resilience of these novel ecosystems (SIA 2013). In turn, the vegetation should also attract pollinators and support them with food, nesting places and reproduction sites. As for the third point, it is known from applied ecology that to a moderate disturbance correspond to a higher biodiversity (Bellini et al. 2025; Catalano et al. 2016b). Therefore, biodiverse green roofs require only a minimum maintenance limited to eradication of unwanted invasive species or trees juveniles. In practice, for example, could consist in planting shrubs on deeper substrate of 15 cm, sowing herbs on lower substrate depth of 10 cm, and spreading Sedum sprouts on the thinnest substrate depth of 6-8 cm, finally leaving open surfaces (beside the drainage outlets) free from vegetation for arthropods (sand patches or stripes). A critical phase is the dry period, normally in summer, which can cause the death of green roofs dwellers (both flora and fauna). For this, the installation of extra designed features such as dead woods and stones can provide cooler micro-conditions where species can find refugia.

Maintenance

Maintenance on this roof is comparable to extensive green roofs, considering that the area with grasses is not homogeneous and, in any case, works as refugia for species during more extreme conditions and should be kept in place. In case of temporary pond installation, the membrane used to detain water shall be periodically checked. In general, considering that to moderate disturbance often corresponds to a higher biodiversity, these roofs only need low yearly maintenance (eradication of unwonted seedlings and saplings of woody species which might be eventually too heavy for the roof structure or can damage the waterproof membrane). However, the low maintenance regime required for these kinds of GR systems should not influence the periodical check-up of the technical and structural parts.

Section C - Societal challenges

Biodiversity enhancement

Biodiverse green roofs are created to increase urban bio permeability, by mimicking nearby natural habitat sharing similar conditions that on roofs. For example, it would be possible to mimic dry grassland also belonging to priority habitat (Catalano et al. 2016a) such as that of 6220 (Pseudo-steppe with grasses and annuals of the *Thero-Brachypodietea*) of the Natura 2000 Directive (Council Directive 92/43/EEC), but also ruderal habitats (Dunnett 2015). The selection of plant species belonging to the regional species pool and therefore already adapted to local conditions enhances the resilience of these novel ecosystems (SIA 2013). In this way, green roofs can improve the ecological network as they can host metapopulations of targeted species (Ksiazek-Mikenas et al. 2019). To select the right species, Lundholm (2006) introduced the habitat template approach aiming at finding habitat analogues (Lundholm and Richardson 2010) to be imitated on GRs, while Catalano et al. (2021) suggested a phytosociological approach to select the species that grow together in shared environmental condition. In any circumstances on biodiverse green roofs, spontaneous colonization shall be encouraged (Muratet et al. 2024), except for invasive species or trees juveniles. When biodiversity conservation is concerned, the use of local soil (topsoil) is also encouraged because of the seed bank, microorganisms and fungi contained in it (Best et al. 2015; Van Der Kolk et al. 2023). In some countries the creation of biodiverse roofs is considered as a compensation measure by law (Ishimatsu and Ito 2013) when favouring specific endangered species (as in the case of the black redstart in UK, and the lapwing in Switzerland).

Climate Resilience and Water management

Regarding both the performance of biodiverse green roofs, possessing both the characteristics of extensive and semi-intensive green roofs, they have an intermediate performance regarding their benefits towards the challenges of climate resilience and water management. However, they contribute in mitigating UHI water quality. The benefits offered by GR can be categorized as follows

Energy benefits directly expressed through the reduction of the cooling and heating load depend strongly on building characteristics and heat transfer processes

Water management services provided by GRs depend on the plant species composition, plant strategy to uptake water, substrate type and thickness (water storage capacity), as well as the intensity of the rain event, where the role of spontaneous colonising vegetation is in this type of green roof quite relevant (Schrieke et al. 2023).

Health, Well-being and Air Quality

As the other green roof types, biodiverse green roofs (BGR) contribute to improve air quality by direct thanks to both plant and soil, in an intermediate level compared to extensive and semi-intensive green roofs. BGR are not thought to be visited by people to keep the disturbance of the biotope at minimum level. Nevertheless, such roofs can be used for education purposes in schools to increase awareness for biodiversity but also towards nexus among ecosystem services and biodiversity (Cole et al. 2024).

Biosolar roof

Section A - General description

Fig. 5 – Biosolar roof on Hallenbad roof (Muttenz, Basel) (Source: Catalano 2014).

Description

Biosolar roofs integrate photovoltaic (PV) panels on green roofs (generally extensive green roofs with an average substrate depth of approximately 12 cm) enhancing the multifunctionality of green roofs by producing electricity (up to 5 %) as well as increasing biodiversity, reducing pollution and other ecosystem services compared to conventional roofing systems (Ciriminna et al. 2019; Fleck et al. 2022; Irga et al. 2023; Lamnatou and Chemisana 2015; Singh and Brar 2020; Schindler et al. 2016). Plant species/PV interaction showed to increase the electricity yield depending also on other factors such as climatic conditions, evapotranspiration and albedo. Higher albedo and evapotranspiration can be obtained at higher plant coverage and can be increased using plants with light-coloured (or with silver hairs) leaves and light watering regime during summer. Succulents (such as *Sedum* spp.) showed to perform better than other forbs not only for the dense cover but also for the relatively low hight thus reducing the risk of shading the panels (Lamnatou and Chemisana 2015). However, *Sedum* species have a reduced evapotranspiration during hot sunny days, therefore also other species can perform well on biosolar roofs such as pulvinate, and prostrate plants (Catalano and Baumann 2017). From biodiversity perspective, PV increase niche diversity than same green roof without PV sheltering plants and animals (Nash et al. 2016). Compared with the combination of PV systems and white or cool roofs (i.e., reflective coatings or materials), biosolar roofs are recommended by multi-criteria decision frameworks that account for both the multiple ecosystem services provided by green roofs and stakeholder preferences (Maurer et al., 2023). By integrating vegetation and photovoltaic systems, biosolar roofs optimize overall performance while maximizing benefits for buildings (e.g., thermal insulation and energy generation) and the environment (e.g., biodiversity enhancement) (Rousset-Rouvière et al., 2025).

Synonyms

Photovoltaic-green roof; Bio Solar Terrace

Section B - Technical details

Implementation conditions

The design of Biosolar roofs must take into consideration both vegetation requirements and panels' energy productivity. In fact, PV modify both the microclimatic conditions beneath and behind them due to the casted shadow, and the way rainwater reach the ground due to the shield effect. Nevertheless, this creates a range of possible niches for species tolerating temporary shading and needing protection from direct sun exposure. Before deciding plant species, take into consideration the expectant maximum height that the plant can reach because tall growing plants can shade the panels and are less able to withstand strong wind. Rainwater accumulated more at the bottom edges of the modules, and it is transmitted through the substrate by capillarity, or it is actively diverted under the panels with capillarity fleeces below the modules. The distribution of water beneath the panels will also depend on the slope of the roof. If the slope of the whole roof area is less than 2%, an appropriately dimensioned and hydraulic effective drainage must be implemented. If the slope exceeds 9%, the waterproofing/root protection must be prevented from slipping off. Besides water storage in the substrate itself, further irrigation systems can be installed, depending on the resources, needs and region (also cooling the air thus increasing panels performance and energy yield). Regarding the statics, the main difference between biosolar roofs compared with other extensive green roofs is the weight of the photovoltaic or thermal panels together with the wind actions which generate extra load.

Design features

The built up of Biosolar green roofs depends on the type and structure holding the solar: Solar systems need to be securely fixed to the roof either weighted down (ballast) or anchored to some the roof of building structure to prevent wind lift effect; the substrate can provide ballast to the structure of PV. Nevertheless, the built up below the substate is the same as conventional green roofs (FLL 2018; Catalano et al. 2018): 1) structural support; 2) root-resistant waterproofing; 3) mechanical protection layer; 4) drainage layer (gravel, plastic honeycomb elements, or modular drainage panels) that allows excess water to be discharged while retaining a portion useful for root absorption; 5) filter fabric to prevent the passage of fine particles; 6) growing substrate; 7) vegetation. As well as biodiverse green roofs, provide spatial heterogeneity through its varying substrate thickness: in front of the panels, where the conditions favour low growing species and succulents, the recommended thickness is 5-7 cm for a length of 50cm. At the back of the panels, where the conditions favour plant growth and biomass, the recommended thickness is 15 cm which can be increased up to 20 cm with the distance to the previous solar array is wider (to 80 cm). It is also advisable to increase the area free from vegetation at the edge and at the water outlets to favour xeric insects. As the substrate constitutes a ballast for the solar panel structure against the wind, the use of excavation soil mixed with sandy gravel from local pits is recommended. There are opportunities to create different habitats of various plant associations within the solar panels' arrays and water percolation strategies (it is also important that the water necessary for plant growth can reach the area below the panels), because the variation of the substrate thickness and the shade of the panels support plant species with different adaptabilities. Drought and stress tolerant species can be planted at the front of the panels while at the back where conditions are shaded and humid, competitive and ruderal species are recommended. What is important is that the plants do not shade the panels thus affecting the energy production; therefore, pulvinate, creeping and prostrate plants should be preferred. More recently, bifacial photovoltaic modules have been implemented on roofs. These modules generate electricity from direct solar radiation incident on the front surface as well as from reflected (indirect) radiation captured on the rear surface. The backside of bifacial modules is typically transparent, allowing the solar cells to harvest light from both sides (Rousset-Rouvière et al. 2025). Their energy yield can be further enhanced when integrated with green roofs, due to increased light reflectance and improved microclimatic conditions (Baumann et al. 2019).

Maintenance

Maintenance of biosolar green consists of regular cleaning, debris removal and when necessary, prune the vegetation in front and between the panels to keep the power outputs at the maximum, but also as for other green roofs, eradicate phanerophytes and invasive weeds. Mowing is typically not required; however, it may be necessary in areas adjacent to the panels. In these cases, removal of aboveground biomass is essential to avoid excessive nutrient accumulation in the substrate. It is also necessary to verify that the vegetation is healthy and the soil is not eroded or moved by winds exposing underlying layers working as ballast for the PV. Supplementary or electronic devices such as irrigation and drainage systems but also inverters and electric wires, should be also checked to prevent floods or fires or reduce the performance of the PV. Finally, as all extensive green roofs plants can dry out in hot summers, thus objects that can generate sparks, glass (e.g. bottles) or cigarette ends must be avoided. However, the risk of spreading fire through wind is limited because the biomass is relatively small and the mineral substrate layer is reducing the potential inflammability risk.

Section C - Societal Challenges

Biodiversity enhancement

Biosolar roofs are a win-win solution for both the building and biodiversity as the presence of panels creates different micro climatic conditions below and between the panels for insects and plants favoured by shading or the protection from wind (Rousset-Rouvière et al. 2025). The installation of a solar systems on green roof can mitigate some of the harsh conditions typical of extensive green roofs: high temperatures, higher winds, constant sun exposure, high evaporation. In fact, panels or collectors shade against wind and sun creating more favourable conditions for plant which generally increase in density and diversity, but also an increased water retention as the rate of evapotranspiration ratio is reduced. Thus, biosolar roofs are richer in species (both flora and fauna) than conventional extensive green roofs due to the diverse ecological niches and habitats created by the panels (Nash et al. 2016).

Climate Resilience and Water management

The cooling effect of green roofs through evapotranspiration can benefit an integrated solar system by reducing not just the surrounding air temperature, but panel temperatures as well: the milder micro-climate due to the presence of the vegetation can help reduce the operating temperature, keeping PV closer to their optimal working temperature. The degree to which this effect increases electricity generation ranges from 2 to 8% annually (Catalano and Baumann 2017; Shafique et al. 2020). These benefits will depend on several factors including the climate, the panel height from the substrate, the plant species used and their density (cover), and the presence of irrigation. For example, panels that are mounted too close to the substrate will limit the circulation of air underneath, reducing the cooling effect. Similarly, different plant species transpire at different rates, therefore plant communities have a different impact on cooling. A broad plant palette will provide a broader array of performance and benefit, along with enhancing biodiversity. By employing bifacial photovoltaic modules (which generate electricity on both sides of the panel), albedo plays a crucial role: PV can have a 17% higher yield due to the higher albedo provided, for example, by silver-leaved plants or light-coloured substrates, when compared with standard green roof (Rousset-Rouvière et al. 2025).

Health, Well-being and Air Quality

As other green roofs, plants on roofs bind and absorb fine dust and other particulates, filtering them out of circulation. Similarly, green roofs bind and store carbon over time, in growing media and plants, storing and utilizing it for photosynthesis. Finally, the harvesting of green roof derived biomass can be used to contribute to regenerative energy concepts on a district scale.

Blue-green roof

Section A - General Description

Fig. 6 – Blue-green roof in Nevio Scala Winery in Lozzo (Source: DAKU Italia 2025).

Description

Blue and green roofs are characterised by vegetated roofs that collect, store and reuse rainwater. These roofs prevent water wastage, ensure proper water management during periods of drought and protect against heavy rainfall (Haer et al. 2022). A distinctive feature of the blue and green roof is its double cavity underneath to collect and retain rainwater. The first cavity collects and retains every raindrop of the water. The second cavity collects excess water from the first cavity, which is then used for irrigation. Irrigation water, instead of being delivered by traditional systems, is released slowly to the substrate from bottom to top, favouring horizontal diffusion and working by capillarity. Using sensors, an IoT system controls the release of water collected between the two cavities to manage rainfall loads in a balanced manner in relation to the weather forecast (DAKU 2024; Eisemberg et al. 2022).

Synonyms

Smart roof, stormwater management roof, capillar smart roof

Section B - Technical details

Implementation conditions

The successful implementation of a blue-green roof requires the integration of specific structural, hydraulic, ecological, and management conditions, all of which are crucial to ensure the proper functioning and long-term performance of the system.

From a structural standpoint, the roof must provide sufficient load-bearing capacity to support the combined weight of the saturated substrate and retained water - often exceeding 200 kg/m^2 - and must incorporate a waterproof and root-resistant membrane that complies with recognised standards of durability and impermeability (Almaaitah and Joksimovic 2022).

In hydraulic terms, the system should include a storage layer designed to retain between 20 and 80 L/m^2 of rainwater, coupled with a controlled drainage mechanism. In advanced systems, this may be automated through smart valves operating on weather-forecast-based management, which can reduce runoff by up to 90% during extreme rainfall events (Busker et al. 2022; Haer et al. 2022).

From an ecological perspective, the use of plant species tolerant to alternating hydric stress is essential, along with a lightweight substrate (8-25 cm thick) capable of ensuring adequate water retention, root aeration, and mechanical stability (Cristiano et al. 2022).

The management component requires periodic maintenance and, in more advanced configurations, the integration of monitoring sensors to measure water levels and vegetation health, thereby optimising the functional response of the roof (Richter et al. 2023).

Finally, urban and climatic conditions must guarantee compliance with local runoff regulations and adaptation to site-specific rainfall patterns, in order to maximise flood-risk mitigation and enhance the roof's microclimatic contribution within the urban environment (Richter et al. 2023).

Design features

From a constructional perspective, the blue-green roof is configured as a multi-layered system, in which each layer performs a specific and interdependent function. Above the load-bearing structure lies the waterproof and root-resistant membrane, typically made of PVC, EPDM, or modified bitumen, combined with a protective geotextile layer that distributes loads and prevents mechanical damage (Cristiano et al. 2022).

The blue layer, the technological core of the system, consists of cellular or modular units made of HDPE or recycled polypropylene, with a height ranging from 5 to 12 cm and a storage capacity between 20 and 80 L/m^2. This component enables the temporary retention of rainwater and its gradual release through manual or automated control devices (Busker et al. 2022; Haer et al. 2022).

Above the hydraulic layer, a geotextile filter prevents the migration of fine particles and preserves the system's permeability. The green layer, or growing medium, consists of a lightweight and porous substrate composed of materials such as pumice, perlite, expanded clay, and organic compost, with a thickness of 8–25 cm, providing adequate water retention, root aeration, and mechanical stability.

The vegetative cover includes species adapted to the local climate and ecological objectives of the project, mainly sedum, grasses, and aromatic plants capable of withstanding alternating hydric stress (Richter et al. 2023). In more advanced systems, integrated IoT sensors monitor water levels, substrate moisture, and surface temperature, enabling adaptive and predictive management of drainage and irrigation (Busker et al. 2022). In this configuration, the blue-green roof functions as a technical-ecological device that combines hydraulic efficiency, thermal comfort, and urban environmental value.

Maintenance

Regular maintenance represents a critical aspect in ensuring the long-term durability and operational efficiency of blue-green roofs. The main activities concern the hydraulic, vegetative, and structural domains. From a hydraulic perspective, it is essential to periodically verify the performance of drainage and storage devices, clean control valves, and check sensor functionality to prevent blockages and maintain the system's designed water retention capacity (Busker et al. 2022; Haer et al. 2022).

Vegetative maintenance involves the removal of invasive species, replacement of deteriorated plants, and reintegration of the substrate every three to five years. In arid or Mediterranean climates, seasonal supplementary irrigation may be required to preserve vegetation health and coverage uniformity (Cristiano et al. 2022).

On the structural level, an annual inspection of the waterproofing membrane and verification of static loads are essential, particularly in intensive roof systems where accumulated water and mature vegetation may significantly increase weight (Richter et al. 2023).

Finally, the integration of digital monitoring systems enables a predictive maintenance approach, improving water management efficiency, anticipating performance issues, and reducing long-term operational costs (Almaaitah and Joksimovic 2022).

Section C - Societal challenges

Biodiversity enhancement

Blue-green roofs serve as habitats and ecological corridors for urban wildlife (Ndayambaje et al. 2024). Numerous studies highlight their role as biodiversity refuges by mimicking natural habitats. Bird species have been observed using green roofs for feeding and nesting (Washburn et al. 2016). Some cities actively promote rooftop biodiversity through policies. For instance, Basel (Switzerland) requires native plants and soil (Kazmierczak and Carter 2010), Toronto offers biodiversity guidelines (Torrance et al. 2013), and London mandates green roofs to support biodiversity and related benefits (Williams et al. 2014). Species richness on roofs depends on factors like vegetation diversity, roof age, and structural complexity. Higher plant diversity often correlates with greater biomass and more niches, supporting a wider range of species (Cook-Patton 2015; Dinnage et al. 2012). This diversity can also benefit trophic levels beyond biomass, increased plant variety boosts faunal diversity (Brenneisen 2006), with notable rises in animal abundance on roofs featuring complex vegetation layers, from moss/sedum to woody shrubs (Madre et al. 2013). Arthropod diversity also peaks where vegetation is most structurally diverse (Gedge and Kadas 2004). Ultimately, plant diversity creates habitats that attract and sustain diverse insect and wildlife communities (Köhler and Ksiazek-Mikenas 2018).

Climate Resilience

Blue-green roofs decrease CO_2 levels through photosynthesis and storing carbon in plants and roots (Kavehei 2018). Researchers propose that increasing vegetation density in green roof systems can improve their capacity to absorb carbon (Charoenkit and Yiemwattana 2017). Variety of plant species on roofs can significantly impact CO_2 sequestration. For example, plant diversity plays a role in both carbon storage and reducing carbon loss in the short term and further found that a higher diversity of grassland species and specific plant characteristics enhance the absorption of carbon into the soil, increase storage of carbon (Steinbeiss et al. 2008). Consequently, ecosystems with diversity have the potential to facilitate the movement of carbon from the atmosphere to the soil. The impact of plant diversity on carbon sequestration on roofs with different vegetation (sedum, annual plants and a combination of sedum and annual plants) exceeds the decrease in CO_2 concentrations compared to monoculture plantation (Agra et al. 2017).

Urban runoff from surfaces like rooftops is known to contribute to water pollution (Lapointe et al. 2022). Having a variety of plant species on roofs can help address these issues by absorbing stormwater, reducing runoff, and aiding water infiltration (Lundholm et al. 2010). Plant diversity helps to improve the retention of stormwater by developing a range of canopy structures that catch rain, root systems that enhance soil absorption, growth patterns that optimize water uptake in different seasons and efficient use of nutrients to support greater plant growth and water absorption (Dunnett et al. 2008). Plant mixtures outperform monocultures in terms of water retention capabilities (Lundholm et al. 2010). The efficiency in reducing rainwater runoff can be improved by including both annuals and sedum (Maclvor and Lundholm 2011). While sedum is not the most effective at absorbing water and preventing runoff compared to higher diversity plantings, it is resilient and can survive drought conditions without irrigation. Having plants that can quickly absorb moisture between rain events in the season can enhance the water management capabilities of roofs. Recognizing the roles of green roofs for water mangement, it is suggested to use plant combinations to enhance water interception, absorption, and infiltration. Particularly, combinations that include sedum are noted for their ability to withstand disturbances, offering an approach to maximizing the functions of green roofs (Vasl et al. 2017).

Health, Well-being and Air Quality

Blue-green roofs in an urban setting can be beneficial to mental health by decreasing stress and anxiety just from observing them in an urban setting (Wang et al. 2016), while improving cognitive function (Lee et al. 2015), as well as overall wellbeing (Rezaei et al. 2021).

Blue and green roofs are great places for communities to meet and can become attractive places for intergenerational activities, social interaction, and collaboration (World Bank 2021). In addition, blue and green roofs provide recreational spaces encouraging community participation in green projects and fostering a sense of happiness and connection with nature, among city residents (Ndayambaje et al. 2024).

Rooftop agricultural entrepreneurship can create much needed low skill and part-time jobs and engage local communities on cooperative production (World Bank 2021). Moreover, blue-green roofs systems give benefits in terms of energy efficiency, building resilience and property value enhancement (Ndayambaje et al. 2024). They also contribute economically by increasing property value (Manso et al. 2021), sometimes by as much as 16 % (Ichihara and Cohen 2011).

Green façade

Section A - General Description

Fig. 7 – Green façade in Budapest at Bastya Park (Source: Hasanaj 2024).

Description

Green façades are characterised by extensive vegetation that develops vertically and maintains its roots in the ground. The development of green façades occurs in two forms: direct and indirect systems. Direct systems concern with free growth, thanks to the contact of the plants with the building façade or with the aid of anchoring systems inserted into the wall. Indirect systems works with the use of modular and/or tensile systems (grid or linear). Green façades include climbing plants, with long, folding, slender, drooping branches and also trellised plantations of third-size trees. This is the most historicised form of green wall realised with natural elements anchored on vertical building elements (Lambertini 2014; Bit 2012).

Synonyms

Vertical greening; climbing green walls; ground-based greening; vertical greening systems

Section B - Technical details

Implementation conditions

The proper design of a green façade requires compliance with a series of technical, environmental, botanical, managerial, and regulatory conditions that ensure its structural stability and long-term durability.

From a structural perspective, the wall must possess sufficient mechanical strength to support the combined weight of vegetation, substrate, and water, with particular attention to dynamic loads generated by wind and rainfall. In indirect systems, the use of steel cables or metal frameworks positioned 5–15 cm from the wall surface promotes ventilation and prevents moisture accumulation (ENEA 2024). The design must also guarantee safe and accessible maintenance pathways in accordance with building safety regulations.

Microclimatic conditions represent another decisive factor. The orientation of the building directly influences solar radiation exposure and consequently determines the most suitable plant species: south-facing façades favour species adapted to living in arid environments or in conditions of limited water availability, whereas north-facing walls require shade-tolerant plants (Chojnacka et al. 2024). Additional climatic variables - such as wind velocity, relative humidity, and seasonal temperature variation - affect both plant water requirements and irrigation frequency (Cuce et al. 2021).

From a regulatory standpoint, the installation of green façades must comply with local building rules and landscape conservation regulations, particularly within heritage-protected contexts (ENEA 2024).

Design features

A green façade is a composite system that integrates both architectural and biological components to ensure hydraulic efficiency, mechanical stability, and long-term vegetative vitality. Its main elements include the load-bearing structure, the vegetation support system, the growth substrate, and the irrigation and drainage systems.

The load-bearing structure may coincide with the building's external wall or consist of an independent substructure made of stainless steel or anodised aluminium, anchored by spacer brackets that create a ventilated air cavity. This configuration enhances transpiration, prevents moisture accumulation, and helps preserve the integrity of the façade cladding (ENEA 2024).

The vegetation support system sustains the growth of climbing or trailing plants, which may either adhere directly to the wall surface (direct façades) or develop on detached metallic frameworks (indirect façades). The latter configuration offers greater durability, improved air circulation, and easier maintenance (Cuce et al. 2021).

The growth substrate, the biological core of the system, consists of a lightweight, porous mixture of organic and inert materials such as coconut fibre, perlite, lapillus, and expanded clay. Its thickness ranges from 10 to 30 cm, depending on the vegetation type. The growth modules or containers, typically made of stainless steel or high-density polyethylene (HDPE), are equipped with drainage openings and replaceable anchoring systems (ENEA 2024).

Plant selection favours native or well-acclimatised species with non-invasive root systems: tolerant to drought and water scarcity plants for south-facing façades, shade-tolerant species for north-facing ones, and deciduous species for temperate climates, providing summer shading and winter solar permeability (ENEA 2024).

The irrigation systems generally employ drip micro-irrigation, managed by automatic control units equipped with temperature and humidity sensors. In more advanced configurations, the system integrates fertigation units and rainwater storage tanks, thereby promoting water sustainability (Knifka et al. 2023). The drainage layer, composed of geotextile filters and granular materials, prevents water stagnation and ensures root health and substrate aeration.

Maintenance

A scheduled maintenance strategy is fundamental to ensuring the long-term durability and vegetative performance of a green façade system. Routine maintenance activities should be performed on a quarterly basis, while technical inspections of the irrigation network and structural supports are recommended annually (ENEA 2024). These activities typically include periodic pruning, phytosanitary assessment, replacement of non-viable plants, and inspection of the irrigation infrastructure, accompanied by seasonal calibration of the watering system to optimise plant health and water distribution efficiency (ENEA 2024; Knifka et al. 2023).

From a sustainability perspective, the integration of substrate moisture sensors and rainwater harvesting and reuse systems is essential to minimise potable water consumption. In advanced applications, continuous monitoring through sensors measuring temperature, relative humidity and solar radiation, connected to a Building Management System (BMS), enables automated control of irrigation and maintenance operations. This digital management approach enhances operational efficiency, reduces water and energy demand, and ensures consistent performance monitoring of the façade over time (Knifka et al. 2023).

Section c - Societal Challenges

Biodiversity enhancement

Green façades, through the vertical integration of vegetation on building surfaces, play an increasingly recognised role in supporting urban biodiversity. By introducing living plant structures into built environments, they help increase the connectivity of natural areas, acting as ecological stepping stones between fragmented habitats. This is particularly valuable in dense urban settings where continuous green corridors are often limited.

The layered vegetation of green façades creates diverse microhabitats for a range of organisms, including insects, birds, and small invertebrates. As such, they contribute to an increase in habitat diversity, offering shelter, food sources, and nesting opportunities across varying vertical levels. Over time, these conditions support local species richness, promoting an increase in both native species and taxonomic groups (Francis and Lorimer 2011; Manso and Castro-Gomes 2015).

Climate Resilience

Green façades remove carbon through storage in vegetation and associated soil layers. Plants on green façades absorb atmospheric CO_2 during photosynthesis, while the substrate and plant biomass serve as carbon sinks, aiding in the long-term sequestration of carbon (Perini et al. 2011).

Green façades reduce greenhouse gas emissions indirectly by lowering building energy consumption. The vegetative layer provides insulation and shading, thereby reducing the need for air conditioning in summer and heating in winter (Puppim de Oliveira et al. 2024).

Green façades enhance microclimatic mitigation capacity in urban environments. By shading building surfaces, reducing heat absorption, and releasing moisture through evapotranspiration, they contribute to lower surface and air temperatures, helping to mitigate the urban heat island effect and improving thermal comfort at the pedestrian level (Ottelé et al. 2011).

Green façades contribute to the urban stormwater management by reducing the surface runoff. Vegetation integrated into building walls intercepts rainfall, retaining a portion of it on leaves and stems through canopy storage. A fraction of this intercepted water is then lost through evapotranspiration, while the remainder is slowed down, reducing the intensity and volume of water reaching the ground (Puppim de Oliveira et al. 2024). In systems where green façades include a growing medium or are combined with green roofs or permeable surfaces, their capacity to absorb and delay runoff is enhanced (Li and Babcock 2014). This reduction in peak flow contributes to lowering the risk of urban flooding, particularly during intense rain events. Green façades help to reduce the burden on traditional drainage systems, thus playing a valuable role in sustainable urban drainage strategies (Öztürk et al. 2024).

Health, Well-being and Air Quality

Green façades and green spaces have benefits for mental health and the reduction of chronic stress. Research conducted using virtual reality experiments has shown that exposure to vertical vegetation on building façades produces a greater stress-reducing effect compared to simple aesthetic interventions such as painting a wall (Chan et al. 2021). The integration of natural vertical elements into the urban environment can significantly contribute to people's psychological well-being.

Furthermore, studies on long-term exposure to residential green spaces have found that greater access to nature is associated with a lower risk of anxiety and depression (Engemann et al. 2019). The presence of urban green therefore plays a protective role for mental health, helping to reduce symptoms of common psychological disorders and enhance the overall well-being of the population.

Green wall

Section A - General Description

Fig. 8 – Green wall in the Sorgane neighborhood in Florence (Source: Hasanaj 2025).

Description

Green walls are controlled-growth living plant systems that grow on a vertical structure with above-ground vegetation, including ground cover plants, shrubs, grasses and herbs. They are complex systems involving planting of species that are integrated with technological and plant components, including the irrigation system that provides the water and mineral essential nutrients. Green walls mainly consist of four functional layers: structural support, growing substrate, operating and management system and plant structure (Lambertini 2014; Croce and Vettorato 2021).

The substrate of green walls can be organic or artificial (expanded resin, felt, perlite, mineral wool). The solution system is characterised by hydroponic cultivation and allow a wide variety of vegetation along the vertical surface (Perini 2013; Croce and Vettorato 2021).

Two methods exist for the application of the vegetation; plants can grow in lightweight felt layers without requiring a soil substrate (i.e. continuous green walls), or in panels constituted by specific supporting elements (i.e. modular green walls) (Manso and João Castro-Gomes 2015).

Synonyms

Living walls; vertical gardens; green walls systems; moss walls

Section B - Technical details

Implementation conditions

The implementation of a green wall requires the definition of structural, mechanical, and biological parameters to ensure stability, durability, and long-term sustainability. The supporting structure must be designed to withstand both permanent and variable loads resulting from the weight of the substrate, water, vegetation, and accidental actions. When saturated with water, such systems can reach loads of 150–250 kg/m^2, making it essential to verify the load-bearing capacity and assess compatibility with waterproofing and anchoring systems (ENEA 2024; FLL 2018; Manouchehri et al. 2024).

A ventilated cavity between the wall surface and the vegetated modules is recommended to prevent moisture accumulation and to promote natural convection, with positive effects on material durability and on the thermo-hygrometric performance of the building envelope (ENEA 2024; City of Hamburg 2018; State of Victoria 2014).

The solution should include automated irrigation and efficient drainage, with provisions for rainwater collection and reuse. The integration of moisture sensors and control systems reduces water consumption and optimises resource management (ENEA 2024; GIZ 2024; Ode Sang et al. 2022).

Plant species selection should be consistent with local microclimatic conditions, orientation, and water availability. The use of hardy, perennial species with non-invasive root systems is recommended, alongside a planned maintenance and replacement schedule (ENEA 2024; City of Hamburg 2018).

Life Cycle Assessment (LCA) analyses have demonstrated that the choice of materials, particularly the substrate and supporting structure, and water management strategies significantly influence the environmental impact of green walls. The use of low-energy-intensity components and water recirculation systems contributes to improving the overall environmental performance (Irga et al. 2023; Manouchehri et al. 2024).

Design features

From a construction standpoint, a green wall consists of a metal framework made of galvanised steel or aluminium, which provides mechanical stability and accommodates a ventilated cavity of at least 5 cm between the wall surface and the vegetated modules. The modular panels, manufactured from HDPE, technical felt, or recycled plastic materials, contain the substrate and plant species (ENEA 2024; GIZ 2024; City of Hamburg 2018).

The substrate serve as both anchoring and nutrient. Optimal mixtures combine organic and inorganic components (such as coconut fibre, perlite, and silica sand) to ensure physical stability, adequate drainage, and aeration (ENEA 2024; Manouchehri et al. 2024; FLL 2018).

The irrigation system, a key functional component of the green wall, must ensure uniform water distribution through drip or micro-spray systems. The water used should maintain optimal chemical conditions for nutrient absorption and to prevent physiological imbalances in plants. The integration of collection tanks and recirculation systems enables sustainable water management (ENEA 2024; Irga et al. 2023; GIZ 2024).

Floristic selection should follow both functional and ecological criteria: evergreen and perennial species ensure visual continuity and biological stability, while tropical understorey plants are suitable for indoor or shaded environments. Hardy species are more appropriate for sun-exposed locations (Ode Sang et al. 2022; City of Hamburg 2018).

Installation must comply with a quality control protocol including cleaning and waterproofing of the wall surface, static verification, fixing of the supporting structure with stainless steel anchors, assembly of the modules, and functional testing of the irrigation system. An acclimatisation phase of at least two weeks is recommended, characterised by intensive irrigation and monitoring of microclimatic parameters (ENEA 2024; State of Victoria 2014; GIZ 2024).

Maintenance

The maintenance of a green wall represents an essential phase in the system's life cycle and must be planned from the design stage. Effective management includes monitoring of hydrological and vegetative parameters, scheduled inspections of the structure and irrigation system, replacement of deteriorated plant species, and biomass management through pruning and controlled fertigation (ENEA 2024; GIZ 2024; Manouchehri et al. 2024).

Structural inspections, to be carried out at least biannually, should assess the integrity of metallic components, the stability of fixings, and the functionality of the ventilated cavity. Waterproofing and sealing systems must also be checked to prevent water infiltration (FLL 2018; City of Hamburg 2018). The irrigation system requires periodic cleaning of filters and nozzles, verification of flow rate, and water quality control. The efficiency of drainage and recirculation tanks is crucial to prevent waterlogging and root stress (ENEA 2024; Irga et al. 2023).

Vegetation monitoring should be conducted monthly, supported by environmental sensors. Quarterly pruning and annual replacement of 5–10% of the plants help maintain biological continuity and uniform coverage (State of Victoria 2014; City of Hamburg 2018). Automated fertigation with nutrient solutions should alternate fertilised and non-fertilised cycles to prevent salt accumulation (ENEA 2024; Irga et al. 2023).

Phytosanitary control should prioritise ecological approaches based on preventive monitoring and targeted biological treatments, avoiding broad-spectrum pesticides (Ode Sang et al. 2022). A scheduled maintenance plan with routine, semi-annual, and annual inspections ensures traceability of interventions and overall system efficiency (GIZ 2024). The service life of a well-maintained green wall is estimated at 20–25 years, with replacement of modules and major components every 8–10 years (ENEA 2024). Systematic maintenance preserves both the ecological functionality and the long-term durability of green infrastructure in the urban context.

Section C - Societal challenges

Biodiversity enhancement

Green walls contribute to an increase in habitat diversity within urban environments by offering new ecological niches for a wide range of organisms, including pollinating insects, birds, and small invertebrates. Thanks to the variety of plant species that can be cultivated on these vertical structures, there is an observable rise in local biodiversity, both in terms of flora and fauna. The integration of green walls into the urban landscape not only enhances aesthetics and air quality, but also supports the creation of microhabitats that sustain richer and more diverse biological communities, thereby contributing to the ecological resilience of urban ecosystems (Collins et al. 2017; Vannik et al. 2025).

Green walls can support biodiversity in cities at a landscape scale by acting as a "corridor" or "stepping stone" to facilitate movement and despersal (Angold et al. 2006). A well-connected network, managed at a landscape scale, will increase the stability of urban biodiversity in the face of increased disturbances and stochastic changes (Goddard et al. 2010).

Climate Resilience

Green walls play a significant role in enhancing climate resilience. Through the process of photosynthesis, the vegetation in green walls sequesters atmospheric carbon dioxide, contributing to direct carbon removal. Moreover, by providing natural insulation and shading, green walls can effectively reduce cooling energy consumption in various urban microclimates, thereby indirectly decreasing greenhouse gas emissions associated with energy production (Bakhtyari et al. 2024).

Additionally, green walls contribute to improved microclimatic conditions by moderating temperature extremes, increasing humidity and reducing wind speed around buildings. The optimal orientation of green walls can significantly reduce building surface temperatures, enhancing thermal comfort and reducing the urban heat island effect (Jayasooriya et al. 2025). The integration of green walls with renewable energy systems, such as photovoltaic panels, has been explored to enhance energy production.

The integration of green walls into buildings not only improves water quality but also contributes to sustainable water management practices. By treating greywater on-site, these systems decrease the load on municipal wastewater treatment facilities.

Green walls can support urban greywater recycling by using vegetation and lightweight growing layers to improve water quality before reuse. Recent studies show that systems with ornamental plants can be effective in treating greywater and can therefore be integrated into urban design strategies (Dal Ferro et al. 2021). Large-scale applications have also shown promising results in reducing unwanted substances and microorganisms, although the choice of the growing layer requires careful attention to avoid negative effects on water quality (Lakho et al. 2021).

Health, Well-being and Air Quality

Green walls contribute to improved air quality by filtering pollutants and particulate matter, thereby enhancing urban environmental conditions (Perini et al. 2017). Beyond their ecological benefits, green walls have been linked to positive mental health outcomes, including reduced chronic stress and anxiety. Exposure to natural elements and biophilic environments, such as vertical greenery, fosters psychological restoration and emotional well-being (Xiaoxue and Huang 2024; Fonseca et al. 2023; Gunn et al. 2022; Shao et al. 2024).

Visual interaction with green walls and natural views promotes a faster recovery from both physiological and psychological stress in older adults, reducing heart rate and perceived anxiety levels (Xiaoxue and Huang 2024).

Both indoor and outdoor green walls contribute to stress reduction, mood enhancement, and an improved perception of psychological comfort, aligning with the broader framework of biophilic design theory (Fonseca et al. 2023). In educational settings, the introduction of green walls in schools has been found to support students' emotional well-being and concentration (Gunn et al. 2022), whereas in workplace environments, living wall systems have been shown to reduce occupational stress and enhance environmental satisfaction (Shao et al. 2024). Exposure to vertical natural elements produces measurable psychological benefits, consistent with the notion that interaction with nature facilitates emotional restoration and the physiological regulation of stress (Bringslimark et al. 2009).

Planter green wall

Section A - General Description

Fig. 9 – Planter green roof in Fukuoka, Japan, designed by Emilio Ambasz (Source: Kenta Mabuchi 2013).

Description

Planter Green Walls represent a typology of indirect vertical greening systems characterised by the use of self-contained planting units - such as pots, planters, boxes, or prefabricated modules—that are not connected to the natural soil but are instead anchored, supported, or integrated into the building façade or an independent structural frame. Within these containers, plants develop in lightweight or engineered substrates, with their root systems confined to the modules and without direct contact with the wall surface (Perini and Rosasco 2013; Lambertini 2014; Bustami et al. 2018; Ottelé 2011).

These systems exhibit a modular design and high configurational flexibility, positioning them as an intermediate solution between conventional direct-rooting green façades and technologically advanced living wall systems (Bustami et al. 2018). Unlike traditional green façades, where vegetation grows from the ground and climbs vertically with the aid of support structures, planter-based systems are entirely independent of the soil and can be installed at any height along the façade, including roofs, parapets, balconies, or freestanding metal frameworks. This structural autonomy enables their application in both new developments and urban retrofit interventions, offering a versatile strategy for the greening and ecological regeneration of existing buildings (GIZ 2024).

Planter Green Walls frequently integrate automated irrigation and fertigation systems, together with rainwater harvesting and recirculation technologies, allowing precise management of water and nutrient resources. Such integrated systems enhance operational efficiency and contribute to the long-term sustainability and performance of vertical greening solutions (Lambertini 2014; Irga et al. 2023).

Synonyms

Hybrid green wall, planter-box-based façade, modular green wall system, indirect greening façade

Section B - Technical details

Implementation conditions

The implementation of a modular container-based vertical greening system follows a well-defined operational sequence. During the design phase, factors such as building orientation, microclimatic conditions, and structural characteristics are analysed in order to determine the optimal arrangement of modules and the most suitable plant species (ENEA 2024; Kraus et al. 2018). Although this solution is particularly suitable for integration into newly constructed buildings—allowing full exploitation of the benefits of an integrated design approach with purpose-built façade containers—it can also be effectively applied to existing structures.

In the latter case, the process includes the installation of a supporting framework composed of load-bearing elements. The subsequent installation of the container modules must ensure proper connection of the irrigation and drainage networks, verifying both water flow efficiency and the integrity of joints.

For both new and retrofit applications, plant installation may involve the use of pre-grown specimens or rooted cuttings, in order to minimise acclimatisation time and achieve an immediate visual and functional impact (Bit 2015; GIZ 2024).

Design features

From a construction perspective, Planter Green Walls can be categorised into two main typologies: terraces and planter boxes, or container-wall systems. Both configurations represent complex systems that integrate structural engineering, architecture, ecology, and landscape design.

The use of terraces or planter boxes as architectural elements enables the controlled growth of trees, shrubs, and herbaceous species within the building structure (Giacomello and Valagussa 2015; Bono et al. 2020). A notable example is the *Bosco Verticale* in Milan, where cantilevered reinforced concrete balconies—projecting up to 3.25 m—incorporate planters for vegetation (1.10 × 1.10 m deep for trees and 0.50 m deep for shrubs), allowing full canopy development (Bianchini n.d.). The multilayer stratigraphy includes a waterproof bituminous membrane, root barrier, drainage layer, geotextile filter, and a volcanic lapillus-based substrate. The drip irrigation system utilizes treated greywater and rainwater, regulated through climatic sensors and automated control (Baratta 2015). Plants are anchored with steel frames and tension cables engineered to withstand wind loads of up to 90 km/h (Giacomello and Valagussa 2015).

Container-wall systems, such as those implemented in the Physics Building of Humboldt University in Berlin-Adlershof, comprise a supporting structure, vegetated modules, and an integrated irrigation and drainage network (Köhler 2015; Oppla n.d.). The modular containers filled with technical substrates are either integrated into the building façade or assembled on independent frames that allow the cultivation of climbing, shrubby, or small-sized species, adapting to diverse architectural configurations and urban contexts.

The functional performance of these systems depends primarily on the correct dimensioning of the growing substrate, which must ensure an optimal balance between water retention capacity, aeration, and mechanical stability, and on the supporting structure, designed to withstand both static and dynamic loads arising from the saturated substrate and plant biomass. The system should be equipped with automated irrigation and fertigation technologies, incorporating sensors to monitor moisture and water supply in relation to climatic conditions. Plant selection must prioritise resilient species compatible with the façade's microclimate and orientation, while climbing plants require the integration of guide structures such as cables or grids (Köhler 2015; Kraus et al. 2018).

Maintenance

The maintenance of Planter Green Walls is a continuous and technically specialised process aimed at ensuring the physiological stability of the vegetation and the durability of the construction components.

A key factor in long-term performance is the efficiency of water supply, which must be achieved through drip irrigation systems, water-retention mechanisms within the containers, and the selection of plant species with low water requirements (Bono et al. 2020).

Routine maintenance includes the periodic calibration of the automated irrigation system, inspection of the fertigation network, and replacement of any deteriorated components. Annual or semi-annual pruning operations, performed by professionals specialised in arboriculture, are essential to control plant growth and to preserve both the safety and the aesthetic quality of the façade covering (Kraus et al. 2018).

Continuous phytosanitary and nutritional monitoring allows the assessment of plant establishment, growth dynamics, and substrate balance, enabling the early detection of environmental stress factors (Bono et al. 2020). The service life of the system may exceed thirty years, provided that regular management of both vegetative and technical components is maintained, with careful attention to substrate quality, drainage efficiency, and compatibility between plant species, microclimatic conditions, and façade orientation (Kraus et al. 2018).

The long-term success of Planter Green Walls depends on an integrated maintenance strategy involving agronomic, engineering, and other expertise, ensuring water-use efficiency, ecological stability, and sustainable management of modular green façades (Köhler 2015).

Section C - Societal challenges

Biodiversity enhancement

The integration of planter green walls into building infrastructure has contributed to increasing habitat diversity in urban environments, providing vertical ecological niches that support a wider range of plant and animal species, and promoting functional biodiversity in highly anthropised settings (Francis and Lorimer 2011). Planter green walls contribute to increasing local diversity, in terms of species, through the creation of heterogeneous microhabitats along vertical surfaces. These provide varied environmental conditions - such as light, moisture, and substrate - that are capable of supporting a broader range of plant and invertebrate organisms, thereby enhancing ecological richness in densely built urban contexts (Ottelé et al. 2011). Finally, the integration of Nature-based Solutions, such as rain gardens, green roofs, and planter green walls, contributes to enhancing connectivity between scattered natural areas, facilitating the ecological flow of species, seeds, and resources, and promoting the resilience of fragmented urban ecosystems (Tzoulas et al. 2007).

Climate Resilience

Planter green walls contribute to the removal of atmospheric carbon through storage in plant biomass, enhancing carbon sequestration capacity in urban settings and mitigating the effects of climate change through photosynthesis and the accumulation of organic carbon in plant tissues (Reyhani et al. 2022). Planter green walls contribute to improving microclimatic mitigation in urban environments by reducing surface temperatures and the urban heat island effect, thanks to plant evapotranspiration and the shading of vertical surfaces (Perini and Rosasco 2013). This mitigation capacity is made possible by the vegetative structure, which modulates the local microclimate by increasing relative humidity and absorbing solar radiation, thereby creating cooler and more comfortable environmental conditions for the surrounding urban spaces (Ascione 2020).

Planter green walls play a significant role in urban stormwater management by mitigating surface runoff. By integrating vegetation into building containment structures, these systems capture rainfall not only from the leaves and stems, where part of the water is temporarily stored (canopy storage), but also in the containers that host the plants. Some of the water is lost through evapotranspiration, while the remaining water is released more slowly, reducing both the flow rate and the overall volume that reaches ground level (Puppim de Oliveira et al. 2024).

Planter green walls used in combination with green roofs or permeable surfaces increase their ability to retain and delay runoff (Li and Babcock 2014). This delay in peak flows contributes to reducing the risk of urban flooding, especially during heavy rainfall.

Health, Well-being and Air Quality

The presence of trees, shrubs, and other types of vegetation in planter green walls significantly improves air quality in urban environments. These plants, in green wall configurations, contribute to capture airborne pollutants such as particulate matter (PM), nitrogen dioxide (NO_2), and carbon dioxide (CO_2) (Viecco et al. 2021). Dense foliage and layered planting in these systems increase the surface area available for filtering contaminants, confirming the general effectiveness of green walls in filtering air (Paull et al. 2020) and making planter green walls an effective tool for enhancing environmental health in cities.

Incorporating natural vertical features into urban settings can play a crucial role in enhancing mental health. Additionally, research examining prolonged exposure to green spaces near homes indicates that increased contact with nature correlates with a reduced likelihood of experiencing anxiety and depression (Engemann et al. 2019).

Co-benefits and key design features of Nature-Based Solutions in the built environment

Nature-Based Solutions (NbS) integrated into buildings create new habitats for flora and fauna. The selection of plant species, substrate depth, and ecological connectivity are determining factors in their ecological effectiveness (Calviño et al. 2023). Studies have shown an increase in plant diversity in older green roofs (Nash et al. 2016) and a greater presence of pollinators associated with flowering species (Jacobs et al. 2023). Higher vegetation cover and structural complexity have been found to enhance arthropod richness (Calviño et al. 2023) and to support urban bird communities (Partridge and Clark 2018).

The implementation of green roofs and walls significantly contributes to the microclimatic regulation of buildings. Compared with conventional roofs, vegetated surfaces can reduce external surface temperatures by up to 35 °C (He et al. 2017) and internal temperatures by up to 20 °C, thereby improving indoor thermal comfort (Hao et al. 2022). Thermal inertia is increased, delaying heat-load peaks and reducing diurnal temperature fluctuations (Guttari et al. 2020). In temperate and cold climates, NbS also provide an insulating effect, maintaining higher indoor temperatures during winter (Juras 2022) and reducing thermal stresses on building materials (Tariku and Hagos 2022).

At the urban scale, building-integrated NbS generate wider environmental benefits by lowering ambient air temperatures by up to 6.4 °C in the airspace between vegetation and building façades (Juras 2022). The associated cooling effect contributes to mitigating the urban heat-island phenomenon (Almaaitah and Joksimovic 2022) and can enhance the efficiency of photovoltaic panels by reducing their surface temperature by more than 8 °C (Arenandan et al. 2022).

Energy performance improvements are also well documented: NbS applied to buildings can reduce cooling energy demand by up to 25 % during summer (Tan et al. 2020) and heating demand by up to 18 % in winter (Zheng 2021). A green roof can yield energy savings of approximately 11.53 kWh/m^2 per year (Cai et al. 2019), with CO_2 emission reductions of up to 27 tonnes per summer season for extensive large-scale installations (Jim and Peng 2012). Although the direct carbon-sequestration capacity of vegetated systems is relatively modest yet measurable, the indirect benefits derived from reduced energy consumption are substantially greater (Kandel et al. 2024).

Green roofs also improve stormwater management, reducing runoff volumes by up to seven-fold compared with conventional roofs (Perales-Momparler et al. 2017) and lowering flood peaks by 82–85 % in intensive systems (Almaaitah and Joksimovic 2022). They can retain up to 96 % of rainfall during light precipitation events (Abualfaraj et al. 2018), with runoff delays exceeding one hour (Tariku and Hagos 2022). Furthermore, they enhance water quality, with reductions of 79–97 % in suspended solids and significant decreases in nitrogen and phosphorus concentrations (Liu et al. 2021).

Beyond environmental outcomes, NbS integrated into buildings deliver notable social and economic benefits. Users report improved well-being and positive perceptions of green spaces (Mesimäki et al. 2019), alongside reductions in noise and enhanced thermal comfort. From an economic perspective, energy savings are substantial (Fleck et al. 2022), and edible living walls can provide up to 46 % of household food requirements (Nagle et al. 2017). Return-on-investment values as high as 660 % have been reported, albeit with relatively long payback periods (Pérez-Urrestarazu et al. 2017).

The effectiveness of NbS applied to buildings depends on a set of critical design parameters that directly influence system performance (Kandel et al. 2024).

A primary consideration concerns the selection of plant species and the quality of the root system, both of which are fundamental to vegetative resilience and to the chemical-physical stability of the substrate. Informed plant selection helps to reduce thermal fluctuations and structural stress, thereby enhancing building durability (Zhang et al. 2019).

Water management is another key factor. The efficiency of green roofs and walls is strongly dependent on substrate moisture rather than vegetation density (Bevilacqua et al. 2015). Well-designed irrigation systems and drainage layers help to maintain optimal moisture content, support plant growth, and improve thermal performance (Tan et al. 2017). Substrate depth contributes to maintaining lower root-zone temperatures (Benedito al. 2023), while the use of root barriers protects building structures from potential damage (Tariku and Hagos 2022).

Substrate design - encompassing depth, composition, and structure - forms the functional foundation of NbS. Greater substrate thickness increases the building's thermal capacity and inertia (Stella and Personne 2021), while the use of porous materials such as lightweight expanded clay aggregate (LECA) improves water retention, reduces overall weight, and enhances thermal efficiency (Tan et al. 2017). Substrate composition also affects filtration capacity, with more porous and heterogeneous mixtures demonstrating higher efficiency in nutrient and pollutant removal (Abualfaraj et al. 2018).

Vegetation design must be tailored to the climatic context. Parameters such as leaf area index (LAI), canopy density, and photosynthetic pathway significantly affect cooling performance and urban heat-island mitigation (Kandel et al. 2024). Moreover, species diversity broadens the range of ecosystem services provided (Olivieri et al. 2013).

Additional influencing factors include the distance between vegetation and the building façade—as observed in vertical greening systems - which affects insulation properties (Piro et al. 2018); as well as building height and surrounding urban context, which influence solar radiation exposure and habitat suitability for insects (Jacobs et al. 2023). Façade orientation also plays a key role: south-facing façades are particularly effective in reducing surface temperatures in temperate climates (Sendra-Arranz et al. 2020).

References

Abualfaraj, Noura, Joseph Cataldo, Yara Elborolosy, et al. 2018. "Monitoring and Modeling the Long-Term Rainfall-Runoff Response of the Jacob K. Javits Center Green Roof." *Water* 10, 11: 1494. https://doi.org/10.3390/w10111494.

Agra, Har'el, Tamir Klein, Amiel Vasl, Gyongyver Kadas, e Leon Blaustein. 2017. "Measuring the Effect of Plant-Community Composition on Carbon Fixation on Green Roofs." *Urban Forestry & Urban Greening* 24: 1-4. https://doi.org/10.1016/j.ufug.2017.03.003.

Almaaitah, Tamer, e Darko Joksimovic. 2022. "Hydrologic and Thermal Performance of a Full-Scale Farmed Blue–Green Roof." *Water* 14, 11: 1700. https://doi.org/10.3390/w14111700.

Andreucci, Maria Beatrice, Alessio Russo, e Agnieszka Olszewska-Guizzo. 2019. "Designing Urban Green Blue Infrastructure for Mental Health and Elderly Wellbeing." *Sustainability* 11, 22: 6425. https://doi.org/10.3390/su11226425.

Angold, P.G., J.P. Sadler, M.O. Hill, et al. 2006. "Biodiversity in Urban Habitat Patches." *Science of the Total Environment* 360, 1: 196-204. https://doi.org/10.1016/j.scitotenv.2005.08.035.

Arenandan, Vanisha, Jee Khai Wong, Ali Najah Ahmed, e Ming Fai Chow. 2022. "Efficiency Enhancement in Energy Production of Photovoltaic Modules through Green Roof Installation under Tropical Climates." *Ain Shams Engineering Journal* 13, 5: 101741. https://doi.org/10.1016/j.asej.2022.101741.

Ascione, Fabrizio, Rosa Francesca De Masi, Margherita Mastellone, Silvia Ruggiero, e Giuseppe Peter Vanoli. 2020. "Green Walls, a Critical Review: Knowledge Gaps, Design Parameters, Thermal Performances and Multi-Criteria Design Approaches." *Energies* 13, 9: 2296. https://doi.org/10.3390/en13092296.

Bakhtyari, Vahid, Kaveh Fattahi, Khosro Movahed, e Anna Franz. 2024. "Investigating the Effect of Living Walls on Cooling Energy Consumption in Various Urban Microclimates, Building Heights, and Greenery Coverage Areas." *Sustainability* 16, 2: 920. https://doi.org/10.3390/su16020920.

Baratta, Adolfo F.L. 2015. "Il laterizio celato: Soluzioni tecnologiche nel Bosco Verticale." *Costruire in Laterizio* 163. https://www.laterizio.it/pubblicazioni/costruire-in-laterizio/cil-183-oltre-confine.html (2025-06-21).

Baumann, Nathalie. 2006. "Ground-Nesting Birds on Green Roofs in Switzerland: Preliminary Observations." *Urban Habitats* 4, 1: 37-50. https://www.urbanhabitats.org/v04n01/birds_pdf.pdf (2025-06-21).

Baumann, Thomas, Hartmut Nussbaumer, Markus Klenk, Andreas Dreisiebner, Fabian Carigiet, e Franz Baumgartner. 2019. "Photovoltaic Systems with Vertically Mounted Bifacial PV Modules in Combination with Green Roofs." *Solar Energy* 190: 139-46. https://doi.org/10.1016/j.solener.2019.08.014.

Bellini, Amii, Valentina Savo, Giulia Caneva, Elettra D'Amico, Roberto Casalini, e Flavia Bartoli. 2025. "How a Green Roof Becomes Biodiverse: Vegetation Analysis on a Green Roof with No Maintenance in Rome (Italy)." *Plants* 14, 20: 3180. https://doi.org/10.3390/plants14203180.

Best, Brooke Byerley, Rebecca K. Swadek, e Tony L. Burgess. 2015. "Soil-Based Green Roofs." In *Green Roof Ecosystems*, edited by Richard K. Sutton. Ecological Studies. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-14983-7_6.

Bevilacqua, Piero, Julià Coma, Gabriel Pérez, et al. 2015. "Plant Cover and Floristic Composition Effect on Thermal Behaviour of Extensive Green Roofs." *Building and Environment* 92: 305-16. https://doi.org/10.1016/j.buildenv.2015.04.026.

Bianchini, Riccardo. s.d. "Il Bosco Verticale di Boeri: da fenomeno ad archetipo?" *Inexhibit*. https://www.inexhibit.com/it/case-studies/il-bosco-verticale-di-boeri-da-fenomeno-ad-archetipo/ (2025-06-21).

Bit, Eduardo. 2012. *Il nuovo verde verticale. Tecnologie, progetti, linee guida*. Assago: Wolters Kluwer Italia.

Bono, Lorenzo, Marco Callerio, Giulio Conte, Anacleto Rizzo, e Iliriana Sejdullahu. 2020. *Soluzioni naturalistiche (NBS) per la città metropolitana di Milano: schede tecniche – verde tecnico in ambiente costruito*. Progetto LIFE Metro Adapt. https://www.lifemetroadapt.eu/it/wp-content/uploads/sites/2/2020/05/Schede-Tecniche_Verde-Tecnico_pub.pdf (2025-06-21).

Braaker, S., J. Ghazoul, M.K. Obrist, e M. Moretti. 2014. "Habitat Connectivity Shapes Urban Arthropod Communities: The Key Role of Green Roofs." *Ecology* 95, 4: 1010-21. https://doi.org/10.1890/13-0705.1.
Brenneisen, Stephan. 2006. "Space for Urban Wildlife: Designing Green Roofs as Habitats in Switzerland." *Urban Habitats* 4, 1: 27-36. https://www.urbanhabitats.org/v04n01/wildlife_full.html (2025-06-21).
Bringslimark, Tina, Terry Hartig, e Grete G. Patil. 2009. "The Psychological Benefits of Indoor Plants: A Critical Review of the Experimental Literature." *Journal of Environmental Psychology* 29, 4: 422-33. https://doi.org/10.1016/j.jenvp.2009.05.001.
Busker, Tim, Hans de Moel, Toon Haer, et al. 2022. "Blue-Green Roofs with Forecast-Based Operation to Reduce the Impact of Weather Extremes." *Journal of Environmental Management* 301: 113750. https://doi.org/10.1016/j.jenvman.2021.113750.
Bustami, Rosmina A., Martin Belusko, James Ward, e Simon Beecham. 2018. "Vertical Greenery Systems: A Systematic Review of Research Trends." *Building and Environment* 146: 226-37. https://doi.org/10.1016/j.buildenv.2018.09.045.
Cai, Lu, Xiao-Ping Feng, Jing-Yan Yu, Qian-Chao Xiang, e Rui Chen. 2019. "Reduction in Carbon Dioxide Emission and Energy Savings Obtained by Using a Green Roof." *Aerosol and Air Quality Research* 19, 11: 2432-45. https://doi.org/10.4209/aaqr.2019.09.0455.
Calviño, Ana A., Julia Tavella, Hernán M. Beccacece, et al. 2023. "The Native – Exotic Plant Choice in Green Roof Design: Using a Multicriteria Decision Framework to Select Plant Tolerant Species That Foster Beneficial Arthropods." *Ecological Engineering* 187: 106871. https://doi.org/10.1016/j.ecoleng.2022.106871.
Catalano, Chiara, e Nathalie Baumann. 2017. "Biosolar Roofs: A Symbiosis between Biodiverse Green Roofs and Renewable Energy." *City Green* 15: 42-49. https://www.nparks.gov.sg/cuge/resources/publications/citygreen/verdant-cities (2025-06-21).
Catalano, Chiara, Stephan Brenneisen, Nathalie Baumann, e Riccardo Guarino. 2016a. "I Tetti Verdi di Tipo Estensivo: Biodiversità ad Alta Quota." *Reticula* 12: 1-10. https://www.isprambiente.gov.it/it/pubblicazioni/periodici-tecnici/reticula/reticula-n.-12-2016 (2025-06-21).
Catalano, Chiara, Vito Armando Laudicina, Luigi Badalucco, e Riccardo Guarino. 2018. "Some European Green Roof Norms and Guidelines through the Lens of Biodiversity: Do Ecoregions and Plant Traits Also Matter?" *Ecological Engineering* 115: 15-26. https://doi.org/10.1016/j.ecoleng.2018.01.006.
Catalano, Chiara, Corrado Marcenò, Vito Armando Laudicina, e Riccardo Guarino. 2016b. "Thirty Years Unmanaged Green Roofs: Ecological Research and Design Implications." *Landscape and Urban Planning* 149: 11-19. https://doi.org/10.1016/j.landurbplan.2016.01.003.
Catalano, Chiara, Salvatore Pasta, e Riccardo Guarino. 2021. "A Plant Sociological Procedure for the Ecological Design and Enhancement of Urban Green Infrastructure." In *Urban Services to Ecosystems: Green Infrastructure Benefits from the Landscape to the Urban Scale*, edited by Chiara Catalano, Maria Beatrice Andreucci, Riccardo Guarino, Francesca Bretzel, Manfredi Leone, e Salvatore Pasta. Future City 17. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-75929-2_3.
Chan, Sarah Hian May, Lin Qiu, Gianluca Esposito, e Ky Phong Mai. 2021. "Vertical Greenery Buffers against Stress: Evidence from Psychophysiological Responses in Virtual Reality." *Landscape and Urban Planning* 213: 104127. https://doi.org/10.1016/j.landurbplan.2021.104127.
Chenot, Julie, Elie Gaget, Cannelle Moinardeau, Renaud Jaunatre, Elise Buisson, e Thierry Dutoit. 2017. "Substrate Composition and Depth Affect Soil Moisture Behavior and Plant-Soil Relationship on Mediterranean Extensive Green Roofs." *Water* 9, 11: 817. https://doi.org/10.3390/w9110817.
Chojnacka, Katarzyna, Barbara Widera, Marcel Macarulla, et al. 2025. "Green Urban Transition: Interdisciplinary Insights on Green Façades Design in Hot Climates as One of Crucial Strategies for Low-Carbon Development." *Clean Technologies and Environmental Policy* 27, 12: 8533-53. https://doi.org/10.1007/s10098-024-02957-1.

Ciriminna, Rosaria, Francesco Meneguzzo, Mario Pecoraino, e Mario Pagliaro. 2019. "Solar Green Roofs: A Unified Outlook 20 Years On." *Energy Technology* 7, 6: 1900128. https://doi.org/10.1002/ente.201900128.

Climate-Adapt. 2020. "Green Roofs in Basel, Switzerland: Combining Mitigation and Adaptation Measures." https://climate-adapt.eea.europa.eu/en/metadata/case-studies/green-roofs-in-basel-switzerland-combining-mitigation-and-adaptation-measures-1 (2025-06-21).

Cole, Laura B., Lilian Priscilla, Laura Zangori, et al. 2024. "Raising the Green Roof: Enhancing Youth Water Literacy through Built Environment Education." *Sustainability* 16, 10: 4262. https://doi.org/10.3390/su16104262.

Collins, Rebecca, Marije Schaafsma, e Malcolm D. Hudson. 2017. "The Value of Green Walls to Urban Biodiversity." *Land Use Policy* 64: 114-23. https://doi.org/10.1016/j.landusepol.2017.02.025.

Cook-Patton, Susan C. 2015. "Plant Biodiversity on Green Roofs." In *Green Roof Ecosystems*, edited by Richard K. Sutton. Ecological Studies. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-14983-7_8.

Council Directive 92/43/EEC. 1992. *European Council Directive 92/43/EEC of 21 May 1992 on the Conservation of Natural Habitats and of Wild Fauna and Flora*. Official Journal of the European Communities L 206, 22 July 1992: 7-50. https://eur-lex.europa.eu/eli/dir/1992/43/oj/eng (2025-06-21).

Cristiano, Elena, Antonio Annis, Ciro Apollonio, et al. 2022. "Multilayer Blue-Green Roofs as Nature-Based Solutions for Water and Thermal Insulation Management." *Hydrology Research* 53, 9: 1129-49. https://doi.org/10.2166/nh.2022.201.

Croce, Silvia, e Daniele Vettorato. 2021. "Urban Surface Uses for Climate Resilient and Sustainable Cities: A Catalogue of Solutions." *Sustainable Cities and Society* 75: 103313. https://doi.org/10.1016/j.scs.2021.103313.

Cuce, Pinar Mert, Erdem Cuce, Tamer Guclu, e Veysel Demirci. 2021. "Energy Saving Aspects of Green Facades: Current Applications and Challenges." *Green Building & Construction Economics* 2: 18-28. https://doi.org/10.37256/gbce.2220211007.

Daku Italia. 2024. *Blue Green Roof (BGR)*. https://www.daku.it/storage/media/pdf/wStdsj/2024_brochure-daku_bgr_web_compressed.pdf (2025-06-21).

Dal Ferro, Nicola, Chiara De Mattia, Mario Andres Gandini, et al. 2021. "Green Walls to Treat Kitchen Greywater in Urban Areas: Performance from a Pilot-Scale Experiment." *Science of the Total Environment* 757: 144189. https://doi.org/10.1016/j.scitotenv.2020.144189.

Dinnage, Russell, Marc W. Cadotte, Nick M. Haddad, Gregory M. Crutsinger, e David Tilman. 2012. "Diversity of Plant Evolutionary Lineages Promotes Arthropod Diversity." *Ecology Letters* 15, 11: 1308-17. https://doi.org/10.1111/j.1461-0248.2012.01854.x.

Dunnett, Nigel. 2015. "Ruderal Green Roofs." In *Green Roof Ecosystems*, edited by Richard K. Sutton. Ecological Studies. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-14983-7_10.

Dunnett, Nigel, Ayako Nagase, Rosemary Booth, e Philip Grime. 2008. "Influence of Vegetation Composition on Runoff in Two Simulated Green Roof Experiments." *Urban Ecosystems* 11, 4: 385-98. https://doi.org/10.1007/s11252-008-0064-9.

Durà, Vicent Benedito, Enric Meseguer, Carmen Hernández Crespo, Miguel Martín Monerris, Ignacio Andrés Doménech, e M. Eugenia Rodrigo Santamaría. 2023. "Contribution of Green Roofs to Urban Arthropod Biodiversity in a Mediterranean Climate: A Case Study in València, Spain." *Building and Environment* 228: 109865. https://doi.org/10.1016/j.buildenv.2022.109865.

European Environment Agency. 2021. *Nature-Based Solutions in Europe – Policy, Knowledge and Practice for Climate Change Adaptation and Disaster Risk Reduction*. Report no. 01/2021. Luxembourg: Publications Office of the European Union.

Eisenberg, Bernd, Cecilia Chiesa, Leonie K. Fischer, Kristen Jakstis, Vera Polcher, e Hans-Georg Schwarz-v.Raumer. 2022. *Nature-Based Solutions. Technical Handbook Factsheets*. UNaLab Urban Nature Labs e Institut für Landschaftsplanung und Ökologie – ILPÖ.

Elliott, R.M., R.A. Gibson, T.B. Carson, D.E. Marasco, P.J. Culligan, e W.R. McGillis. 2016. "Green Roof Seasonal Variation: Comparison of the Hydrologic Behavior of a Thick and a Thin Extensive System in New York City." *Environmental Research Letters* 11, 7: 074020. https://doi.org/10.1088/1748-9326/11/7/074020.

ENEA. 2024. *Tetti e pareti verdi – Linee guida per l'edilizia sostenibile*. https://italiainclassea.enea.it/filesystemMedia/1/2024/07/3884d264d0ed658791663d963b55bd62.pdf (2025-06-21).

Engemann, Kristine, Carsten Bøcker Pedersen, Lars Arge, Constantinos Tsirogiannis, Preben Bo Mortensen, e Jens-Christian Svenning. 2019. "Residential Green Space in Childhood Is Associated with Lower Risk of Psychiatric Disorders from Adolescence into Adulthood." *Proceedings of the National Academy of Sciences* 116, 11: 5188-93. https://doi.org/10.1073/pnas.1807504116.

Environmental Protection Agency. 2008. *Reducing Urban Heat Islands: Compendium of Strategies – Green Roofs (Chapter 3)*. Washington, DC: EPA. https://www.epa.gov/sites/default/files/2014-08/documents/greenroofscompendium_ch3.pdf (2025-06-21).

European Commission. 2013. *Green Infrastructure (GI) — Enhancing Europe's Natural Capital*. COM(2013) 249 final. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52013DC0249 (2025-06-21).

European Commission. 2021. *Forging a Climate-Resilient Europe – The New EU Strategy on Adaptation to Climate Change*. COM(2021) 82 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN (2025-06-21).

European Commission. 2022. "How to Increase the Use of Nature-Based Solutions in Urban Areas." https://environment.ec.europa.eu/news/how-increase-use-nature-based-solutions-urban-areas-2022-12-07_en (2025-06-21).

Fernandez-Canero, Rafael, e Pedro Gonzalez-Redondo. 2010. "Green Roofs as Habitat for Birds: A Review." *Journal of Animal and Veterinary Advances* 9, 15. https://idus.us.es/bitstream/handle/11441/16209/file_1.pdf?sequence=1 (2025-06-21).

Fleck, R., R. Gill, T.J. Pettit, F.R. Torpy, e P.J. Irga. 2022. "Bio-Solar Green Roofs Increase Solar Energy Output: The Sunny Side of Integrating Sustainable Technologies." *Building and Environment* 226: 109703. https://doi.org/10.1016/j.buildenv.2022.109703.

Fonseca, Fernando, Marina Paschoalino, e Lígia Silva. 2023. "Health and Well-Being Benefits of Outdoor and Indoor Vertical Greening Systems: A Review." *Sustainability* 15, 5: 4107. https://doi.org/10.3390/su15054107.

Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau. 2018. *Green Roof Guidelines: Guidelines for the Planning, Construction and Maintenance of Green Roofs*. https://commons.bcit.ca/greenroof/files/2019/01/FLL_greenroofguidelines_2018.pdf (2025-06-21).

Francis, Robert A., e Jamie Lorimer. 2011. "Urban Reconciliation Ecology: The Potential of Living Roofs and Walls." *Journal of Environmental Management* 92, 6: 1429-37. https://doi.org/10.1016/j.jenvman.2011.01.012.

Frisk, Carl A., e Hans Martin Hanslin. 2025. "Optimizing Plant Species Composition of Green Roofs for Ecological Functionality and Biodiversity Conservation." *Urban Ecosystems* 28, 2: 12. https://doi.org/10.1007/s11252-024-01657-4.

Gehrels, Hans, Suzanne van der Meulen, Femke Schasfoort, Peter Bosch, Reinder Brolsma, Danielle van Dinther, Gertjan Geerling, Martin Goossens, Cor Jacobs, Merijn de Jong, Sien Kok, Harry Massop, Leonard Osté, Marta Pérez-Soba, Vera Rovers, Annemieke Smit, Peter Verweij, Barry de Vries, e Ernie Weijers. 2016. *Designing Green and Blue Infrastructure to Support Healthy Urban Living*. Utrecht: TO2 Federatie. https://openresearch.amsterdam/image/2021/3/9/designing_green_and_blue_infrastructure_to_support_healthy_urban_living-613014262.pdf (2025-06-21).

Getter, Kristin L., D. Bradley Rowe, G. Philip Robertson, Bert M. Cregg, e Jeffrey A. Andresen. 2009. "Carbon Sequestration Potential of Extensive Green Roofs." *Environmental Science & Technology* 43, 19: 7564-70. https://doi.org/10.1021/es901539x.

Giacomello, Elena, e Massimo Valagussa. 2015. *Vertical Greenery: Evaluating the High-Rise Vegetation of the Bosco Verticale, Milan*. Chicago: Council of Tall Buildings and Urban Habitat.

Gesellschaft für Internationale Zusammenarbeit. 2024. *Implementation Guideline: Green Walls and Green Roofs – Urban Ecosystem-Based Adaptation to Climate Change in Viet Nam*. https://www.adaptationcommunity.net/wp-content/uploads/2024/04/Implementation-Guideline-Green-walls-and-green-roofs.pdf (2025-06-21).

Goddard, Mark A., Andrew J. Dougill, e Tim G. Benton. 2010. "Scaling up from Gardens: Biodiversity Conservation in Urban Environments." *Trends in Ecology & Evolution* 25, 2: 90-98. https://doi.org/10.1016/j.tree.2009.07.016.

Goodwin, Sean, Marta Olazabal, Antonio J. Castro, e Unai Pascual. 2023. "Global Mapping of Urban Nature-Based Solutions for Climate Change Adaptation." *Nature Sustainability* 6, 4. https://doi.org/10.1038/s41893-022-01036-x.

Grant, Gary. 2006. "Extensive Green Roofs in London." *Urban Habitats* 4, 1: 51-65. https://www.urbanhabitats.org/v04n01/london_full.html (2025-06-21).

Guattari, Claudia, Luca Evangelisti, Francesco Asdrubali, e Roberto De Lieto Vollaro. 2020. "Experimental Evaluation and Numerical Simulation of the Thermal Performance of a Green Roof." *Applied Sciences* 10, 5: 1767. https://doi.org/10.3390/app10051767.

Gunn, Charlotte, Maria Vahdati, e Mehdi Shahrestani. 2022. "Green Walls in Schools – The Potential Well-Being Benefits." *Building and Environment* 224: 109560. https://doi.org/10.1016/j.buildenv.2022.109560.

Haer, Toon, Thomas Busker, Hans de Moel, Menno Wens, Lisa Meijer, Jeroen Aerts, Joris Brüggen, Anna Solcerova, Daniel Föllmi, Laura Corpel, e Jasper Kluck. 2022. *Final Report: The Building-Scale Performance of Blue-Green Roofs (RESILIO Deliverable O6.3.1)*. Amsterdam: Urban Innovative Actions; Vrije Universiteit Amsterdam; Hogeschool van Amsterdam. https://openresearch.amsterdam/image/2022/4/8/final_report_resilio_o6_3_1_impact_on_roof.pdf (2025-06-21).

Hamburg, City of. 2018. *Manual Green Walls*. https://www.hamburg.com/resource/blob/1057970/2e371f779846efd8f7b012ab2f4d63fc/d-manual-green-walls-data.pdf (2025-06-21).

Hao, Xiaoli, Liping Liu, Hang Tan, Yaolin Lin, Jinhua Hu, e Wei Yin. 2022. "The Impacts of Greenery Systems on Indoor Thermal Environments in Transition Seasons: An Experimental Investigation." *Buildings* 12, 5: 506. https://doi.org/10.3390/buildings12050506.

He, Yang, Hang Yu, Akihito Ozaki, Nannan Dong, e Shiling Zheng. 2017. "Long-Term Thermal Performance Evaluation of Green Roof System Based on Two New Indexes: A Case Study in Shanghai Area." *Building and Environment* 120: 13-28. https://doi.org/10.1016/j.buildenv.2017.04.001.

Hedblom, Marcus, Bengt Gunnarsson, Behzad Iravani, et al. 2019. "Reduction of Physiological Stress by Urban Green Space in a Multisensory Virtual Experiment." *Scientific Reports* 9, 1: 10113. https://doi.org/10.1038/s41598-019-46099-7.

Hop, Margareth E.C.M., e Jelle A. Hiemstra. 2013. "Contribution of Green Roofs and Green Walls to Ecosystem Services of Urban Green." *Acta Horticulturae* 990: 475-80. https://doi.org/10.17660/ActaHortic.2013.990.61.

Huang, Yi-Yu, Chien-Teh Chen, e Yen-Chi Tsai. 2016. "Reduction of Temperatures and Temperature Fluctuations by Hydroponic Green Roofs in a Subtropical Urban Climate." *Energy and Buildings* 129: 174-85. https://doi.org/10.1016/j.enbuild.2016.07.023.

Ichihara, Kiku, e Jeffrey P. Cohen. 2011. "New York City Property Values: What Is the Impact of Green Roofs on Rental Pricing?" *Letters in Spatial and Resource Sciences* 4, 1: 21-30. https://doi.org/10.1007/s12076-010-0046-4.

Intergovernmental Panel on Climate Change. 2022. "Chapter 6: Cities, Settlements and Key Infrastructure." In *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by H.O. Pörtner, D.C. Roberts, e M. Tignor. Cambridge: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-6/ (2025-06-21).

Intergovernmental Panel on Climate Change. 2023. "Summary for Policymakers." In *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to*

the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Core Writing Team, H. Lee, e J. Romero. Geneva: Intergovernmental Panel on Climate Change. https://doi.org/10.59327/IPCC/AR6-9789291691647.001.
IPBES. 2019. *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Version 1. A cura di Eduardo Brondizio, Sandra Diaz, Josef Settele, e Hien T. Ngo. Zenodo. https://doi.org/10.5281/ZENODO.6417333.
Irga, Peter J., Fraser R. Torpy, Daniel Griffin, e Sara J. Wilkinson. 2023. "Vertical Greening Systems: A Perspective on Existing Technologies and New Design Recommendation." *Sustainability* 15, 7: 6014. https://doi.org/10.3390/su15076014.
Irga, Peter, Robert Fleck, Eamonn Wooster, Jack Rojahn, e Fraser Torpy. 2023. "Biosolar Green Roofs – Achieving Biodiversity Outcomes and Solar Power on the Same Roof, at the Same Time." *Research Matters* 38: 2-8. http://hdl.handle.net/10453/171911 (2025-06-21).
Ishimatsu, Kazuhito, e Keitaro Ito. 2013. "Brown/Biodiverse Roofs: A Conservation Action for Threatened Brownfields to Support Urban Biodiversity." *Landscape and Ecological Engineering* 9, 2: 299-304. https://doi.org/10.1007/s11355-011-0186-8.
Jacobs, Jeffrey, Natalie Beenaerts, e Tom Artois. 2023. "Green Roofs and Pollinators, Useful Green Spots for Some Wild Bee Species (Hymenoptera: Anthophila), but Not so Much for Hoverflies (Diptera: Syrphidae)." *Scientific Reports* 13, 1: 1449. https://doi.org/10.1038/s41598-023-28698-7.
Jayasooriya, Varuni Maheshika, Chathuri Tharanga Liyanage, Shobha Muthukumaran, e Rathmalgodage Thejani Nilusha. 2025. "Impact of Green Wall Orientation on Building Energy Performance in a Tropical Climate: An Experimental Assessment." *PLOS Sustainability and Transformation* 4, 1: e0000156. https://doi.org/10.1371/journal.pstr.0000156.
Jim, C.Y., e Lilliana L.H. Peng. 2012. "Weather Effect on Thermal and Energy Performance of an Extensive Tropical Green Roof." *Urban Forestry & Urban Greening* 11, 1: 73-85. https://doi.org/10.1016/j.ufug.2011.10.001.
Juras, Peter. 2022. "Positive Aspects of Green Roof Reducing Energy Consumption in Winter." *Energies* 15, 4: 1493. https://doi.org/10.3390/en15041493.
Kandel, Suzanne, e Niki Frantzeskaki. 2024. "Nature-Based Solutions and Buildings: A Review of the Literature and an Agenda for Renaturing Our Cities One Building at a Time." *Nature-Based Solutions* 5: 100106. https://doi.org/10.1016/j.nbsj.2023.100106.
Kazmierczak, Aleksandra, e Jeremy Carter. 2010. *Adaptation to Climate Change Using Green and Blue Infrastructure. A Database of Case Studies*. Manchester: University of Manchester. https://www.researchgate.net/publication/228720496 (2025-06-21).
Knifka, Wiebke, Raphael Karutz, e Heinrich Zozmann. 2023. "Barriers and Solutions to Green Facade Implementation—A Review of Literature and a Case Study of Leipzig, Germany." *Buildings* 13, 7: 1621. https://doi.org/10.3390/buildings13071621.
Köhler, Manfred. 2015. "Das Physikgebäude Berlin-Adlershof." *Neue Landschaft*, 18 dicembre 2015. https://neuelandschaft.de/artikel/das-physikgebaeude-berlin-adlershof-1452 (2025-06-21).
Kolasa-Więcek, Alicja, e Dariusz Suszanowicz. 2021. "The Green Roofs for Reduction in the Load on Rainwater Drainage in Highly Urbanised Areas." *Environmental Science and Pollution Research* 28, 26: 34269-77. https://doi.org/10.1007/s11356-021-12616-3.
Kraus, Florian, Johannes Anschober, Philippe Bodénan, Marjorie Musy, e Olivier Damas. 2018. *Planter Green Wall*. CRACC/Green4Cities/Cerema. https://www.adaptation-changement-climatique.gouv.fr/sites/cracc/files/inline-files/Planter_green_wall.pdf (2025-06-21).
Ksiazek-Mikenas, Kelly, Jeremie B. Fant, e Krissa A. Skogen. 2019. "Pollinator-Mediated Gene Flow Connects Green Roof Populations Across the Urban Matrix: A Paternity Analysis of the Self-Compatible Forb *Penstemon hirsutus*." *Frontiers in Ecology and Evolution* 7: 299. https://doi.org/10.3389/fevo.2019.00299.
Lakho, Fida Hussain, Jarne Vergote, Hafiz Ihsan-Ul-Haq Khan, et al. 2021. "Total Value Wall: Full Scale Demonstration of a Green Wall for Grey Water Treatment and

Recycling." *Journal of Environmental Management* 298: 113489. https://doi.org/10.1016/j.jenvman.2021.113489.

Lambertini, Anna. 2014. "Nuove Nature Urbane / New Urban Natures." In *The Rampant Garden: Let's Make Building Walls Live. Solutions for Sustainable Cities*, edited by Riccardo Maria Pulselli, Gabriele Paolinelli, e Simone Bastianoni, 20-45. Florence: Edifir Edizioni Firenze.

Lamnatou, Chrysovalantou, e Daniel Chemisana. 2015. "A Critical Analysis of Factors Affecting Photovoltaic-Green Roof Performance." *Renewable and Sustainable Energy Reviews* 43: 264-80. https://doi.org/10.1016/j.rser.2014.11.048.

Landolt, Elias. 2001. "Orchideen-Wiesen in Wollishofen (Zürich) – ein erstaunliches Relikt aus der Anfang des 20. Jahrhunderts." *Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich* 146, 2-3: 41-51. https://ngzh.ch/wp-content/uploads/2024/08/146_14.pdf (2025-06-21).

Lapointe, Mathieu, Chelsea M. Rochman, e Nathalie Tufenkji. 2022. "Sustainable Strategies to Treat Urban Runoff Needed." *Nature Sustainability* 5, 5: 366-69. https://doi.org/10.1038/s41893-022-00853-4.

Lee, Kate E., Kathryn J.H. Williams, Leisa D. Sargent, Nicholas S.G. Williams, e Katherine A. Johnson. 2015. "40-Second Green Roof Views Sustain Attention: The Role of Micro-Breaks in Attention Restoration." *Journal of Environmental Psychology* 42: 182-89. https://doi.org/10.1016/j.jenvp.2015.04.003.

Li, Yanling, e Roger W. Babcock. 2014. "Green Roof Hydrologic Performance and Modeling: A Review." *Water Science and Technology* 69, 4: 727-38. https://doi.org/10.2166/wst.2013.770.

Liu, Lijiao, Junjun Cao, Mehran Ali, Jiaxin Zhang, e Zhaolong Wang. 2021. "Impact of Green Roof Plant Species on Domestic Wastewater Treatment." *Environmental Advances* 4: 100059. https://doi.org/10.1016/j.envadv.2021.100059.

Liu, Li, Liwei Sun, Jie Niu, e William J. Riley. 2020. "Modeling Green Roof Potential to Mitigate Urban Flooding in a Chinese City." *Water* 12, 8: 2082. https://doi.org/10.3390/w12082082.

Lundholm, Jeremy. 2006. "Green Roofs and Facades: A Habitat Template Approach." *Urban Habitats* 4, 1: 87-101. https://urbanhabitats.org/v04n01/habitat_pdf.pdf (2025-06-21).

Lundholm, Jeremy T., e Paul J. Richardson. 2010. "Habitat Analogues for Reconciliation Ecology in Urban and Industrial Environments." *Journal of Applied Ecology* 47, 5: 966-75. https://doi.org/10.1111/j.1365-2664.2010.01857.x.

Lundholm, Jeremy, J. Scott MacIvor, Zachary MacDougall, e Melissa Ranalli. 2010. "Plant Species and Functional Group Combinations Affect Green Roof Ecosystem Functions." *PLOS ONE* 5, 3: e9677. https://doi.org/10.1371/journal.pone.0009677.

MacIvor, J. Scott, e Jeremy Lundholm. 2011. "Performance Evaluation of Native Plants Suited to Extensive Green Roof Conditions in a Maritime Climate." *Ecological Engineering* 37, 3: 407-17. https://doi.org/10.1016/j.ecoleng.2010.10.004.

Madre, Frédéric, Alan Vergnes, Nathalie Machon, e Philippe Clergeau. 2013. "A Comparison of 3 Types of Green Roof as Habitats for Arthropods." *Ecological Engineering* 57: 109-17. https://doi.org/10.1016/j.ecoleng.2013.04.029.

Mancuso, Stefano. 2023. *Fitopolis, la città vivente*. Bari: Laterza.

Manouchehri, Mitra, Joaquín Santiago López, e Mercedes Valiente López. 2024. "Sustainable Design of Vertical Greenery Systems: A Comprehensive Framework." *Sustainability* 16, 8: 3249. https://doi.org/10.3390/su16083249.

Manso, Maria, e João Castro-Gomes. 2015. "Green Wall Systems: A Review of Their Characteristics." *Renewable and Sustainable Energy Reviews* 41: 863-71. https://doi.org/10.1016/j.rser.2014.07.203.

Manso, Maria, Inês Teotónio, Cristina Matos Silva, e Carlos Oliveira Cruz. 2021. "Green Roof and Green Wall Benefits and Costs: A Review of the Quantitative Evidence." *Renewable and Sustainable Energy Reviews* 135: 110111. https://doi.org/10.1016/j.rser.2020.110111.

Maurer, Bettina, Judit Lienert, e Lauren M. Cook. 2023. "Comparing PV-Green and PV-Cool Roofs to Diverse Rooftop Options Using Decision Analysis." *Building and Environment* 245: 110922. https://doi.org/10.1016/j.buildenv.2023.110922.

Mayrand, Flavie, e Philippe Clergeau. 2018. "Green Roofs and Green Walls for Biodiversity Conservation: A Contribution to Urban Connectivity?" *Sustainability* 10, 4: 985. https://doi.org/10.3390/su10040985.

Maryanti, M.R., H. Khadijah, A. Muhammad Uzair, e M.A.R. Megat Mohd Ghazali. 2016. "The Urban Green Space Provision Using the Standards Approach: Issues and Challenges of Its Implementation in Malaysia." In *Sustainable Development and Planning*, 369-79. https://doi.org/10.2495/SDP160311.

Mesimäki, Marja, Kaisa Hauru, e Susanna Lehvävirta. 2019. "Do Small Green Roofs Have the Possibility to Offer Recreational and Experiential Benefits in a Dense Urban Area? A Case Study in Helsinki, Finland." *Urban Forestry & Urban Greening* 40: 114-24. https://doi.org/10.1016/j.ufug.2018.10.005.

Mihalakakou, Giouli, Manolis Souliotis, Maria Papadaki, et al. 2023. "Green Roofs as a Nature-Based Solution for Improving Urban Sustainability: Progress and Perspectives." *Renewable and Sustainable Energy Reviews* 180: 113306. https://doi.org/10.1016/j.rser.2023.113306.

Muratet, Audrey, Marc Barra, Laurent Hardion, e François Chiron. 2024. "Origins and Drivers of Roof Plant Assemblages: Designing Green Roofs for Biodiversity Conservation." *Urban Forestry & Urban Greening* 94: 128247. https://doi.org/10.1016/j.ufug.2024.128247.

Nagle, Lara, Stuart Echols, e Ken Tamminga. 2017. "Food Production on a Living Wall: Pilot Study." *Journal of Green Building* 12, 3: 23-38. https://doi.org/10.3992/1943-4618.12.3.23.

Nash, C., J. Clough, D. Gedge, et al. 2016. "Initial Insights on the Biodiversity Potential of Biosolar Roofs: A London Olympic Park Green Roof Case Study." *Israel Journal of Ecology and Evolution* 62, 1-2: 74-87. https://doi.org/10.1080/15659801.2015.1045791.

Ndayambaje, Patrick, J. Scott MacIvor, e Marc W. Cadotte. 2024. "Plant Diversity on Green Roofs: A Review of the Ecological Benefits, Challenges, and Best Management Practices." *Nature-Based Solutions* 6: 100162. https://doi.org/10.1016/j.nbsj.2024.100162.

Nevermann, Stella, Hannes Hoffmann, Panagiotis Theodorou, Irene Peters, e Martin Husemann. 2025. "Metabarcoding Assessment of Arthropod Diversity on Green Roofs in the Metropolitan City of Hamburg." *Journal of Urban Ecology* 11, 1: juaf003. https://doi.org/10.1093/jue/juaf003.

Ode Sang, Åsa, Petra Thorpert, e Ann-Mari Fransson. 2022. "Planning, Designing, and Managing Green Roofs and Green Walls for Public Health – An Ecosystem Services Approach." *Frontiers in Ecology and Evolution* 10: 804500. https://doi.org/10.3389/fevo.2022.804500.

Oliveira Santos, Thácia Danily de, Fernando António Leal Pacheco, e Luís Filipe Sanches Fernandes. 2024. "A Systematic Analysis on the Efficiency and Sustainability of Green Facades and Roofs." *Science of the Total Environment* 932: 173107. https://doi.org/10.1016/j.scitotenv.2024.173107.

Olivieri, Francesca, Costanzo Di Perna, Marco D'Orazio, Lorenzo Olivieri, e Francisco Javier Neila-González. 2013. "Experimental Measurements and Numerical Model for the Summer Performance Assessment of Extensive Green Roofs in a Mediterranean Coastal Climate." *Energy and Buildings* 63: 1-14. https://doi.org/10.1016/j.enbuild.2013.03.054.

Oppla. s.d. "Adlershof Berlin: Combination of Decentralised Rainwater Management and Building Greening." https://oppla.eu/case-study/adlershof-berlin-combination-decentralised-rainwater-management-building-greening (2025-06-21).

Ottelé, Marc. 2011. "The Green Building Envelope: Vertical Greening." PhD diss., Delft University of Technology. https://www.carlstahl.nl/wp-content/uploads/2019/06/The-Green-Building-Envelope-def.pdf (2025-06-21).

Ottelé, Marc, Katia Perini, A.L. Alex Fraaij, E.M. Haas, e Rossana Raiteri. 2011. "Comparative Life Cycle Analysis for Green Façades and Living Wall Systems." *Energy and Buildings* 43, 12: 3419-29. https://doi.org/10.1016/j.enbuild.2011.09.010.

Ottelé, Marc, Hein D. Van Bohemen, e Alex L.A. Fraaij. 2010. "Quantifying the Deposition of Particulate Matter on Climber Vegetation on Living Walls." *Ecological Engineering* 36, 2: 154-62. https://doi.org/10.1016/j.ecoleng.2009.02.007.

Partridge, Dustin R., e J. Alan Clark. 2018. "Urban Green Roofs Provide Habitat for Migrating and Breeding Birds and Their Arthropod Prey." *PLOS ONE* 13, 8: e0202298. https://doi.org/10.1371/journal.pone.0202298.

Paull, Naomi J., Daniel Krix, Peter J. Irga, e Fraser R. Torpy. 2020. "Airborne Particulate Matter Accumulation on Common Green Wall Plants." *International Journal of Phytoremediation* 22, 6: 594-606. https://doi.org/10.1080/15226514.2019.1696744.

Peck, Steven W., e Monica E. Kuhn. 2002. *Design Guidelines for Green Roofs*. Toronto: Ontario Association of Architects e Canada Mortgage and Housing Corporation.

Perales-Momparler, Sara, Ignacio Andrés-Doménech, Carmen Hernández-Crespo, et al. 2017. "The Role of Monitoring Sustainable Drainage Systems for Promoting Transition towards Regenerative Urban Built Environments: A Case Study in the Valencian Region, Spain." *Journal of Cleaner Production* 163: S113-24. https://doi.org/10.1016/j.jclepro.2016.05.153.

Pereira Barboza, Evelise, Marta Cirach, Sasha Khomenko, et al. 2021. "Green Space and Mortality in European Cities: A Health Impact Assessment Study." *The Lancet Planetary Health* 5, 10: e718-30. https://doi.org/10.1016/S2542-5196(21)00229-1.

Pérez, Gabriel, e Julià Coma. 2018. "Green Roofs Classifications, Plant Species, Substrates." In *Nature Based Strategies for Urban and Building Sustainability*. Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-812150-4.00006-9.

Pérez-Urrestarazu, Luis, Ana Blasco-Romero, e Rafael Fernández-Cañero. 2017. "Media and Social Impact Valuation of a Living Wall: The Case Study of the Sagrado Corazon Hospital in Seville (Spain)." *Urban Forestry & Urban Greening* 24: 141-48. https://doi.org/10.1016/j.ufug.2017.04.002.

Perini, Katia. 2013. *Progettare il verde in città*. Milano: FrancoAngeli.

Perini, Katia, e Paolo Rosasco. 2013. "Cost–Benefit Analysis for Green Façades and Living Wall Systems." *Building and Environment* 70: 110-21. https://doi.org/10.1016/j.buildenv.2013.08.012.

Perini, Katia, Marc Ottelé, A.L.A. Fraaij, E.M. Haas, e Rossana Raiteri. 2011. "Vertical Greening Systems and the Effect on Air Flow and Temperature on the Building Envelope." *Building and Environment* 46, 11: 2287-94. https://doi.org/10.1016/j.buildenv.2011.05.009.

Pétremand, Gaël, Yannick Chittaro, Sonja Braaker, et al. 2018. "Ground Beetle (Coleoptera: Carabidae) Communities on Green Roofs in Switzerland: Synthesis and Perspectives." *Urban Ecosystems* 21, 1: 119-32. https://doi.org/10.1007/s11252-017-0697-7.

Piro, Patrizia, Marco Carbone, Marilena De Simone, Mario Maiolo, Piero Bevilacqua, e Natale Arcuri. 2018. "Energy and Hydraulic Performance of a Vegetated Roof in Sub-Mediterranean Climate." *Sustainability* 10, 10: 3473. https://doi.org/10.3390/su10103473.

Reyhani, Milad, Enrica Santolini, Patrizia Tassinari, e Daniele Torreggiani. 2023. "Environmental Assessment of Design Choices of Green Walls Based for Materials Combination and Plants." *The International Journal of Life Cycle Assessment* 28, 9: 1078-91. https://doi.org/10.1007/s11367-023-02181-x.

Rezaei, Mehdi, Nyirumuringa Emmanuel, Juyeon Kim, e Doo Hwan Kim. 2021. "Analyzing the Impact of Green Roof Functions on the Citizens' Mental Health in Metropolitan Cities." *Iranian Journal of Public Health*, ahead of print. https://doi.org/10.18502/ijph.v50i5.6107.

Richter, Michael, e Wolfgang Dickhaut. 2023. "Long-Term Performance of Blue-Green Roof Systems—Results of a Building-Scale Monitoring Study in Hamburg, Germany." *Water* 15, 15: 2806. https://doi.org/10.3390/w15152806.

Rousset-Rouvière, Sophie, Steven W. Peck, Vera Enzi-Zechner, Jakob Ploteny, Blaine Stand, Trygve Mongstad, Heinz Meier, Kai van Gool, Sean Erik Foss, e Dusty Gedge. 2025. *Solar Green Roofs Resource Guide*. European Federation of Green Roof and Living Wall Associations; World Green Infrastructure Network; SolarPower Europe. https://efb-greenroof.eu/wp-content/uploads/2025/12/Solar-Green-Roof-Guideline-V9.pdf (2025-06-21).

Santamouris, Matthaios. 2014. "Cooling the Cities – A Review of Reflective and Green Roof Mitigation Technologies to Fight Heat Island and Improve Comfort in Urban Environments." *Solar Energy* 103: 682-703. https://doi.org/10.1016/j.solener.2012.07.003.

Santana, Taize Calvacante, Cristiane Guiselini, Abelardo Antônio De Assunção Montenegro, et al. 2023. "Green Roofs Are Effective in Cooling and Mitigating Urban Heat Islands to Improve Human Thermal Comfort." *Modeling Earth Systems and Environment* 9, 4: 3985-98. https://doi.org/10.1007/s40808-023-01743-0.

Schindler, Bracha Y., Lior Blank, Shay Levy, Gyongyver Kadas, David Pearlmutter, e Leon Blaustein. 2016. "Integration of Photovoltaic Panels and Green Roofs: Review and Predictions of Effects on Electricity Production and Plant Communities." *Israel Journal of Ecology and Evolution* 62, 1-2: 68-73. https://doi.org/10.1080/15659801.2015.1048617.
Schrieke, Dean, Joel Lönnqvist, Godecke-Tobias Blecken, Nicholas S.G. Williams, e Claire Farrell. 2021. "Socio-Ecological Dimensions of Spontaneous Plants on Green Roofs." *Frontiers in Sustainable Cities* 3: 777128. https://doi.org/10.3389/frsc.2021.777128.
Schrieke, Dean, Christopher Szota, Nicholas S.G. Williams, e Claire Farrell. 2023. "Evaluating the Effectiveness of Spontaneous Vegetation for Stormwater Mitigation on Green Roofs." *Science of the Total Environment* 898: 165643. https://doi.org/10.1016/j.scitotenv.2023.165643.
Sendra-Arranz, Rafael, Valentina Oquendo, Lorenzo Olivieri, Francesca Olivieri, Cesar Bedoya, e Álvaro Gutiérrez. 2020. "Monitorization and Statistical Analysis of South and West Green Walls in a Retrofitted Building in Madrid." *Building and Environment* 183: 107049. https://doi.org/10.1016/j.buildenv.2020.107049.
Shafique, Muhammad, Xiaowei Luo, e Jian Zuo. 2020. "Photovoltaic-Green Roofs: A Review of Benefits, Limitations, and Trends." *Solar Energy* 202: 485-97. https://doi.org/10.1016/j.solener.2020.02.101.
Shao, Yiming, Zhenghuan Zhou, Ding Ding, Yuanlong Cui, e Xianfeng Wu. 2024. "Psychological Effects of a Living Wall System on Office Occupants: A Comparative Study Based on Physiological Responses." *Buildings* 14, 7: 1981. https://doi.org/10.3390/buildings14071981.
Singh, Avitesh, e Tejwant Brar. 2020. "Bio Solar Terrace: A Review on Benefits of Photovoltaic Green Roof." *International Journal of Contemporary Architecture "The New ARCH"* 7, 4. https://www.researchgate.net/publication/353285337_Bio_Solar_Terrace_A_Review_on_Benefits_of_Photovoltaic_Green_Roof (2025-06-21).
Sistema Nazionale per la Protezione dell'Ambiente. 2022. *Città in transizione: i capoluoghi italiani verso la sostenibilità ambientale. Documento di valutazione integrata della qualità dell'ambiente urbano*. Report SNPA 31/2022. https://www.snpambiente.it/notizie/snpa/citta-in-transizione-i-capoluoghi-italiani-verso-la-sostenibilita-ambientale-documento-di-valutazione-integrata-della-qualita-dellambiente-urbano/ (2025-06-21).
Speak, Andrew F., James J. Rothwell, Sara J. Lindley, e Claire L. Smith. 2012. "Urban Particulate Pollution Reduction by Four Species of Green Roof Vegetation in a UK City." *Atmospheric Environment* 61: 283-93. https://doi.org/10.1016/j.atmosenv.2012.07.043.
State of Victoria. 2014. *Growing Green Guide: A Guide to Green Roofs, Walls and Facades in Melbourne and Victoria, Australia*. Melbourne: State of Victoria. https://safes.unimelb.edu.au/__data/assets/pdf_file/0005/4956467/growing-green-guide.pdf (2025-06-21).
Stella, Patrick, e Erwan Personne. 2021. "Effects of Conventional, Extensive and Semi-Intensive Green Roofs on Building Conductive Heat Fluxes and Surface Temperatures in Winter in Paris." *Building and Environment* 205: 108202. https://doi.org/10.1016/j.buildenv.2021.108202.
Susca, T., S.R. Gaffin, e G.R. Dell'Osso. 2011. "Positive Effects of Vegetation: Urban Heat Island and Green Roofs." *Environmental Pollution* 159, 8-9: 2119-26. https://doi.org/10.1016/j.envpol.2011.03.007.
Tan, Chun Liang, Puay Yok Tan, Nyuk Hien Wong, Hiroyuki Takasuna, Tadashi Kudo, Yuichi Takemasa, Chin Voon Jesslyn Lim, e Hui Xuan Valerie Chua. 2017. "Impact of Soil and Water Retention Characteristics on Green Roof Thermal Performance." *Energy and Buildings* 152: 830-42. https://doi.org/10.1016/j.enbuild.2017.01.011.
Tan, Hang, Xiaoli Hao, Pinhan Long, Qingwei Xing, Yaolin Lin, e Jinhua Hu. 2020. "Building Envelope Integrated Green Plants for Energy Saving." *Energy Exploration & Exploitation* 38, 1: 222-34. https://doi.org/10.1177/0144598719875529.
Tariku, Fitsum, e Sara Hagos. 2022. "Performance of Green Roof Installed on Highly Insulated Roof Deck and the Plants' Effect: An Experimental Study." *Building and Environment* 221: 109337. https://doi.org/10.1016/j.buildenv.2022.109337.

Thuring, Christine E., e Nigel Dunnett. 2014. "Vegetation Composition of Old Extensive Green Roofs (from 1980s Germany)." *Ecological Processes* 3, 1: 4. https://doi.org/10.1186/2192-1709-3-4.
Thuring, Christine, e Gary Grant. 2015. "The Biodiversity of Temperate Extensive Green Roofs: A Review of Research and Practice." Preprint. https://doi.org/10.13140/RG.2.1.3836.0403.
Tran, Stephanie, Jeremy T. Lundholm, Maja Staniec, Clare E. Robinson, Charles C. Smart, James A. Voogt, e Denis M. O'Carroll. 2019. "Plant Survival and Growth on Extensive Green Roofs: A Distributed Experiment in Three Climate Regions." *Ecological Engineering* 127: 494-503. https://doi.org/10.1016/j.ecoleng.2018.09.027.
Tzoulas, Konstantinos, Kalevi Korpela, Stephen Venn, Vesa Yli-Pelkonen, Aleksandra Kaźmierczak, Jari Niemela, e Philip James. 2007. "Promoting Ecosystem and Human Health in Urban Areas Using Green Infrastructure: A Literature Review." *Landscape and Urban Planning* 81, 3: 167-78. https://doi.org/10.1016/j.landurbplan.2007.02.001.
United Nations Environment Programme. 2021. *Smart, Sustainable and Resilient Cities: The Power of Nature-Based Solutions*. https://www.unep.org/resources/report/smart-sustainable-and-resilient-cities-power-nature-based-solutions (2025-06-21).
United Nations Human Settlements Programme, a cura di. 2022. *Envisaging the Future of Cities. World Cities Report 2022*. Nairobi: UN-Habitat.
Öztürk, Şevki, Kutay Yılmaz, A. Ersin Dinçer, e Volkan Kalpakcı. 2024. "Effect of Urbanization on Surface Runoff and Performance of Green Roofs and Permeable Pavement for Mitigating Urban Floods." *Natural Hazards* 120, 13: 12375-99. https://doi.org/10.1007/s11069-024-06688-w.
Vacek, Petr, Karel Struhala, e Libor Matějka. 2017. "Life-Cycle Study on Semi Intensive Green Roofs." *Journal of Cleaner Production* 154: 203-13. https://doi.org/10.1016/j.jclepro.2017.03.188.
Van Der Kolk, Henk-Jan, Petra Van Den Berg, Thijs Van Veen, e Martijn Bezemer. 2023. "Substrate Composition Impacts Long-Term Vegetation Development on Blue-Green Roofs: Insights from an Experimental Roof and Greenhouse Study." *Ecological Engineering* 186: 106847. https://doi.org/10.1016/j.ecoleng.2022.106847.
Vasl, Amiel, Hadar Shalom, Gyongyver J. Kadas, e Leon Blaustein. 2017. "Sedum–Annual Plant Interactions on Green Roofs: Facilitation, Competition and Exclusion." *Ecological Engineering* 108: 318-29. https://doi.org/10.1016/j.ecoleng.2017.07.034.
Vidaller, Christel, Anaïs Jouet, Carmen Van Mechelen, et al. 2023. "Coexistence and Succession of Spontaneous and Planted Vegetation on Extensive Mediterranean Green Roofs: Impacts on Soil, Seed Banks, and Mesofauna." *Land* 12, 9: 1726. https://doi.org/10.3390/land12091726.
Viecco, Margareth, Héctor Jorquera, Ashish Sharma, Waldo Bustamante, Harindra J.S. Fernando, e Sergio Vera. 2021. "Green Roofs and Green Walls Layouts for Improved Urban Air Quality by Mitigating Particulate Matter." *Building and Environment* 204: 108120. https://doi.org/10.1016/j.buildenv.2021.108120.
Wang, Xinxin, Susan Rodiek, Chengzhao Wu, Yi Chen, e Yuxian Li. 2016. "Stress Recovery and Restorative Effects of Viewing Different Urban Park Scenes in Shanghai, China." *Urban Forestry & Urban Greening* 15: 112-22. https://doi.org/10.1016/j.ufug.2015.12.003.
Washburn, Brian E., Ryan M. Swearingin, Craig K. Pullins, e Matthew E. Rice. 2016. "Composition and Diversity of Avian Communities Using a New Urban Habitat: Green Roofs." *Environmental Management* 57, 6: 1230-39. https://doi.org/10.1007/s00267-016-0687-1.
Whittinghill, Leigh J., e D. Bradley Rowe. 2012. "The Role of Green Roof Technology in Urban Agriculture." *Renewable Agriculture and Food Systems* 27, 4: 314-22. https://doi.org/10.1017/S174217051100038X.
Woods-Ballard, Bridget, Steve Wilson, Helen Udale-Clarke, Sue Illman, Tamasine Scott, Richard Ashley, e Richard Kellagher. 2015. *The SuDS Manual (C753)*. London: CIRIA.
World Bank. 2021. *A Catalogue of Nature-Based Solutions for Urban Resilience*. Washington, DC: World Bank. https://doi.org/10.1596/36507.
World Health Organization: Regional Office for Europe. 2016a. *Green Spaces and Health*. Copenhagen: WHO Regional Office for Europe. https://iris.who.int/handle/10665/345751 (2025-06-21).

World Health Organization: Regional Office for Europe. 2016b. *Urban Green Spaces and Health: A Review of Evidence*. Copenhagen: WHO Regional Office for Europe. https://www.euro.who.int/__data/assets/pdf_file/0005/321971/Urban-green-spaces-and-health-review-evidence.pdf (2025-06-21).

World Health Organization. 2024. "Ambient (Outdoor) Air Quality and Health." 24 ottobre 2024. https://www.who.int/news-room/fact-sheets/detail/ambient-%28outdoor%29-air-quality-and-health (2025-06-21).

Xiaoxue, Su, e Xuan Huang. 2024. "Promoting Stress and Anxiety Recovery in Older Adults: Assessing the Therapeutic Influence of Biophilic Green Walls and Outdoor View." *Frontiers in Public Health* 12: 1352611. https://doi.org/10.3389/fpubh.2024.1352611.

Xie, Linjun, Harriet Bulkeley, e Laura Tozer. 2022. "Mainstreaming Sustainable Innovation: Unlocking the Potential of Nature-Based Solutions for Climate Change and Biodiversity." *Environmental Science & Policy* 132: 119-30. https://doi.org/10.1016/j.envsci.2022.02.017.

Zhang, Lei, Zhichao Deng, Lisha Liang, et al. 2019. "Thermal Behavior of a Vertical Green Facade and Its Impact on the Indoor and Outdoor Thermal Environment." *Energy and Buildings* 204: 109502. https://doi.org/10.1016/j.enbuild.2019.109502.

Zheng, Xiandi, Fanhua Kong, Haiwei Yin, et al. 2021. "Outdoor Thermal Performance of Green Roofs across Multiple Time Scales: A Case Study in Subtropical China." *Sustainable Cities and Society* 70: 102909. https://doi.org/10.1016/j.scs.2021.102909.

ZinCo. 2024a. *System Solutions for Intensive Green Roofs: Planning Guide*. https://zinco-greenroof.com/sites/default/files/2024-10/ZinCo_Intensive_Green_Roofs_0.pdf (2025-06-21).

ZinCo. 2024b. *Extensive Green Roofs*. https://zinco-greenroof.com/sites/default/files/2024-10/ZinCo_Extensive_Green_Roofs_0.pdf (2025-06-21).