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ENHANCING NATURE IN CITIES

frameworks and strategies for resilient and healthy urban environments

Lorenzo Diana, Simona Colajanni, Gaetano Sciuto, Francesco Sommese
editors

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ENC |International ENHANCING NATURE in CITIES Conference

Frameworks and strategies for resilient and healthy urban enviroments

College of Engineering - Piazzale V. Tecchio, 80 – University of Naples Federico II, Italy

13-14 November 2025

Conference Proceedings

Editing: Lorenzo Diana, Simona Colajanni, Gaetano Sciuto, Francesco Sommese
Cover design and layout: Francesco Sommese

Under the patronage of

DICEA – Department of Civil, Building and Environmental Engineering, University of Naples Federico II

Founding

This work was founded by the European Union EU Next Generation Italian PRIN 2022 PNRR Programme under the "Greenwork—An interdisciplinary framework for urban health and urban resilience enhancement based on greening strategies on buildings and open spaces" project, CUP: E53D23019110001.

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e-mail: info@lucianoeditore.net

Online version: http://lucianoeditore.net

ISBN: 978-88-6026-380-3

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Introduction

Lorenzo Diana, Simona Colajanni, Gaetano Sciuto, Francesco Sommese

Editors

The international conference "Enhancing Nature in Cities" (ENC) stems from the extensive work carried out within the national research project "Greenwork: an interdisciplinary framework for urban health and urban resilience enhancement based on greening strategies on buildings and open spaces", funded by the PNRR (National Recovery and Resilience Plan). The project's main objective was the development of a comprehensive framework for defining and applying greening strategies in built-up urban environments, with the aim of ensuring their effectiveness across multiple spatial scales and varying local conditions.

Today's cities face increasingly complex challenges that directly affect citizens' well-being, public health, climate resilience, and the ecological quality of outdoor spaces. Critical issues such as air pollution, the intensification of urban heat islands, biodiversity loss, and rising natural and human-made risks call for strategic rethinking in urban planning, land-use policy, program development, and building design, prioritizing integrated, adaptive, and sustainable solutions.

Nature-based Solutions (NbS), recognized by numerous European and international initiatives and regulatory frameworks (e.g., the Green Deal, EU Biodiversity Strategies, the Urban Agenda for the EU, and the UN Sustainable Development Goals), offer a powerful and promising approach to re-establishing a practical, functional, and meaningful relationship between nature and urban environments. While mitigation of climate change has often fallen short of expectations, the potential of NbS is now increasingly acknowledged, especially as a key adaptation measure to climate-related stressors rather than a direct solution for emission reduction.

Nevertheless, despite the well-established benefits, the implementation of urban greening and NbS still encounters numerous obstacles. These include scientific knowledge gaps, operational difficulties, and fragmented policy frameworks. Particularly challenging is the integration of NbS into coherent systems that effectively address resilience to both anthropogenic and climatic pressures, support the regeneration of existing urban environments, and contribute meaningfully to the physical and psychological well-being of individuals and communities.

The aim of the ENC conference is to restore visibility and centrality to the issue of greenery and sustainability in the built environment. For decades, the academic community has recognized the fundamental importance of these themes to the survival, adaptability, and development of urban society. However, recent international geopolitical shifts and evolving global priorities are redirecting research funding and attention towards other sectors, like defense technologies and automated systems, often at the expense of sustainability.

Refocusing academic and institutional attention on the sustainability of cities and the role of nature in shaping urban life constitutes both a gesture of scientific responsibility and an act of political resilience. It represents a deliberate effort to reaffirm the enduring relevance of environmental and social well-being within research agendas.

The conference takes its first steps from the outcomes of the “Greenwork” project, which successfully brought together multiple disciplines to define a shared and adaptable framework for the implementation of green interventions, intended to operate effectively across different spatial scales and urban contexts.

Both the project and the scientific contents of the conference highlight a significant evolution: a shift from an interdisciplinary and multi-scalar approach toward a genuinely transdisciplinary and transcalar perspective.

Transdisciplinarity implies a fusion of varied forms of knowledge into a unified, deeply integrated perspective that goes beyond multidisciplinarity (where multiple disciplines work in parallel) and interdisciplinarity (where disciplines interact and influence one another). Transcalarity refers to the necessity of addressing urban sustainability across multiple spatial and governance levels (from the scale of the individual building to that of region) through coherent, context-sensitive strategies.

Urban greening in cities is, therefore, a vital tool for addressing a wide spectrum of urban challenges: from mitigating the effects of heat islands and improving stormwater management, to enhancing public health and fostering stronger forms of social cohesion. By bringing together scholars and professionals from different disciplinary backgrounds and spatial domains, this conference aims to deepen the collective understanding of green infrastructure as a pivotal component of sustainable urban futures.

The transcalarity and transdisciplinary nature of the conference is clearly demonstrated by the numerous topics and subtopics addressed which engage a wide range of actors, methodologies, and research perspectives. The sections into which the conference has been structured are: 1) resilience to urban risks, 2) urban microclimate and outdoor spaces, 3) interventions at the building level.

Within the broader discourse on urban resilience, the contributions delve into a variety of interconnected themes that explore the multifaceted role of NbS in addressing both natural and anthropogenic risks. Particular attention is given to multi-risk assessment tools aimed at enhancing cities’ adaptive capacities, alongside investigations into stormwater management systems and their integration with NbS. Both experimental and numerical approaches are presented to evaluate the feasibility and effectiveness of these solutions within complex urban environments. In parallel, several studies reflect on the potential of NbS to foster urban well-being and public health, highlighting their capacity to alleviate environmental anxiety and enhance overall quality of life. Moreover, the social dimension of green interventions emerges as a crucial aspect, with a focus on participatory planning, shared responsibility, and the cultivation of a collective sense of belonging through community engagement in the design and stewardship of green spaces. This exploration is further enriched by analyses of the economic and social repercussions of greening strategies, as well as by contributions examining statistical, agronomic, and biological factors vital for ecosystem protection.

When turning to the theme of urban microclimate and outdoor spaces, the discussion centers on the potential of NbS to mitigate urban heat island effects and to enhance outdoor thermal comfort. Contributions investigate how greening strategies can be effectively integrated into dense urban fabrics, and reflect on the economic and administrative frameworks necessary to support such interventions.

At the building scale, the dialogue shifts toward specific applications such as green roofs, living façades, and pocket gardens, considered not only for their aesthetic value but also for their impact on passive climate control and user well-being. The integration of greenery with energy-efficient strategies, especially in the context of historic buildings, is another area of interest, accompanied by reflections on the cost-effectiveness, management, and long-term maintenance of green infrastructure in architectural contexts.

It is within this broad landscape that the conference positions itself as a distinguished platform for dialogue and exchange, where researchers and practitioners from various disciplinary backgrounds are invited to engage in a shared reflection on effective strategies for regenerating urban spaces, strengthening the resilience of environmental systems, and envisioning new paradigms of sustainable well-being. This moment of collective engagement aspires to initiate a more layered and multidimensional reflection on the transformative potential of NbS, not only as instruments of mitigation and adaptation, but also as powerful cultural and social drivers capable of reshaping the profound relationship between human communities, the environment, and the city.

Topic A

Resilience to urban risks

Co-creating Nature-based Solutions in city-port areas. Reflecting on the role of environmental regeneration measures in the SPArTaCHus project

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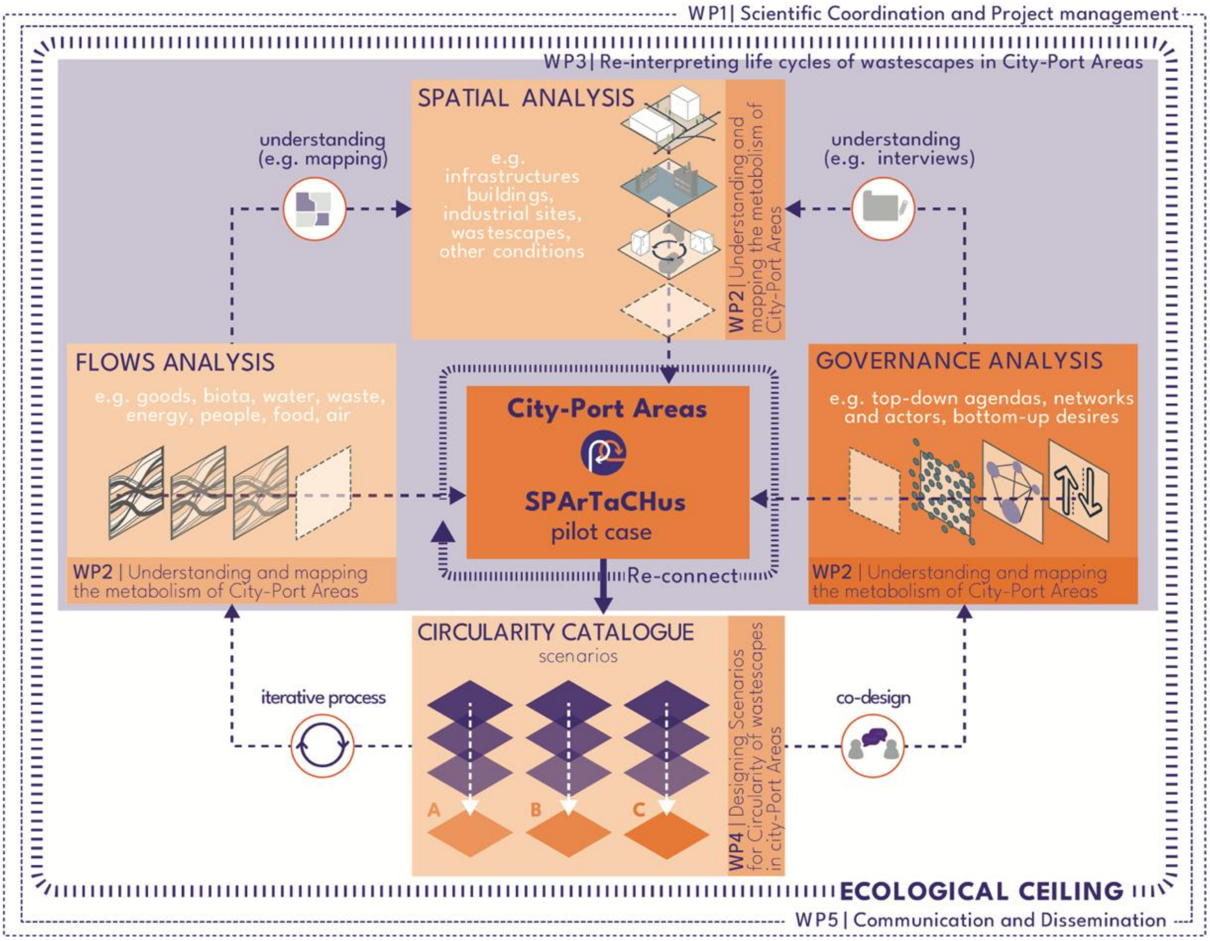
Highlights

- City-Port Areas (CPA) are multi-risk environments characterized by high degree of complexity
- Wastescapes in CPA lack the main characteristics of publicness: ownership, accessibility, management, and inclusiveness
- NBs could be linked to negative impacts on socio-economic balance and gentrification

Keywords

Co-Creation, Wastescapes, City-Port Areas, Circular Urban Metabolism, Environmental and Climate Justice



SPArTaCHus methodological framework. Image source: graphic by Libera Amenta, adapted from SPArTaCHus Research proposal. Corresponding proponent: Libera Amenta

Research background and approach

The complexity of City-Port Areas (CPA) [4, 5] is exacerbated by multi-risks (environmental, natural and anthropic risks) overlapping in their environments, making them an important field of experimentation. CPA are mostly affected by climate change, resource scarcity and linear urban metabolism processes, resulting in a significant amount of wastescapes [3, 7]. The latter are abandoned or underused territories, at the end of their life cycles, that lack the main characteristics of publicness: ownership, accessibility, management, and inclusiveness [6]. In Italy, coastal areas are the contexts that have been mainly transformed in the last decades, contributing to alterations of coastal ecosystems and worsening the ongoing climate crisis.

To achieve a better resilience for CPA, the ongoing research SPArTaCHus investigates multifaceted approaches that are necessary to cope with these interconnected challenges, to foster regenerative solutions for re-inputting wastescapes in the circular urban metabolic processes. The regeneration process for the wastescapes in CPA present diverse challenges related to climate change issue, soil scarcity and difficulties to grow within ecosystem boundaries, overtourism, together with the additional pressure of high population density that generally exists in coastal territories.

The planning approaches for wastescapes regeneration, based on principles of circularity and through the implementation of Nature-Based Solutions (NBS), are sensitive to the needs of the different stakeholders, to the circularity of energy and materials, as well as to the preservation of unbuilt soil, green areas and permeable open spaces that can assure long-term availability of land for agricultural purposes, and the provision of ecosystem services for all.

Assumed that land in CPA is a scarce resource, this contribution aims to show how in these territorial contexts wastescapes can become circular hot spots and potential networks of available public spaces functioning as incubators of innovation for circular and regenerative solutions based e.g. on mitigation and adaptation measures [1] and on regeneration processes through NBS. Enhancing nature in the city has been showing its relevance increasingly in the last decades due to the need for climate change adaptation measures and due to COVID pandemic, and it is a right for all the inhabitants.

Aims and scope of the SPArTaCHus research

This contribution is part of a research SPArTaCHus ‘Sustainable City-Port Areas Towards Circular Hubs’ and offers a reflection on how to restore the publicness of wastescapes in CPA through a co-created regeneration process based on nature interventions, while ensuring environmental and climate justice.

To this end, the methodological approach of the SPArTaCHus research is presented (Fig.):

- It is structured by merging insights from urban ecology, urban metabolism, ecological urbanism, including a more-than-human perspectives to support the understanding of the complexity of a circular and nature-based regeneration process for wastescapes in CPA.
- It is based on case-study research—moving from site-specific configurations to broader “proof of concept” approaches—by examining practices, narratives, and discourses, including more-than-human perspectives.
- It adopts a regenerative approach which goes beyond conventional notions of circularity, moving from the circular loop of resources to the circular regeneration of territories which are at the end of their planned life cycles.

By focusing on the regenerative potential of wastescapes, SPArTaCHus highlights how targeted interventions can simultaneously address multiple challenges—such as port-related pressures, land scarcity, and climate risks—within planetary safe and just limits. To do so, the research aims to develop, (in a collaborative way), a Circularity Catalogue which identifies a set of “recommendations” or “guidelines” that are co-designed to foster “alternative scenarios” for CPA, where innovative land-use strategies, adaptive infrastructure, and stakeholder engagement converge to enhance social well-being, economic vitality, and ecological integrity.

This co-created Circularity Catalogue aims to contribute to a definition of a sustainable and just regeneration of wastescapes in CPA that can be implemented through NBS, while securing an advance on the sustainable transition for CPA. This is achieved through a systemic implementation of circular initiatives, which can allow at the same time climate justice, ensuring that equity and human rights are central for the decision-making processes and for the definition of actions on climate change [10].

Co-creation activities for CPA

This contribution aims to show that the active participation of citizens in the decision-making process is a primary tool for the circular regeneration of CPA. To ensure the understanding of the importance and of the possible modalities to actively involve citizens in the co-design process and management of NBS [7] is an essential part of the ongoing research. The research fosters that co-creation activities are relevant for the just transition of CPA, where all stakeholders can participate in decision-making and in the process of implementation of policies and plans, improving their awareness and preparedness towards overlapping multi-risks. Implementing co-creation activities is thus identified as a necessary condition for the transition towards climate justice.

Indeed, through different co-creation activities, SPArTaCHus project fosters dialogue with diverse stakeholders—including researchers, local authorities, professionals, students, and private-sector representatives—through interviews, co-design activities, and walking co-design workshop. These are all participating to the SPArTaCHus Lab, namely a collaborative virtual and physical platform where different stakeholders can interact and bring their own view and expertise and that can finally contribute to align public and private interests.

SPArTaCHus applies this methodology to the Metropolitan Area of Naples, and specifically to the case-study of Castellammare di Stabia, where it is possible to identify coastal fragmented ecosystems as at the mouth of the Sarno River. In particular, in the case-study of Castellammare, the project has been implementing different practices of community engagement, such as surveys, site visits with university students, workshops with experts, students and local actors, namely the Urban Co-Design Laboratory: “Multi-Risk: Water, Heritage, Circularity” held in Castellammare on the 14.04.2025 and developed in collaboration with IUAV University of Venice,[1] and a walking co-design laboratory for landscapes to be regenerated, namely the Jane’s walk organized in Castellammare on the 16th of June 2025,[2] as well as a design studio Lab of the second semester of the academic year 2024-2025 of the study-course ACTA, International Master’s Degree in Architecture for Communities, Territories and Environment of the Department of Architecture of the University of Naples Federico II.[3] All these initiatives have been aimed at the development of new circular and shared visions for the city.

SPArTaCHus is analysing -at the same time and through master thesis investigations and research activities abroad- European circular and NBS practices examining which are the main elements and methods that might be transferred and adapted to the Neapolitan contexts. By reimagining wastescapes as catalysts for circular growth, SPArTaCHus underscores how CPA can decouple economic development from resource depletion, charting a path toward sustainable and regenerative futures.

Discussion and open questions

While it is evident that NbS can have positive impacts on the circular regeneration of wastescapes, for human and non-human inhabitants, and although widely recognised at the European and global level by many policies and programs (e.g. Green Deal, EU Biodiversity Strategies, Urban Agenda for the EU, UN SDGs) for their positive role to address complex challenges in urban areas, especially in relation to the increasing climate crisis, however NBS could be also linked to negative impacts on socio-economic balance in cities. The implementation of NBS for the resilience of urban areas can indeed lead to the rising inaccessibility of housing market due to the escalation of housing rental and purchase costs in green-based regenerated urban areas. In fact, NBS can be -unintentionally - the cause of the so-called environmental, green, or ecological gentrification.

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[1] Interaction with the project MIRACLE, coordinated by Francesco Musco, IUAV University of Venice.

[2] Activity developed in collaboration with Francesca Nocca, University of Naples Federico II.

[3] Teachers of the integrated Laboratory entitled “Laboratory of implementation processes for the ecosystemic design of habitats [Laboratorio di processi attuativi per la progettazione ecosistemica degli habitat]” of the study-course ACTA, International Master’s Degree in Architecture for Communities, Territories and Environment of the Department of Architecture of the University of Naples Federico II, are Dora Francese, Giovanni Multari and Libera Amenta.

Greening actions can be indeed related with the risk of the green gentrification and displacement of vulnerable population groups from the new urban vision of regeneration, defining a social process that exacerbates existing inequalities in relation to the economic weakness of residents [2].

This process involves the displacement of fragile communities, as instance lower income residence [9], thus it is important to identify monitoring tools for avoiding gentrification risks while applying NBS for the circular regeneration of wastescapes.

How the results of the co-creation activities developed in the considered case-study of Castellammare, and of the Metropolitan Area of Naples in general, could be scaled up to CPA in general is one of the aims of the research.

Through the (co-)mapping of wastescapes in CPA, and thanks to the organization and development of co-creation sessions with the local community to increase their engagement and risk awareness, the research aims to reach the aim of identifying transferable results through the definition of a Circularity Catalogue that is co-created with students, local community, experts and other relevant stakeholders. It will be composed by a set of guidelines for planning to achieve a climate just city through reflections on 1) collaborative planning methods; 2) the inclusion of the more-than-human perspective in the regeneration of city-port areas; 3) equity of access and compatible uses of the maritime public domain.

Acknowledgments

This paper is part of the outcomes of the Research 'SPArTaCHus. Sustainable city-port areastowards circular hubs. rethinking life cycles of wastescapes in the city-port areas of the metropolitan City of Naples.' Research financed within the framework 'University Research Funding Program – FRA, 2022' (Programma per il Finanziamento della Ricerca di Ateneo – FRA, 2022), of the University of Naples Federico II, Italy. Corresponding proponent: Libera Amenta. Università degli Studi di Napoli Federico II [Iniziativa finanziata nell'ambito del Programma per il Finanziamento della Ricerca di Ateneo (FRA) 2022 dell'Università degli Studi di Napoli FedericoII].

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Green roofs: a preliminary Computational Fluid Dynamics approach

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Highlights

- The characteristics of the substrate have not been sufficiently studied
- CFD can represent rain conditions and improve green roof projects
- Green roofs can absorb up to 100% of the water from high-intensity rainfall

Keywords

Green Roofs; Stormwater Management; Urban ecology; Green infrastructure; Computational Fluid Dynamics (CFD)

Green roof [1]

Introduction

Even with projects to increase green areas, the urbanization process has led to their decrease in most cities worldwide [2]. The loss of infiltration areas leads to an increase in the discharge, velocity and volume of water conveyed into urban sewer systems [3]. If this were not enough to aggravate stormwater management problems, climate change has increased the frequency and intensity of extreme rainfall events [4]. In this context, the use of green solutions represents a reliable approach to couple engineering improvements with interesting environmental and socio-economic co-benefits. Green roofs (Fig.1) take advantage of the retention and infiltration capacity of different layers of vegetation and soil, while providing economic, social and ecological benefits.

The composition of the substrate is a crucial factor since soil texture influences root penetration, impacting plant stability, and water infiltration [5]. Nevertheless, understanding the hydrodynamics of these structures is very challenging, given the variable rainfall actions and the heterogeneous configurations of green roofs.

Previous studies have often modeled green roofs for thermal and comfort analysis, trying to understand their effect in the building and surrounding temperatures. Even if a hydraulic approach is important to understand how these structures can mitigate the derange systems overflow, few works have applied computational fluid dynamics (CFD) in this context trying to understand the hydrological impact, rather than the thermal response. This gap motivated the development of a CFD model that can predict correctly the process of rainwater infiltration in green roofs soil. The objective is to represent the stratigraphy of this structure, its drainage behavior in storm events and enable a tool to support projects aiming mitigate rains negative impacts in cities. This way the stratigraphy of green roofs determines their storage and drainage capacities, what remains unclear is how to optimize its layers to obtain the best results in stormwater management. To address it, a CFD- based rainfall simulation was implemented that represents a real green roof structure and boundary fluxes. This paper details the computational domain, rainfall and numerical settings and preliminary results.

Methodology

With the ability of green roofs to retain water, the idea arose to use them for stormwater management. Aiming to do so, it was decided to develop a CFD model that would be able to represent the rain, the soil and their interaction of infiltration and retention. The representation for the rain was done with a volume of fluid where the inlet had a phase-fraction of water and the soil with a porous medium to represent the flow interference. To be able to study this, it was first necessary to understand the main structure of these architectural projects.

A green roof is composed of many layers with different functions that ensure the effectiveness of the system. The most visible layers are the surface layers, the vegetation and the growth layer, also known as substrate, which promotes plant growth, support, nutrients and water. In the lower side, a filter layer prevents the soil particles from entering and clogging the drainage system. Then, a drainage layer ensures adequate water flow, avoiding its accumulation. At a deeper level, there is a root barrier to protect the main structure. At last, before the roof itself, a waterproofing membrane protects the building ceiling from water infiltration [6]. All these elements were considered to design the following methodology.

Simulation Setup

The setup was based on a real green roof of area 1.78m x 1.78m with no slope, drain outlet beneath for the infiltrated water and on the lateral through gutters for the runoff. Chosen for presenting standard measurements for a real scale and the possibility of sustaining different substrate depths.

A CFD model was developed to represent this case with a porous media to rep-resent the soil and an atmosphere above for rain to develop in free fall. The porous medium was chosen because it represents the resistance to flow generated by real soil, but without the need for an extremely refined mesh that would be necessary to represent the space between the grains and consequently increase the need for computing power. Rain was represented as a partial water volume inlet, assuming high-intensity rain to represent critical cases and with homogeneous distribution in droplet size, as this is a preliminary approach and this can verify the feasibility of the model.

The domain consists of a 2D representation of a longitudinal cut of a green roof with atmosphere above it. This cut results in a bidimensional domain with a positive height of 2.1m that consists of 2.0m representing the atmosphere and 10cm representing the region of runoff. Besides, there is a negative depth to represent the substrate depth of 10cm, thus having all the results with negative depth being below ground level. Being 1.78m

long, the origin of the coordinate axis is located on top of the substrate and in the corner of the domain so that all coordinates in the XY plane are positive.
The surface runoff outlet region and the base of the domain were configured as a zero-gradient region, to avoid return flows. The domain top was set as an inlet region along with liquid film conditions to simulate rainfall. Finally, the porous medium was used to simulate the soil region using parameters of a porous Darcy-Forchheimer medium.
To run the simulation, the open-source software OpenFOAM version 2212 [7] was used. A non-turbulence model was chosen. The flow will be mostly two-dimensional and without recirculation zoning, which removes the need for more robust models. Thus, second-order numerical schemes were used for modeling. Results and discussion

Representation of rain and soil
To model the rainfall, the fraction phase α of water to total volume was set. It represents the amount of water within a computational cell, thus defining the volume convertible into rain flow. However, this would be for each water droplet diameter, so the rain flow rate needs to be multiplied by the fh factor, which is the probability density of droplets with a diameter less than or equal to d [8], resulting in Eq.1.

$$\alpha = R*fh/V \tag{1}$$

where R is the intensity of rain and V the terminal velocity.

A rainfall intensity of 30mm/h was set for simulations, corresponding to a high intensity rainfall [9] for a duration of 10'. A droplet diameter of 3mm of a homogeneous distribution (fh=1) was also selected, which results in a terminal velocity of approximately 8m/s [10].
For soil modelling, a porous medium was chosen, given its capability to effectively model the absorption of the flow energy. The advantage of this choice also relies on not needing to singularly model the grains, making the mesh generation easier with related shorter computational efforts. The momentum sink represented by Eq.2 is modeled.

$$Sm = d*\mu*U + 1/2*f*\rho*U^2 \tag{2}$$

where d is the Darcy coefficient, μ the viscosity of the fluid, U the velocity, f the Forchheimer coefficient and ρ the density of a fluid. Where the Darcy coefficient represents the viscous resistance of the media and the Forchheimer coefficient represents the inertial resistance
For the implementation of the porous medium, a sandy soil was chosen and the values for this type of soil are specified in Table 1.

Table 1. Darcy-Forchheimer

Soil	**Porosity (ε)**	**Particle diameter (dp)**	**Solid Volume Fraction**	**Porous Coefficients**	
				d	**f**
Sand	0,47	1,50E-04	0,53	1,80E+10	5,96E+04

Results and discussion
The water volumes leaving the domain after 5min and 10min of rain were assessed for two scenarios, namely without and with green roof (Table 2).

Table 2. Water volume

Scenario	**Runoff [L/m²]**		**Soil outflow [L/m²]**	
	5min	10min	5min	10min
Without Green Roof	2,5	5	-	-
With Green Roof	0	0	0	0

For the scenario without green roof, the entire water volume would be discharged into the building's drainage system and, almost immediately, into the urban sewer system. For the scenario with green roof, even with heavy rain, all the rain in the vegetated area would not be discharged into the drainage system at the most critical phase of rain. The lack of outflow of water was due to the low speed of runoff into the soil and with the duration of the rain, it did not reach all the way through the soil. In addition, there was no runoff as the amount of water was not enough to saturate the soil and deplete its infiltration capacity. Therefore, it was possible to demonstrate that the model is capable of representing the resistance to water drainage generated by the soil and its capacity to retain rainwater.

However, it is very important to note that even though the results follow the expected pattern, these are still preliminary and not yet validated by real experiments that will be carried out on a full-scale prototype. In addition, they show that a real structure would retain all the rainfall in its area, which results in additional overload that must be properly addressed when designing the building.

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Nature-based Solutions for the regeneration and resilience of smart villages: design, strategies and case studies in Mediterranean inner areas

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Highlights

- NbS applied to preserved rural areas for adaptive regeneration
- A model for Smart Villages integrating greening and heritage
- Case study from Mediterranean context with replicable solutions

Keywords

Smart Villages; Nature-Based Solutions; Rural Resilience; Green Infrastructure; Heritage Landscapes

Bompietro, a village in the Madonie Park: an indissoluble bond between nature and architecture; ©image by author, 2024

Introduction

In recent years, Nature-Based Solutions (NbS) have emerged as key tools for climate adaptation, environmental sustainability, and spatial resilience. By harnessing natural processes and ecosystem services, NbS are widely recognized for their ability to enhance urban comfort, regulate hydrological systems, and support biodiversity [1]. Beyond environmental benefits, the post-pandemic period has highlighted the psychological importance of reconnecting humans with nature, encouraging further exploration of the social and experiential impacts of these solutions. While NbS implementation has been extensively studied in metropolitan areas, rural and inner territories remain underrepresented in both research and policy. Yet, these marginal areas, often rich in environmental resources and cultural heritage, offer ideal conditions to act as experimental laboratories for ecological and social innovation [2]. Small towns and rural settlements face challenges such as demographic decline, infrastructure gaps, and increasing exposure to climate-related stressors. At the same time, their scale, territorial cohesion, and strong local identity create opportunities for context-sensitive and low-impact greening strategies. Within this framework, the concept of the "Smart Village" becomes particularly relevant, representing a development paradigm based on innovation, digital transition, environmental awareness, and community-centered governance. Smart Villages aim to preserve and regenerate both ecological and cultural landscapes while fostering sustainable local development. This study explores the potential of NbS within the Smart Village framework, focusing on their application in preserved rural areas with high environmental and historical value. By adopting a territorial perspective, the research reframes NbS not merely as environmental interventions, but as instruments capable of strengthening local resilience, enhancing everyday life, and fostering place-based innovation [3]. The Madonie region in Sicily serves as the primary case study, exemplifying a territory where landscape protection, architectural tradition, and environmental fragility converge.

Objectives

The main objective of this research is to propose a methodological framework for the integration of Nature-Based Solutions into the adaptive regeneration of small rural settlements, with particular attention to those areas aligned with the Smart Village paradigm [4]. The research investigates how NbS can be applied in fragile yet valuable territorial contexts to improve environmental comfort, support ecological resilience, and enhance overall quality of life. At the same time, it aims to ensure that such strategies remain respectful of the landscape identity, heritage significance, and spatial specificity of each location. Through an in-depth analysis of existing practices and planning approaches, the study seeks to define operational principles that can inform sustainable and context-aware interventions in small towns. The focus on a Mediterranean inner area, such as the Madonie region, makes it possible to evaluate the viability of NbS in territories where climate change, socio-economic fragility, and territorial abandonment often converge. The work aims to demonstrate how these areas, despite their challenges, can become fertile terrain for innovation that respects and builds upon the specific features of place [5].

Methodology

The methodology adopted combines a qualitative and comparative approach, drawing from scientific literature and the critical analysis of existing projects. Rather than directly engaging communities or deploying monitoring technologies, the research examined strategies and practices already implemented in similar territorial contexts to identify approaches aligned with the spatial, environmental, and cultural characteristics of rural settlements, and to understand how these can inform future interventions. The study began with a systematic review of academic contributions, operational guidelines, and European planning frameworks addressing the application of Nature-Based Solutions in rural and peri-urban contexts, with particular attention to Mediterranean experiences where water scarcity, heatwaves, and erosion intersect with complex settlement patterns and historical legacies. This review highlighted key criteria for assessing the relevance and adaptability of NbS to fragile territorial systems. The focus then shifted to the Madonie area in northern Sicily, a representative case of a preserved rural environment challenged by depopulation and infrastructural decay. Characterized by inclusion in the UNESCO Global Geopark network, rich traditional architecture, and high environmental sensitivity, the area was analyzed through an integrated assessment of spatial, morphological, and climatic data alongside recent public interventions [6]. This revealed recurring issues such as the use of inadequate materials, poor coherence between new designs and historical contexts, and limited quality of public spaces in terms of usability and environmental performance. Rather than proposing new interventions, the study interpreted existing spatial conditions, evaluating the design logic and NbS choices of prior projects and their compatibility with the cultural and ecological specificity of the area. To ensure methodological robustness and address Reviewer 1's suggestions, the study introduces a set of quantitative indicators to support long-term monitoring and comparative assessment. The framework considers four interconnected dimensions: community engagement, governance effectiveness, heritage rehabilitation, and digital and technological innovation. Community engagement is evaluated through measures such as the number of active associations, citizen participation in workshops, and continuity of volunteering initiatives, while governance effectiveness considers the percentage of funded projects successfully implemented, decision-making times, and the availability of open data. Heritage rehabilitation is assessed by the surface area of rehabilitated built heritage, the proportion of reused traditional materials, and the number of cultural events tied to local identity, whereas digital and technological innovation is measured via broadband coverage, digitalization of public services, and uptake of ICT tools. Each indicator includes baseline and target values, enabling longitudinal monitoring and cross-comparison across municipalities. These results are aggregated into a Smart Village Performance Index (SVPI), providing a synthetic yet comprehensive tool to assess improvements and guide adaptive strategies. By integrating quantitative metrics with qualitative insights, the framework offers a replicable model for future research and practical application in other Mediterranean inner areas [6][7].

Results

The analysis of the Madonie region revealed both the potential and the criticalities associated with the integration of Nature-Based Solutions in small-scale rural settings. On one hand, the study highlighted how greening interventions, when designed in accordance with local morphology and material culture, can contribute to improving thermal comfort, managing surface runoff, and enhancing the experiential quality of public spaces. On the other hand, it became evident that several projects carried out in the area over recent years have failed to capitalize on these opportunities, often due to the adoption of cost-driven solutions that disregard environmental coherence and spatial sensitivity [8]. Among the most recurring problems identified were the use of non-traditional materials, the lack of shading and ventilation in public areas, and the limited integration between vegetation and built space. These choices, often dictated by economic constraints or standardized planning models, have contributed to the deterioration of local microclimatic conditions, particularly during periods of extreme heat. In some cases, areas that were once highly livable have become difficult to inhabit, especially for vulnerable populations, due to the lack of protective and mitigating elements in the built environment. The study found that NbS interventions can be effective even at a very small scale, if they are conceived as part of a broader strategy of environmental and cultural compatibility. For instance, green roofs and walls, if applied to public buildings using appropriate local materials and techniques, can reduce overheating and improve building integration into the landscape. Likewise, the transformation of abandoned lots into pocket gardens, or the insertion of vegetated pedestrian routes, can have a significant impact on social and environmental quality, especially in villages affected by depopulation and infrastructure decay. However, the research also underlined that the success of such interventions depends not only on their design but also on their ability to resonate with the identity and aspirations of the place. The compatibility between ecological function and architectural language emerged as a fundamental condition for the acceptability and sustainability of NbS in heritage-rich rural contexts. In the Madonie area, the lack of this alignment has frequently resulted in missed opportunities for regeneration and adaptation [9]. Rather than offering prescriptive solutions, the study proposes a conceptual model that can help guide decision-makers, designers, and planners in assessing when and how NbS can be introduced in similar contexts. The findings suggest that planning approaches should move away from standardized environmental devices and instead focus on tailored strategies that are informed by local material cultures, climatic dynamics, and spatial traditions.

Conclusion

This research contributes to the growing discourse on Nature-Based Solutions by shifting the focus from large-scale urban implementation to the specific needs and potentialities of rural and inner areas. By examining the case of the Madonie region through the lens of the Smart Village paradigm, the study demonstrates how small-scale greening strategies can play a crucial role in promoting environmental resilience, spatial quality, and community well-being, even in the absence of large investments or technological infrastructures. The integration of NbS in rural territorial planning requires a deep understanding of local identity, environmental constraints, and spatial morphology. The research highlights the importance of coherent material choices, respectful design approaches, and a forward-looking vision capable of interpreting natural and cultural resources as complementary assets. In this perspective, Smart Villages can become not only recipients of innovation, but active protagonists in shaping place-based strategies for climate adaptation and ecological regeneration [10]. Ultimately, this study affirms that the sustainable future of rural territories will depend on their ability to reconcile tradition with innovation, and on the development of planning models that are both ecologically sound and culturally meaningful. Nature-Based Solutions, when grounded in such an approach, can serve as powerful tools to unlock this potential.

Acknowledgement

This research was founded by the European Union EU Next Generation Italian PRIN/PNRR 2022 Project titled “Greenwork: an interdisciplinary framework for urban health and urban resilience enhancement based on greening strategies on buildings and open spaces” - Project Code MUR P2022MNKEC 003 - Sector: ERC SH7 - CUP: B53D23029580001 - PRJ-1358.

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Urban green barriers as Nature-based Solutions to reduce airborne particulate matter and associated pollutants

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Highlights

- Air pollution causes high mortality; WHO PM limits are frequently exceeded worldwide
- Urban green barriers serve as effective NBS to reduce airborne particulate matter
- Potentially toxic elements and microplastics accumulate more on leaves outside barriers

Keywords

Air pollution, Green Barriers, Particulate Matter, Potentially Toxic Elements, Microplastics

Satellite view of Fratelli De Filippo Urban Park (Naples, Italy), showing the surrounding green barrier composed of Platanus hispanica trees and Nerium oleander hedges along Aldo Merola Street and Luigi Califano Street. Sampling positions of individual trees and hedges are indicated both outside the park (green barrier) and within the internal areas. Image source: Google Earth (2025)

The escalating challenge of urban air pollution, exacerbated by emerging contaminants such as microplastics (MP), potentially toxic elements (PTE), and polycyclic aromatic hydrocarbons (PAH), demands innovative and sustainable mitigation strategies [1]. Among these, urban green barriers composed of carefully selected plant species have shown promising potential as Nature-Based Solutions to reduce the dispersion and deposition of airborne particulate matter (PM) and improve environmental quality in densely populated areas [2]. Given that air pollution remains a leading cause of mortality worldwide and that WHO annual guidelines for PM are frequently exceeded, effective strategies for urban air quality management are imperative [3].

This study was conducted at the Fratelli De Filippo Urban Park, located in Ponticelli, Naples, Italy, focusing on the effectiveness of vegetative green barriers in mitigating airborne PM and associated pollutants within a public park hosting 210 urban allotments, an environment where air quality is critical for public health and wellbeing (Fig. 1). The park is bordered by continuous green barriers on both its northern and southern sides, composed of *Platanus hispanica* planted in rows within individual flowerbeds and *Nerium oleander* shrubs positioned atop 3-meter-high stone walls. These green barriers face two major traffic corridors, both characterized by high vehicle flow.

Sampling campaigns were conducted during both summer and autumn in 2023 and 2024. Leaf samples were collected at a height of 2 meters from both species, both inside and outside the green barriers. Each representative sample was a composite of leaves from three branches per plant. The leaves were individually cut in half along the midrib; one half was subjected to washing (W), while the other remained unwashed (NW). Both halves were analyzed for PTE (ICP-MS) and PAH (GC). Additional samples were collected at 3 and 6 meters for MP analysis (FTIR), including both intact leaves and enzymatically digested tissues to evaluate the presence of MP within internal leaf structures. Soil samples were also collected and analysed for geochemical profile. A three-way ANOVA was performed using SPSS software to evaluate the effects of position (inside vs. outside the green barriers), washing treatment (washed vs. unwashed), and species (*P. hispanica* vs. *N. oleander*) on PTE concentrations. Principal Component Analysis (PCA) complemented these results by revealing multivariate patterns and clustering associated with the same factors. Findings demonstrated significantly elevated levels of key potentially toxic elements (V, Al, Pb, Sb, Cr, Cd, As, Cu) outside the barriers, consistent with urban pollution sources such as vehicular emissions and tire wear [4]. Fine and ultrafine particle number concentrations were simultaneously measured inside and outside the green barriers using a Pro Aerosol Dosimeter (PARTECTOR) for particles ranging from 10 to 300 nm and using a Condensation Particle Counter (CPC) for particles ranging from 20 to 1000 nm. The observed trends aligned with the leaf analysis results, further confirming the reliability of plant leaves as biomonitors of airborne particulate pollution in urban environments. Washing treatments significantly reduced PTE content overall. Elements such as Cu and Cd showed no significant differences between washed and unwashed samples across all sampling campaigns, indicating these elements are primarily absorbed and retained within leaf tissues. In contrast, elements including Al, Co, Cr, Fe, Pb, Sb, and V consistently exhibited higher concentrations in unwashed samples, reflecting substantial atmospheric deposition that can be partially removed by washing. The species exerted a significant and consistent influence on leaf mineral element concentrations: overall, *N. oleander* displayed a broader accumulation spectrum across multiple elements, whereas *P. hispanica* showed a more selective uptake pattern.

PAH levels were always below detection limits, while the total PTE content in soils remained below the threshold contamination limits. MP analysis revealed a pattern like that observed for PTEs, with higher MP concentrations outside the barriers, predominantly as polyethylene (PE) fragments at 3 meters and polyethylene terephthalate (PET) fibers at 6 meters. Differences in PTE accumulation were observed between summer and autumn sampling campaigns in both 2023 and 2024, with a notable reduction in the effectiveness of green barriers during the autumn season. This seasonal trend could be attributed to physiological dynamics specific to the species. In *P. hispanica*, a deciduous species, leaf senescence may reduce physiological activity, such as the capacity to intercept airborne particles via stomata and trichomes, thereby diminishing the barrier's effectiveness [5]. Additionally, the prolonged retention of leaves during autumn could lead to progressive surface saturation by previously deposited particles, further limiting interception capacity. These mechanisms, individually or in combination, could contribute to the decreased efficiency of vegetation as a biological filter in autumn. These findings highlight the importance of considering plant species and their annual physiological cycles when designing green infrastructure for urban air pollution mitigation.

Investment in urban green infrastructure should be grounded in robust scientific evidence to harness the multifunctional benefits of its inherent multifunctionality fully. This study highlights the importance of evidence-based strategies in maximizing the effectiveness of green barriers in improving urban air quality and promoting citizen well-being. Implementing such interventions thoughtfully can significantly reduce exposure to airborne pollutants, safeguarding both public health and urban ecosystems, and addressing urgent challenges in sustainable urban development. While this study provides robust evidence on the local scale, further research is warranted to evaluate the extent to which these findings can be generalized to other contexts. Moreover, future investigations could assess the potential public health and societal benefits associated with reduced particulate matter exposure.

Acknowledgement
National Biodiversity Future Center - NBFC funded by NextGenerationEU under NRRP, M4C2I1.4. CN00000033, CUP E63C22000990007.

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Participatory validation of Nature-based Solutions for urban resilience: a Mediterranean case study

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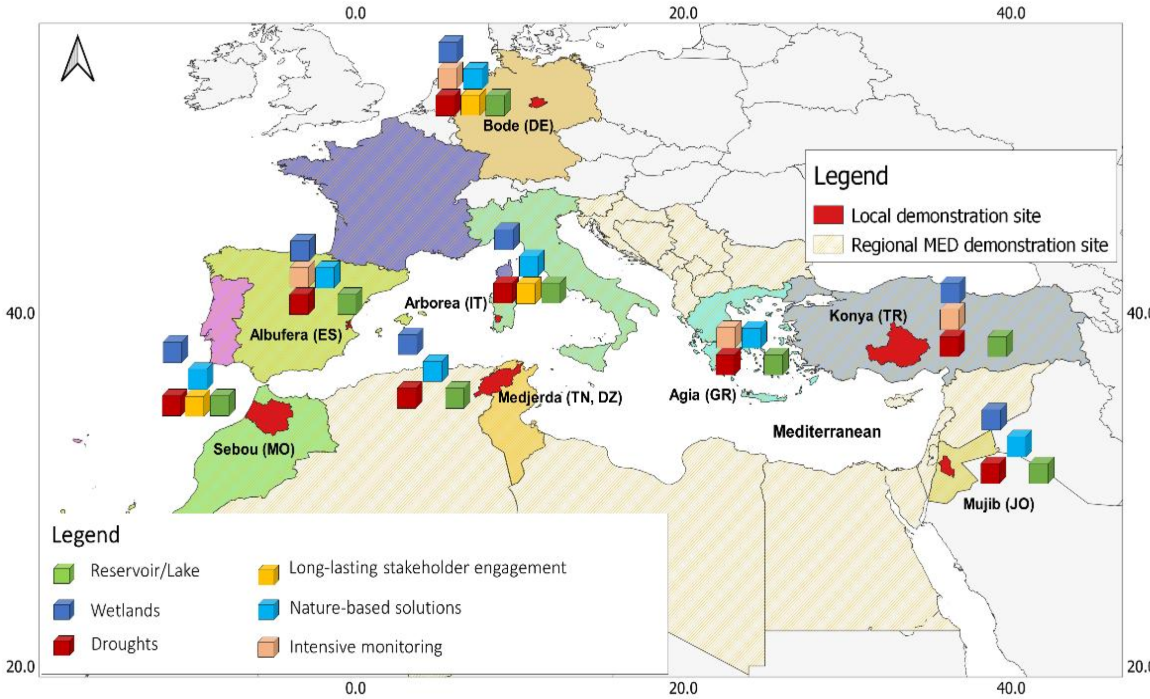
Highlights

- NbS boosts urban resilience ecologically, socially, and economically
- Stakeholder-informed NbS framework enhances urban resilience planning
- Participatory validation refines one-third of the proposed NbS

Keywords: Nature-based Solutions (NbS); Urban resilience; Participatory planning; Mediterranean cities; Climate adaptation



DEMO sites available over the Mediterranean region within the OurMED Project

Introduction

Urban areas represent strategic focal points for advancing climate mitigation and ecosystem restoration strategies. This context demands a strategic focus on sustainable urban development, especially in light of rapid population growth and escalating resource pressures [7]. Urban areas face significant strain from expansion, open space conversion, climate change, and pollution, which threaten natural habitats, human health, biodiversity, and ecosystem services [6]. Cities are dealing with intensifying environmental, social, and economic challenges that cumulatively undermine the resilience of urban areas and affect the well-being of their inhabitants [3].

Nature-based Solutions (NbS) have gained prominence as a transformative strategy to address these multidimensional challenges by leveraging ecosystem services to enhance urban resilience while delivering co-benefits for sustainability and human well-being [3]. NbS are defined as actions inspired by, supported by, or copied from nature, to restore natural processes and ecosystems to address societal challenges. These solutions simultaneously enhance environmental sustainability, socio-economic resilience, and human well-being, providing a multifunctional framework to tackle complex urban challenges through integrated ecological, social, and economic co-benefits [4;5]. The integration of NbS into urban planning is essential for enhancing urban resilience and mitigating biodiversity decline [8]. The implementation of NbS is a multi-faceted approach that simultaneously integrate specific ecological, social, and economic conditions of each urban environment.

Background and Motivation

The strategic importance of advancing the study of NbS in urban contexts arises from the serious shortcomings in conventional urban development models, which have often prioritized economic advancement and infrastructural expansion to the detriment of ecological preservation and social equity. The conventional urban development approaches have contributed to the increase of greenhouse gas emissions, fragmentation of natural habitats, reduction of biodiversity, pronounced urban heat island effects, compromised air and water quality, and heightened vulnerability to extreme weather events [2].

The dominant directional trend of urban development, characterized by its unsustainable practices, poses an exceptional threat to the long-term well-being of urban communities, thereby underscoring the imperative for a fundamental paradigm shift towards sustainable urban planning and development strategies. Therefore, the need is to adopt a comprehensive and integrated approach that re-evaluates the complex interdependencies between urban expansion and ecological integrity, advocating for the structured inclusion of ecological principles into all facets of urban planning and architectural design, as well as promoting a resilient, sustainable, and equitable urban environment.

Research Questions and Objectives

This research aims to investigate the effectiveness of participatory methods in evaluating and implementing NbS for enhancing urban resilience in Mediterranean cities and to analyze the multi-layered (benefits) impacts of these solutions on ecological, social, and economic systems within the urban context.

The research objectives include identifying key stakeholders and local experts, along with their roles in the participatory validation process, evaluating the performance and social acceptance of selected NbS, and assessing the economic viability and long-term sustainability of these interventions. The primary research questions guiding this study are:

- How can participatory validation methods be effectively applied to assess the suitability and performance of NbS in Mediterranean urban environments?
- What are the ecological, social, and economic impacts of implementing NbS in these urban settings?
- How do various groups of key stakeholders and local experts perceive and value the benefits and trade-offs associated with NbS?

The participatory validation process is essential for ensuring that NbS are not only ecologically effective but also socially acceptable and economically viable [7]. Integrating community-based initiatives with strategic urban planning can reconnect urban populations with nature, promote local resilience, and foster inclusive development [10].

Study Area: Mediterranean Urban Context

This study is conducted within the framework of the OurMED project, titled Sustainable Water Storage and Distribution in the Mediterranean, funded under Section I of the PRIMA initiative, with support from the Horizon Europe programme. The project's central aim is to design and evaluate innovative and sustainable water storage and distribution systems fully aligned with ecosystem-based management approaches at the river basin scale. The project encompasses 9 demo sites representing the different mosaics of the Mediterranean basin (seven local, one transboundary, and one regional MED scale), as shown in Figure 1.

The Mediterranean basin, recognized for its distinctive occurrence of climatic gradients, exceptional biodiversity hotspots, and millennia of anthropogenic landscape modification, represents a compelling and complex arena for studying urban resilience and testing NbS implementations [1].

These concentrated features of urban development patterns make the region vulnerable to significant environmental pressures stemming from escalating temperatures, e.g., urban heat island effects, human health, and increased water demand, especially during the summer season [7]. NbS integration can enhance urban resilience and slow down biodiversity decline through new green neighborhoods, as well as fostering the regeneration of neglected urban areas [8].

Methodology

This study employs a three-stage, spatially explicit framework to identify and prioritize NbS within the targeted landscapes. Further details on the original framework can be found in Sarwar et al. [9].

Stage 1: Catchment Classification

The catchment classification integrates ecosystem, climate, soil type, and slope classifications to generate a baseline ecological profile. This geospatial analysis represents the foundational layer for NbS suitability mapping.

Stage 2: Evidence-Based Screening (Decision Matrix)

Then, a systematic literature review feeds a decision matrix that cross-references the ecological profile of the catchment with documented NbS effectiveness. This yields preliminary NbS suitability maps, validated by the scientific evidence in the literature.

Stage 3: Socio-Ecological Validation

To structure the stakeholders' mapping for the identification and categorization of actors, boundaries are delineated through context analysis of ecological and anthropogenic factors, supplemented by resource analysis and visual mapping. The NbS maps are thus presented to key stakeholders and local experts for iterative refinement through workshops. Given their local knowledge and expertise, the key stakeholders identify mapping biases aimed at stimulating feedback loops useful to improve the accuracy of NbS suitability maps.

The final NbS map consistence of potential, empirical evidence, and priorities of key stakeholders and local experts. This mixed-method approach balances technical rigor with socio-ecological features by addressing both the feasibility of the intervention and the community needs.

Results and Discussion

The workshop, organized to facilitate interaction with local experts, was attended by representatives from all 9 demo sites, including their respective leaders and team members. Each demo site was represented by a minimum of three and a maximum of eight participants. All attendees were highly experienced professionals with extensive expertise in their respective fields and had been working at their demo sites for over a decade.

Participants were provided with preliminary maps derived from the framework developed by [9]. They were given 90 minutes to validate and rectify the identified issues and limitations associated with the proposed NbS. Following this, ten-minute presentations were delivered to illustrate the differences between the preliminary maps and the revised maps generated after the workshop.

This exercise provided us with revised NbS maps for all these demo sites, consistent with local perspectives. Results show distinct NbS clusters emerging along hydro-climatic gradients: arid cities (Konya, Turkey) prioritize water-harvesting interventions, while humid regions (Bode, Germany) emphasize flood mitigation strategies. This demonstrates that a one-size-fits-all approach is inadequate; it is essential to customize NbS to suit the local environment and perspectives. Notably, one-third of the preliminary proposed NbS required adjustments and modifications after the workshop, underscoring the need to integrate local knowledge. The lack of awareness and training about NbS, institutional policy barriers, financial constraints, and technical complexities were identified as further significant obstacles to the implementation of NbS in urban areas. These challenges highlight the need for the development of comprehensive and tailored approaches to effectively design and implement NbS.

Final remarks

This study advances urban resilience theory, exploiting a participatory approach for NbS co-design. It provides a practical approach for selecting potential NbS for municipalities under the Urban Agenda for the EU. Moreover, it presents a transferable framework aligning local context and needs, demonstrating greater stakeholder acceptance compared to only top-down approaches. Future research directions will emphasize longitudinal performance monitoring and climate scenario modeling to strengthen the evidence base for NbS investment decisions.

Acknowledgments

This work was supported by the OurMED PRIMA Program project funded by the European Union's Horizon 2020 Research and Innovation programme under grant agreement No. 2222 and the PRIN Project CHANCES - An integrated modeling approach for mitigating climate CHANge effects through enhanCEd weathering in Southern Italy (CUP: E53D23021850001).

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Urban green spaces environmental performance during heatwave events: remote sensing and GIS mapping for assessing the temporal response and support NbS climate resilient design

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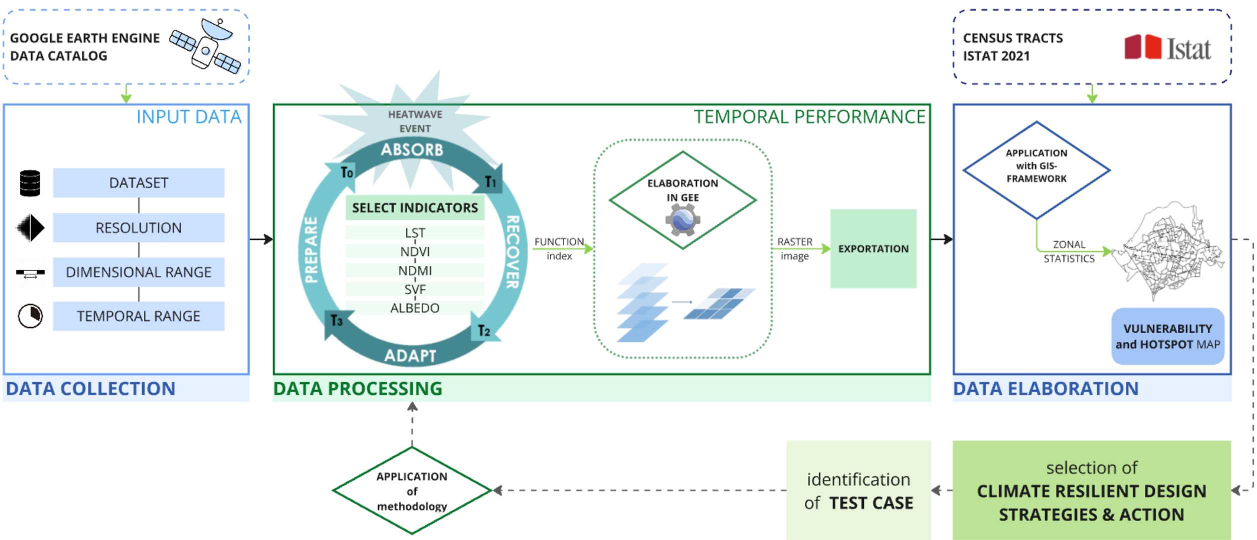
Highlights

- Open-source GIS model to assess urban resilience to heatwaves
- Time-based framework for analysing green space climate indicators
- Data-driven support for planning green interventions in cities

Keywords

Climate Resilient Design; Nature-Based Solutions; Urban Green Spaces; Heatwave events; Remote Sensing



Conceptual workflow

Heat waves are one of the main threats to urban and metropolitan settlements. Their increasing frequency and intensity represent one of the most critical challenges facing contemporary cities [1], with impacts that depend not only on the intensity of the atmospheric phenomenon, but also on the morphological characteristics of the built environment and, in particular, on the quality and configuration of open spaces. In Mediterranean contexts, the combination of high building density, soil sealing and fragmentation of green spaces amplifies the exposure and vulnerability of settlements, reducing the adaptive capacity of the urban system and increasing the thermal stress of the population living in urban areas.

In this scenario, nature-based solutions (NBS) play a strategic role not only in climate mitigation, biodiversity protection and adaptation to climate/environmental risks [2], but also as spatial devices capable of increasing microclimatic resilience and the comfort of open spaces. Recent studies have shown that increasing tree cover and connecting green spaces contribute significantly to reducing urban surface temperatures and improving microclimatic comfort [3, 4, 5], bringing additional benefits in terms of water management and air quality. City-scale programmes such as Paris' Plan Canopée [6], which aims to increase tree cover by 30% by 2030, or Barcelona's Climate Shelters initiative [7], which combines green and blue infrastructure in the redevelopment of schools, are concrete examples of nature-based adaptation applied at the local level and replicable in other Mediterranean contexts.

Gaps remain in their operational integration into urban planning and design processes and monitoring mechanisms [8]. This research addresses this gap by developing and testing a simplified methodological framework [Fig. 1] based on GIS and supported by open-source remote sensing data, which uses the behaviour of greenery as an indicator to determine the vulnerability and resilience of urban open spaces during extreme heat events. The aim is to build a system of indicators capable of describing how open space, through its ecological and morphological dimensions, perform over time.

The framework operates in three phases: data collection, data processing and data elaboration. It is implemented through computational analyses performed on the open-source platform Google Earth Engine (GEE), using time series of climate and environmental indicators to support evidence-based and replicable decision-making.

The first phase involves the collection of input data, defining the temporal range, resolution and dimensional range necessary for subsequent processing. The second phase of data processing involves the selection of key indicators, including: Land Surface Temperature (LST) to map thermal stress; Normalised Difference Vegetation Index (NDVI) and Normalised Difference Moisture Index (NDMI) to assess vegetation health and water retention capacity. Additional indicators such as ALBEDO, Sky View Factor (SVF) and Predicted Mean Vote (PMV) allow for a more refined microclimatic reading and an indirect assessment of the thermo-hygrometric comfort perceived by users in open spaces.

The final step of data processing involves normalising and aggregating each indicator within the ISTAT (2021) census units, considering the average value for each time range, and intersecting them spatially to produce vulnerability maps and hotspot maps useful for defining intervention priorities using empirical approaches based on data and measurable results that guide the decision-making process [9, 10]. Once the vulnerability and the hotspot maps have been elaborated, it is also possible to identify design and climate-resilient actions and then simulate the interventions and assess the effectiveness and performance of the different types of solutions.

The innovative element consists of integrating these indicators into a simplified resilience framework, divided into four phases, in line with the resilience management cycle [11]: Preparation (T0, before the event), Absorption (T1, during the event), Response (T2, short/medium-term recovery) and Adaptation (T3, long-term perspective). This structure makes it possible to capture the behavioural dynamics of open spaces and green areas, providing a dynamic rather than static study of urban vulnerability.

The proposed framework was applied to the Soccavo neighbourhood, located in the western part of Naples, considering the heatwave that occurred from 21 to 31 July 2022. The area is characterised by a heterogeneous urban fabric consisting of compact residential settlements, public and private green areas, residual open spaces and is located near the Naples Hills Metropolitan Park. The analysis conducted in the four defined time windows showed how urban morphology, land use patterns, density and green space configuration significantly influence microclimatic resilience. Areas with higher tree density and lower SVF values maintained lower LST during the heat peak, demonstrating the effectiveness of green space as a thermal barrier. Areas with high impermeability and little greenery, on the other hand, showed a sharp increase in LST, becoming critical urban hotspots. The combination of NDVI and NDMI also made it possible to distinguish between green spaces capable of performing a mitigation function and residual green areas with little microclimatic effectiveness. The proximity to the Parco Delle Colline di Napoli highlighted the importance of ecological continuity in promoting thermal stress mitigation and the recovery capacity of the settlement system.

Through hotspot mapping, the model identified priority areas for intervention, proposing strategic green actions such as the creation of ecological corridors, the greening of urban canyons, the redevelopment of underutilised green spaces and the introduction of vegetation barriers along major mobility infrastructures. These proposed measures, consistent with international literature, highlight the effectiveness of NBS in mitigating the impacts of heatwaves by contributing to the reduction of thermal load [12, 13] and influencing microclimate conditions [14] and the physical and mental health of the population [15].

The proposed framework highlighted how the microclimatic resilience of open spaces depends significantly on urban morphology and green space distribution. Analysis of the four-time ranges showed that tree cover, combined with lower SVF values, helps to maintain lower surface temperatures during heat waves, confirming the effectiveness of NBS as spatial mitigation devices. At the same time, hotspot mapping has made it possible to identify priority areas for intervention, guiding nature-based design strategies. From an operational point of view, the model has proved useful for translating complex environmental data into simple and readable spatial representations, providing concrete support for decisions on the definition of urban adaptation and mitigation strategies and actions aimed at improving both environmental performance and user comfort. Although user comfort was not measured directly at this stage, a possible future development could involve the integration of indicators and indices relating to users' thermo-hygrometric comfort. The integration of indices such as Physiological Equivalent Temperature (PET) or the Heat Stress Index could strengthen the validation of the results and provide a more comprehensive assessment of the environmental quality of spaces and, consequently, of user well-being.

In conclusion, the contribution proposes a conceptual and operational framework that integrates geospatial technologies, resilience theory and ecological design, offering decision-makers replicable tools for planning and designing nature-based solutions capable of responding to extreme weather events. The proposed model is designed as a scalable and replicable tool, applicable to other Mediterranean urban contexts with similar climatic and morphological characteristics, thanks also to its use of open source data and cloud-based calculations, which increase its accessibility. The combination of temporal environmental data, comfort indicators and green strategies makes it possible to orient public policies towards resilient and regenerative urban transformation, in line with the sustainability and climate adaptation objectives of Mediterranean cities.

Acknowledgments

This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005.

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In-stream Nature-based Solutions in river engineering: Cross vanes and J-Hook vanes in city rivers

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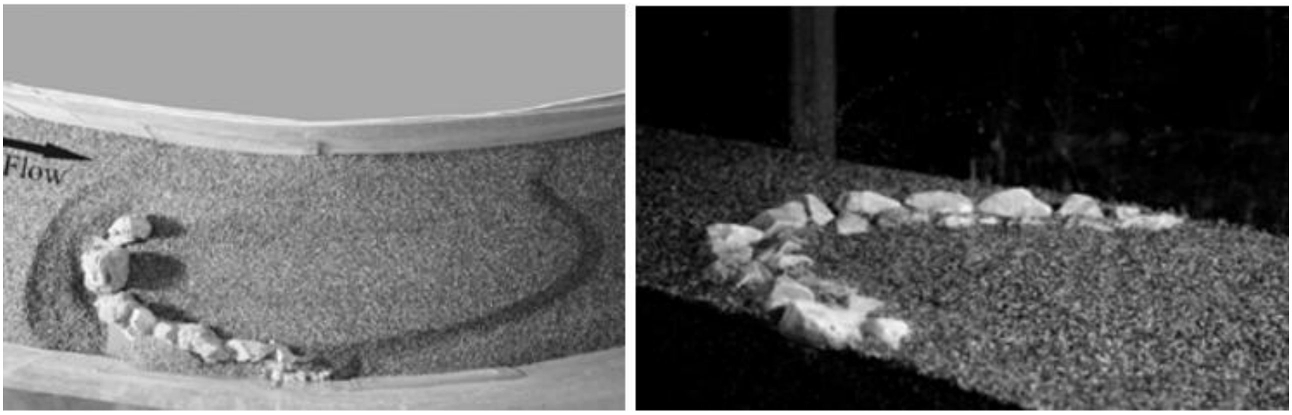
Highlights

- Use of small hydraulic structures in urbanized areas
- Experimental data on NBS hydraulic structures
- Cross vane and J-Hook hydraulic structures

Keywords

Rivers, Hydraulic Structures, River Restoration, Scour



J-hook in a curved channel (left) and cross vane in a straight channel (right),   inserted in a river bed (experiments conducted in physical models – University of Pisa)

River engineering has undergone a paradigm shift in recent decades, moving away from rigid, structural interventions toward more adaptive, sustainable practices that work with natural processes rather than against them. This evolution has given rise to Nature-Based Solutions (NBS) , a set of techniques that integrate ecological principles into hydraulic engineering to address challenges like erosion, sediment transport, habitat degradation, and flood risk in a holistic manner.
Among the most effective NBS applied to rivers are cross vanes and J-hook vanes. These instream structures are designed not only to stabilize channels and control flow dynamics but also to enhance ecological value by creating diverse habitats and maintaining sediment continuity. By influencing the flow path and energy distribution, these structures promote a stable channel form while simultaneously supporting aquatic life.

Definition and Purpose

Nature-Based Solutions are interventions that use natural materials and processes to solve engineering challenges. In river systems, their main goals include:

- Stabilizing riverbanks and preventing erosion.
- Enhancing aquatic and riparian habitat complexity.
- Promoting sediment transport and deposition in a natural manner.
- Improving water quality and hydrological connectivity.
- Creating flood-resilient systems.

NBS differ from traditional infrastructure in their adaptability, reduced environmental footprint, and ability to support multiple ecosystem services.

Cross Vanes

Cross vanes are instream rock structures shaped like a wide “V” pointing upstream (figure 1). They span the channel from one bank to the other, with their arms anchored into the streambanks. At the center of the structure is a low-flow notch that concentrates base flows while allowing fish passage and maintaining sediment movement.
These structures are typically built with large boulders or angular stone to resist displacement during high flows. Their placement must consider channel width, bankfull depth, and bed slope to ensure hydraulic effectiveness.
Cross vanes are designed to modify the stream's hydraulics in a beneficial manner:

- Flow Redirection: High-velocity flow is deflected toward the center of the channel, reducing erosive stress on the banks.
- Energy Dissipation: As water flows over the arms and through the central notch, energy is dispersed, reducing downstream erosion.
- Scour Pool Formation: Downstream of the central notch, flow convergence generates scour holes, which are valuable aquatic habitats.
- Thalweg Maintenance: The thalweg (deepest part of the channel) is preserved in a central position, enhancing channel stability.

The ecological benefits are:

- Erosion Control: By concentrating flow away from banks, cross vanes reduce lateral erosion and protect infrastructure.
- Habitat Enhancement: The scour pools and associated flow patterns provide critical refuge and feeding areas for fish and macroinvertebrates.
- Fish Passage: The low notch ensures that aquatic species can navigate upstream during low and moderate flows.
- Channel Stability: The structures help maintain channel form in systems prone to incision or widening.

Cross vanes perform best in systems with slopes between 0.5% and 2.5%, where flows are neither too mild to generate scour nor too intense to destabilize the structure.
The experimental data conducted at the University of Pisa allows to introduce relationship that foresees the geometrical characteristics of the scour hole and the dune downstream of the structures and a prediction of the

maximum scour depth as a function of the sediment material, the flow discharge and height and the geometry of the structure.
This relationship are useful in order to correctly design the structure.

J-Hook Vanes
A J-hook vane is a variation of the cross vane, consisting of a single-arm or partial vane with a downstream "hook" that extends into the channel (figure 1). This hook intensifies localized hydraulic conditions, producing a more concentrated scour pool and providing greater flow deflection near the bank.
Typically constructed from large angular rocks or boulders, J-hook vanes are shorter than full-span cross vanes and are often installed in series along meander bends or straight reaches where targeted erosion control or habitat creation is needed.
J-hook vanes modify flow in distinct ways:

- Localized Scour Creation: The hook portion of the vane accelerates flow in a circular pattern, deepening pools and encouraging sediment deposition on the downstream side.
- Bank Protection: By altering velocity vectors, J-hooks reduce toe scour and shear stress on vulnerable banks.
- Flow Diversity: These structures introduce eddies, vortices, and turbulence that create microhabitats beneficial to aquatic life.

Unlike cross vanes, which span the entire channel, J-hooks concentrate their influence near one bank and in a smaller area, making them suitable for precision applications.
Effects of a J-hook in the river:

- Increased Habitat Complexity: The pronounced pool and adjacent velocity refugia attract fish, especially during high flows.
- Flexibility in Design: Suitable for use on bends, tight spaces, or in combination with bioengineering elements like vegetated banks.
- Flow Resistance: Acts as an energy dissipator, reducing downstream erosion and protecting critical infrastructure.

J-hooks are especially effective in dynamic channels or those requiring intermittent reinforcement rather than full channel-spanning control.

The experimental tests allows to find simple relationships that foresees the geometrical characteristics of the scour hole and the dune downstream of the structures and a prediction of the maximum scour depth as a function of the sediment material, the flow discharge and height and the geometry of the structure.
This relationship are useful in order to correctly design the structure.
One main result of the J-hooks vane is the fact that the erosion process is moved towards the center of the channel that resolve the problem of near to the riverbank scour that could be dangerous in terms of slope stability.

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Constructing composite indicators for assessing the feasibility of green walls in urban contexts

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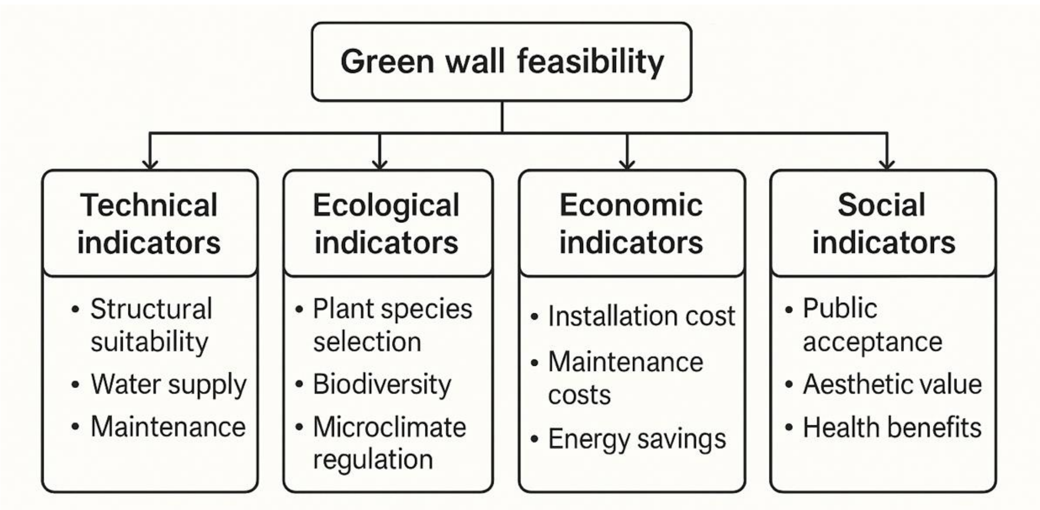
Highlights

- Introducing a comprehensive framework that integrates technical, ecological, economic, and social indicators for assessing the feasibility of green walls
- Developing a novel Transformability Index to evaluate the adaptive capacity and long-term sustainability of green walls
- Applying the framework to university buildings to promote sustainable urban development

Keywords

Green Walls; Urban Resilience; Feasibility Assessment; Transformability Index; Sustainable Cities



Statement of different types of indicators

Urban centers worldwide are increasingly vulnerable to the impacts of climate change, air pollution, urban heat islands, and biodiversity loss. Green infrastructure solutions, such as green walls or vertical gardens, offer promising strategies to enhance urban resilience, promote ecological sustainability, and improve residents' quality of life. However, their successful implementation depends on comprehensive feasibility assessments that consider technical, ecological, economic, social, and regulatory factors. This paper proposes an integrated, multidimensional framework that synthesizes different information into composite indicators, enabling a holistic evaluation of green wall projects. The study introduces a methodological approach that combines the statistical principles of composite indicator construction with practical assessments of green wall feasibility in urban settings. The framework balances methodological rigor with applied urban sustainability planning and is tested on the buildings of the University of Palermo Campus.

Introduction

In recent decades, urban areas have faced increasing pressure to balance development with environmental sustainability [1]. Among various nature-based solutions, green walls have gained prominence due to their ability to reduce urban heat islands, enhance air quality, and support biodiversity [9]. However, integrating green infrastructure into complex urban systems requires careful planning supported by reliable data and comprehensive assessment tools. The challenge is to incorporate diverse, often non-quantifiable dimensions - such as technical feasibility, ecological benefits, economic sustainability, and social acceptance - into a unified evaluation framework (Figure 1).

This study defines evaluation dimensions through a comprehensive literature review, analyzing established approaches to identify relevant criteria aligned with project goals [6, 7, 8]. Consultations with the multidisciplinary research team for the "PRIN 2022/PNRR" project, titled "Greenwork: an interdisciplinary framework for urban health and resilience enhancement through greening strategies for buildings and open spaces," involving experts in building design, landscape architecture, botany, biology, psychology, and statistics, have helped refine and validate our choices. Their insights ensured that the framework is both scientifically sound and practically applicable.

Key evaluation indicators encompass technical aspects (structural integrity, system compatibility, irrigation efficiency, plant resilience) [8], ecological metrics (biodiversity support, air quality, microclimate regulation, water management), economic factors (costs, energy savings, property value impact) [7], social acceptance (community engagement, aesthetics, educational opportunities, health benefits) [6], and regulatory considerations (permits and policy alignment).

To synthesize this multidimensional data, composite indicators (CIs) are employed. These allow decision-makers to aggregate various criteria into a single, interpretable metric. Constructing a CI involves several methodological steps [2]: defining measurement elements (such as dimensions or components), selecting appropriate empirical variables (simple indicators), transforming these variables for comparability, assigning weights for aggregation, and applying an aggregation rule to produce the final indicator. Each step involves subjective decisions that can influence outcomes significantly.

In the context of urban sustainability, robust assessment tools are vital for guiding interventions like vertical greenery installations. Future work will integrate a multicriteria decision-making (MCDM) approach [3], in order to identify multiple equally admissible solutions, depending on the decision-making framework and the scenarios derived from changes in, for instance, the weighting system. The most appropriate indicator is thus not necessarily the technically best performing one, but rather the one best aligned with the initial conditions and the most relevant scenario.

Composite indicators serve as valuable tools for comparing different sites and design strategies [4], facilitating informed decision-making. Case studies from cities such as Milan, Paris, Singapore, Hong Kong, and Los Angeles demonstrate practical applications, showing how green wall projects align with these indicators and contribute to urban sustainability [10]. This research combines theoretical insights into CI construction with a practical case study assessing green walls on 20 university buildings in Palermo, illustrating the framework's relevance and applicability in real-world urban settings.

Methods

The backbone of our methodology is a composite index expressed as:

$$CI = f[T_1(X_1), T_2(X_2), \ldots, T_k(X_k)],$$

where:

- *CI* is the composite indicator;
- X_i are elementary indices or simple indicators, $i = 1,...,k$, which may be technical (e.g., facade orientation), ecological (e.g., CO_2 sequestration), economic (e.g., installation cost), or social (e.g., community approval);
- T_i are transformation functions (e.g., normalization);
- f is the aggregation function (e.g., weighted average).

Different transformations are evaluated including:

- min-max normalization: $T(X) = (X - min(X)) / (max(X) - min(X));$
- z-score standardization: $T(X)=(X-\mu)/\sigma.$

For ordinal data, rank-based transformations were considered, assigning numerical scores to categories.
Additive aggregation functions are the most commonly used in the construction of ICs due to their ease of application and straightforward understanding, leading to the following composite formulation:

$$IC = \sum w_i \, T(x_i).$$

However, it should be verified that the rather restrictive conditions for their applicability are satisfied.
Weights w_i could be assigned using expert judgment and stakeholder inputs or, depending on the type of elementary indicators, they can also be determined using statistical methods designed to reflect the relative importance of each component in the final result [5]. For example, if the data are metric, Principal Component Analysis (PCA) reduces data dimensionality by identifying linear combinations that explain most of the variance, assigning weights to the components based on their proportion of explained variance.

Results

Sensitivity analysis for a composite indicator is a crucial procedure to assess how variations in its components affect the final results, thus changing building rankings of University Campus. This type of analysis helps to understand the robustness of the indicator, identify the most critical components, and improve its reliability. The sensitivity analysis conducted on the composite indicator revealed that its performance and interpretations can vary significantly depending on the methodological choices made.
In particular, normalization and standardization of elementary indicators, whether through min-max methods or z-score, have influenced the distribution of values and, consequently, the overall aggregation. Regarding weighting, it was observed that assigning different weights to elementary indicators can lead to substantial variations in the composite indicator's value, highlighting the importance of a thoughtful and justified weighting scheme.
Finally, the aggregation method produced diverse results, with some approaches being more sensitive to changes in elementary indicators than others.
The variation in the resulting rankings was assessed using Kendall’s tau and Spearman’s rho, as well as the Pearson Bravais–Pearson correlation coefficient.
In conclusion, this analysis underscores the importance of carefully selecting normalization, weighting, and aggregation methodologies to ensure the reliability and consistency of the interpretation of the composite indicator.

Discussion

This research offers a replicable framework that integrates technical and statistical rigor into the assessment of green infrastructure. When properly constructed, composite indicators serve as transparent and adaptable tools to guide urban interventions. Urban sustainability relies on robust evaluation methods that acknowledge the complexity of stakeholder priorities and environmental trade-offs. However, in many applications, composite indicators (CIs) are often developed without sufficient consideration of their mathematical, statistical, and practical aspects. Recognizing this gap, we believe it is essential to establish clear guidelines for constructing meaningful and effective summary metrics, such as CIs. The primary aim of this work is to provide practical tools for the development of CIs by analyzing the dynamics of their creation process. This includes identifying the necessary procedures to ensure that CIs possess desired properties and achieve intended outcomes. By combining advances in indicator construction methodology with sustainability applications, this study offers a practical, adaptable, and scientifically rigorous assessment tool for green infrastructure.

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Modeling green roof aging with HYDRUS-1D: first insights into parameter tuning

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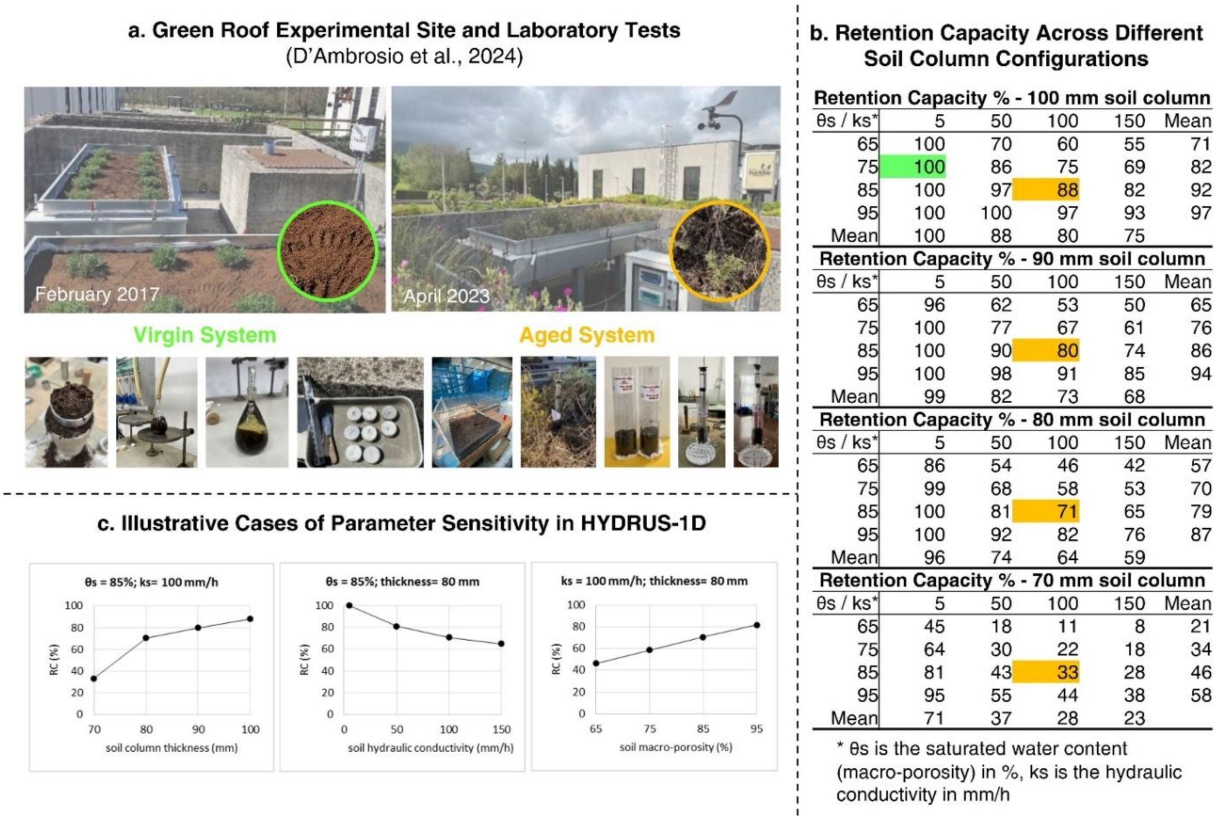
Highlights

- Peat showed increased hydraulic conductivity and porosity over 7 years
- HYDRUS-1D proved to be suitable for modeling green roof aging
- Careful tuning of physical, hydraulic, and geometric parameters is needed

Keywords

Sustainable Drainage; Green Roofs Systems; Medium-Term Retention Capacity; Peat Substrate Ageing; HYDRUS-1D Modeling;



a. Green roof experimental site and laboratory tests; b. Retention Capacity across different soil column configurations; c. Illustrative cases of parameter sensitivity in HYDRUS-1D

Introduction

Green roofs are an increasingly common solution for sustainable stormwater management in urban areas [1]. Their role in reducing flood risk is well established, as they contribute to lowering stormwater runoff volumes and peak flows through both stormwater retention (precipitation storage) and detention (runoff delay). The hydrological performance of green roofs changes over time. As natural systems, they actually undergo aging processes that can affect their hydrological performance [2]. The detention behavior of green roofs is strongly influenced by the porosity and the hydraulic conductivity of the substrate, as these parameters govern the rate at which water infiltrates and drains through the growing medium. The retention capacity is primarily related to the pore-size distribution, which regulates water storage and release, thereby defining both the maximum water-holding potential and the wilting point.

Materials and Methods

A seven-year monitoring campaign conducted on two extensive green roof test beds (Figure 1a), located at the Maritime and Environmental Hydraulics Laboratory of the University of Salerno, revealed an average reduction in retention capacity (RC) of about 12%. The latter was calculated as the relative difference between the average retention capacity (that is, the complement of the runoff-to-rainfall volume ratio) registered over 29 rainfall-runoff events occurred during the initial operational period of the infrastructure (2017-2019), and that registered over 29 events recorded in the latest observation period (2022-2023). Laboratory tests performed on virgin and aged green roofs substrate samples provided additional insights into the observed RC decline [3]. Specifically, the performance reduction was linked to the pedogenesis of the peat substrate. Over the seven-years observation period, saturated hydraulic conductivity increased significantly, from approximately 7 mm/h (virgin substrate) to an average of 108 mm/h (aged substrate). A slight increase in porosity was also recorded, rising from around 75% (virgin substrate) to approximately 85% (aged substrate). These changes were accompanied by visible compaction of the substrate, with thickness reductions of up to 3 cm.

Reliable modeling tools are essential to better understand long-term changes of these systems. HYDRUS-1D [4], a physically based model suitable for simulating one-dimensional water flow in unsaturated soils, shows strong potential in this field. Nevertheless, its application in modelling green roof aging remains limited, largely due to the lack of long-term monitoring data [2]. Based on the findings of [3], this research aims at investigating the ability of HYDRUS-1D to simulate green roof aging and at identifying suitable combinations of Van Genuchten hydraulic parameters and design configurations to reproduce hydrological outputs consistent with experimental observations.

For this reason, an HYDRUS-1D model was developed using a soil column representative of the peat substrate of the experimental green roofs previously described. The model employed an atmospheric boundary condition with a surface layer at the top, and a free drainage condition at the bottom. The drainage layer was excluded from the model based on three considerations: I) it is well known that the drainage layer does not significantly influence retention processes [5]; II) it is the component least affected by aging due to both its material nature (expanded clay) and its limited exposure to atmospheric agents; III) the experimental analyses specifically focused only on peat substrate samples. Multiple configurations were established by varying physical parameters (saturated water content, thus porosity, θs), hydraulic properties (saturated hydraulic conductivity, ks), and geometric characteristics (substrate thickness), all within observed ranges that reflect the behavior of both virgin and aged peat substrates. A porosity range from 65% to 95% was considered, using four discrete values: 65%, 75%, 85%, and 95%. As for saturated hydraulic conductivity, four values were selected within the 5–150 mm/h range: 5 mm/h, 50 mm/h, 100 mm/h, and 150 mm/h. All other Van Genuchten parameters were set based on literature values. Regarding substrate thickness, columns were modelled with depths of 100 mm, 90 mm, 80 mm, and 70 mm. Among the variable boundary conditions, rainfall input was defined as a synthetic triangular event with a total depth of 25 mm and a duration of 10 hours (2.5 mm/h). This specific rainfall intensity was selected for two main reasons: I) it reflects the average rainfall intensity observed during the two monitoring campaigns described in [3] and II) a performance reduction of approximately 12% was observed in response to such events, thus matching the average decrease in RC recorded in the monitored green roof systems. The initial soil water content was set at 10%. A total of 64 simulations were performed. At the end of each simulation, the bottom drainage was recorded and used to calculate the RC, defined as the complement of the ratio between the cumulative bottom flux and the total rainfall input, expressed as a percentage.

Results and Discussion

Figure 1b presents tables showing the modelled retention capacity (RC) of the soil column across the various configurations investigated. It is immediately evident that, with constant porosity and thickness, an increase in hydraulic conductivity leads to a decrease in RC. Conversely, RC improves with increasing porosity, assuming hydraulic conductivity and thickness remain constant. Overall, a reduction in substrate thickness is associated with a significant decrease in RC. These results are fully consistent with expectations, confirming that the HYDRUS-1D model, when operated within realistic parameter ranges, is capable of simulating variations that coherently reflect changes in the input parameters. As illustrated in Figure 1c, the model output is most sensitive to substrate thickness, followed by hydraulic conductivity and porosity. Within realistic ranges of parameter variation due to aging, changes in thickness cause the largest variations in retention capacity (RC), emphasizing the importance of carefully balancing model parameters.

Given this sensitivity, it is crucial to understand how these parameters affect the model's ability to reproduce the aging phenomenon. To this end, the retention capacity (RC) of the "virgin" configuration, as reported by [3] and highlighted in green in the tables in Figure 1b, was compared with that of the "aged" configuration under different geometric layouts, highlighted in orange in the same tables. This comparison aimed to verify whether the modelled reduction in RC aligns with experimental observations for a comparable rainfall event. When substrate thickness is kept constant at 100 mm, variations in physical and hydraulic parameters alone reproduce an RC reduction of approximately 12%, matching the observed value precisely. However, including thickness variation leads to RC reductions of up to 67% for a 3 cm decrease in substrate thickness, which is clearly an unrealistic value for an aging effect. This likely occurs because changes in physical and hydraulic parameters already implicitly account for the effects related to thickness variation. This behavior suggest that thickness changes in the model should be minimal (e.g., 1-2 cm) and generally combined with smaller increases in hydraulic conductivity changes and greater increase in porosity.

Conclusions

Understanding how to use modeling tools to represent complex processes such as substrate aging is essential for scaling these effects up to the urban level. Given the inherent challenges in implementing sustainable retrofitting strategies to enhance urban resilience to climate and land use changes, incorporating aging effects into hydrological and hydraulic modeling becomes crucial for reliably forecasting the long-term performance of projects involving green roofs and other types of sustainable drainage systems (SuDS). The next steps will involve building on these initial insights from one-dimensional HYDRUS model and extending them to semi-distributed hydrological-hydraulic models, such as the widely used SWMM5. The aim will be to integrate both the effects of climate change [6] and infrastructure aging into a unified framework for assessing the long-term performance of SuDS.

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Nature for sustainable cities: planning cost-effective and just solutions for urban issues

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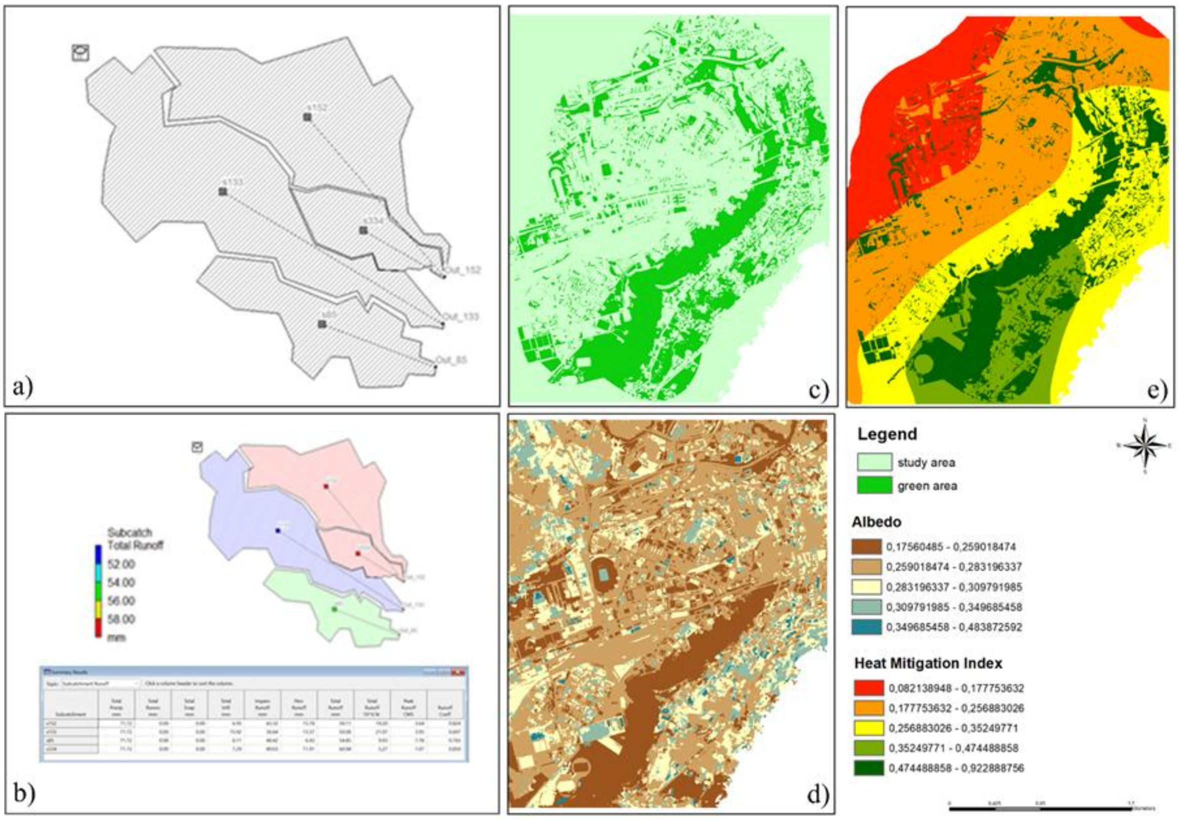
Highlights

- No spatial models help planners select NBS for diverse urban issues
- The main aim is to develop a spatial planning method to assess NBS benefits, costs, and trade-offs
- First results of applying the method to two study areas in Catania and Naples (Italy) are presented

Keywords

Urban planning; Urban Heat Island; Urban Flooding; Spatial Justice; Cost-Benefit



Peak Values of the water run-off for the study area of Catania in Sicily Region, Italy (a, b) and results from the INVEST Urban Cooling model for the study area of Naples, in Campania Region, Italy (c, d, e)

The growing interest of cities in crucial issues such as climate change, social inclusion, gender inequalities, disparities in access to urban services, public health, and the quality of the urban environment reflects an increasingly urgent need to adopt more effective and integrated planning strategies (Liu and Jensen, 2018; Goldenberg et al., 2021). Traditional urban policies tend to intervene in a sectoral manner, with targeted actions on specific issues and limited areas, often within a short-term timeframe.

To address these challenges, the adoption of Nature-Based Solutions (NBS) is emerging as an innovative and strategic approach to make cities more livable, healthy, and resilient. Compared to traditional engineering solutions, NBS not only offer environmental advantages but also generate multiple social and economic benefits, amplifying their distribution at the urban scale (Hoffimann et al., 2017). Their potential is increasingly recognized at the political level as well, finding space in numerous environmental governance and sustainable development initiatives.

However, despite their proven potential, NBS are still underutilized at urban scale for various reasons. One of the main barriers is the limited dissemination of scientific evidence regarding their effectiveness among policymakers, urban planners, and the public. The capacity of NBS to improve environmental quality and generate socio-economic co-benefits is often underestimated, as is their cost-effectiveness compared to conventional solutions (CC). Another obstacle lies in the complexity of their design and the lack of adequate tools to support their selection within urban planning processes. Currently, there are no spatially explicit decision models that allow urban planners to assess and select the most appropriate solutions for different urban problems, preventing a thorough analysis of their economic sustainability and the equitable distribution of benefits.

In the absence of operational tools and guidelines based on solid scientific data, policymakers struggle to justify investments in NBS, hindering their integration into planning processes. Furthermore, international research has not yet systematically addressed the spatial dimension of NBS, i.e., the relationship between their location and the distribution of the benefits they generate within cities. This aspect is crucial to ensure that nature-based solutions effectively meet urban needs, promoting more equitable and sustainable planning.

This contribution presents the preliminary results of the “Nature for sustainable cities: planning cost-effective and just solutions for urban issues (NatSolis)” Project of National Relevant Interest (PRIN 2022) using a multidimensional approach that integrates ecological, urban, and socio-economic expertise.

Methods

The main goal is to develop a spatial and systemic planning method that can evaluate the environmental and social benefits generated by NBS, while also quantifying their implementation costs and identifying possible trade-offs related to their application.

Through this perspective, the project seeks to provide innovative tools to support decision-making processes, facilitating the adoption of NBS as a structural element of urban planning. The proposed approach integrates the most advanced research paradigms to develop an innovative methodological framework, based on systemic analysis and spatial modeling, to address urban issues from a multidimensional perspective.

The objective is to create a Spatial Decision Support System (SDSS) to be implemented within a GIS environment, integrating data and indicators related to NBS to facilitate their application by urban planners, architects, engineers, and public administrators.

The methodology involves the development of a modular system capable of addressing various urban issues. These include climate regulation to face urban heat island, reduction of urban flooding, and ensuring an equal distribution of NBS’s generated benefits.

The first step consists of defining intervention priorities through a dedicated module for constructing urban scenarios, which identifies the specific needs of different city areas and the most suitable NBS to address them. The measurement of urban conditions is based on synthetic indicators, allowing for the combination of environmental, social, and economic variables to identify criticalities and opportunities for intervention.

Once the urban issues to be addressed have been identified, the project foresees the choice and use of GIS-based tools to model the abovementioned issues and to provide a quantitative measure of the performance of proposed NBS. The natural ecosystems’ ability to mitigate urban heat island effects and contribute to energy consumption reduction is assessed using the URBAN InVEST spatial model (Hamel et al, 2021), which estimates the impact of urban greenery on city temperature and energy balance. Similarly, stormwater runoff

regulation is analyzed through a specific tool for managing stormwater, such as the EPA SWMM model, which, among other things, evaluates the contribution of NBS in reducing surface runoff.
Another central aspect concerns accessibility to services and green areas, which is a key factor in ensuring an equitable distribution of NBS benefits. In this case, the SDSS uses GIS-based gravity models and ecological model to analyze the equal distribution of urban functions and their accessibility, considering the characteristics of the urban fabric and social demand (La Rosa and Pappalardo, 2020). This approach optimizes the placement of new NBS, ensuring a more equitable distribution of benefits among the population and improving the overall quality of the urban environment. Finally, a cost-benefits analysis translates in monetary terms both the cost and the benefits associated with local attuned categories of NBS, which are further valuated along different scenarios.
Quantitative results from the models will be used to quantify the costs and benefits, using the Green Infrastructure Valuation Toolkit GI-Val (The Mersey Forest, no date) for the different simulated scenarios (Tab. 1). The model is applied on two portions of Catania and Naples, characterized by similar climatic conditions but different density and characteristics of the urban fabric.

Table 1 – Toolkit for the valuation of costs and benefits in the GI-Val model

	Benefit	**GI-Val Tool**
a	Energy saving	For heating building
		For cooling building
		From reduced stormwater volume entering combined sewers
b	CO_2 emission reduction	From building energy saving for heating
		From building energy saving for cooling
		From reduced stormwater volume entering combined sewers
c	CO_2 sequestration	Carbon sequestered by trees
		Carbon sequestered through other land use change
d	Air pollutant emission reduction/sequestration	Reduced mortality from respiratory illnesses
		Reduced air pollution
e	Flood risk reduction/regulation of water flows	Reduced wastewater treatment costs
f	Local climate regulation	Avoided damage from wind and storms
		Reduction of peak summer surface temperatures

Preliminary Results

The first results derived by the application from the Urban Invest Model and EPA SWMM for the current scenario are reported in Fig. 1 for the study area of Naples and Catania. Values of cooling capacity and peak of water run-off will be used as reference quantity to evaluate the effectiveness of proposed scenarios in terms of reduction of temperature and water run-off. Tab. 2 shows the type of NBS that will be simulated in the scenarios based on the current physical characteristics of the case studies in Naples (Campania Region, Italy) and Catania (Sicily Region, Italy) and obtained results in the models. Finally, Tab. 3 shows the criteria used to design the scenarios to be simulated and then valuated in terms of costs and benefits.

Table 2: Types of Nature-Based Solutions to be simulated in the scenarios

Solutions	**Single**		**Composite/multiple**
Single tree		LC	
Multiple trees (linear)		LC	
Multiple trees (polygonal)		LC	
Shrubs		LC	
Grass		LC	
Garden/park			LC combination
Green roofs (in general)	LID	LC	
Green facades		LC	
Pervious pavement	LID	LC	LC combination
Rain garden	LID	LC	LC combination
Linear filtration/infiltration elements	LID	LC	LC combination
Aeral filtration/infiltration elements (ponds, wetlands, basin)	LID	LC	LC combination

Table 3: Criteria for the definition of the Scenarios of Nature-Based Solutions

Cod	***Target areas***	***Criteria for the selection***
S1	All public spaces	Public space (streets, squares, green spaces, parkings)
S11	Selected public spaces	Basin with higher hydraulic hazard (thresholds to be defined) Areas with less cooling capacities (threshols to be defined) Most used streets (thresholds to be defined) Areas with limited access to greenery?
S2	All public buildings	Administrative, school, universities, hospitals, sport facilities, …
S21	Selected public buildings	Buildings in basin with higher hydraulic hazar Buildings in areas with less cooling capacity Larger buildings Plain roofs
S3	All public spaces and buildings	Public space (streets, squares, green spaces, parkings) & administrative, school, universities, hospitals, sport facilities, …
S31	Selected Public spaces and buildings	Combination of the 2 selections
S4	All Private buildings	Residential, commercial, industrial,
S41	Selected Private Building	Buildings with courtyards with permeable land cover

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Towards an urban eco-energy balance: a geospatial framework for integrating carbon sequestration and renewable energy production in local planning

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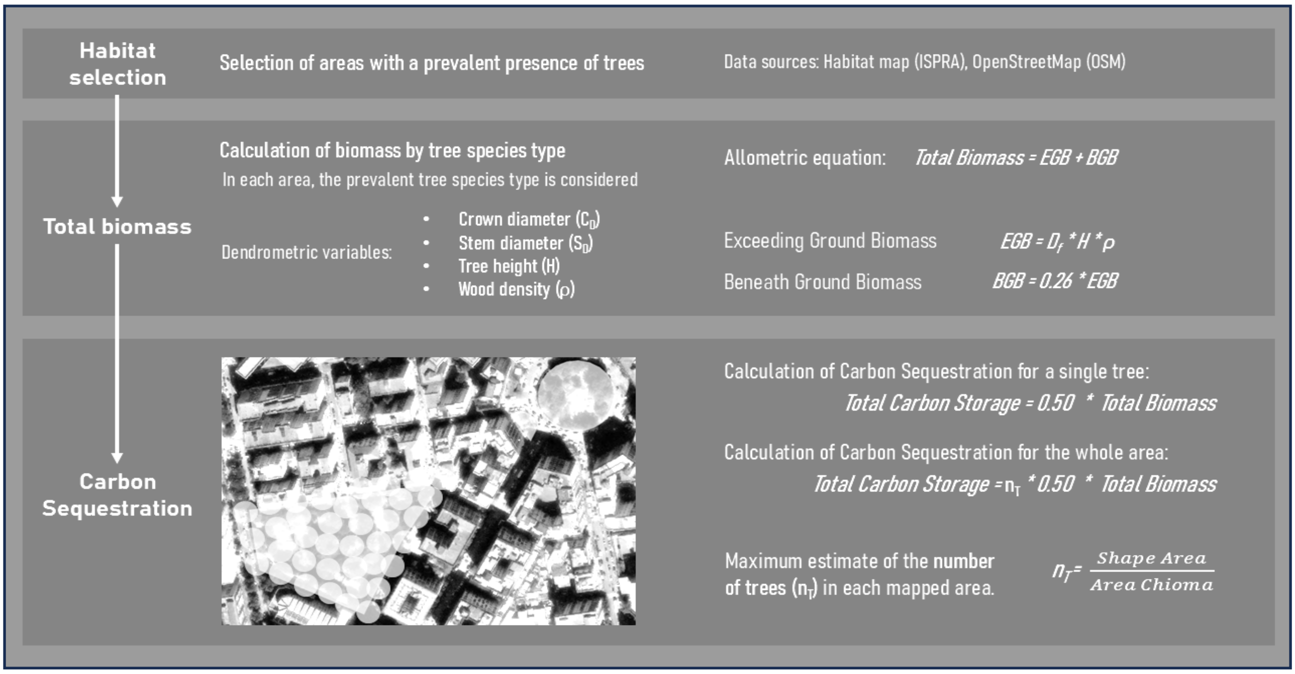
Highlights

- Urban eco-energy balance through GIS-based spatial analysis of green areas
- Integrates green carbon sinks and solar energy production in planning strategies
- Supports local climate action with replicable data-driven decision tools

Keywords

Urban Sustainability; Green Infrastructures; Carbon Sequestration; Renewable Energy; Climate-Resilient Planning.



Workflow of the steps for the definition of the carbon sequestration of the vegetation component over an urban green area, classified in a GIS environment. The tree characteristics considered are tree species, canopy size, and wood density

Introduction

Urban areas are responsible for a large share of global energy consumption and greenhouse gas emissions, positioning at the forefront of both the climate crisis and the search for solutions. Despite their ecological footprint, cities hold a unique potential for driving energetic and ecological transitions through spatial reconfiguration and technological innovation. Against this backdrop, this contribution introduces a methodological proposal aimed at transforming urban territories from high-consumption systems into more balanced and self-sufficient eco-energy configurations. The concept of *urban eco-energy balance* refers to the capacity of cities to locally generate renewable energy and sequester carbon emissions through nature-based interventions, offsetting their ecological impact. This approach builds on the recognition of the strategic role of urban green infrastructure, a line of thought developed over the past thirty years (Trupiano & Fistola, 1988) and recently revisited considering current urban transformations (Fistola, 2023).

This paper presents a geospatial, data-informed methodology to identify, evaluate, and map key areas within the urban fabric suitable for carbon sequestration (Kinnunen et al., 2022) via tree planting and for decentralized energy generation via photovoltaic systems (Jakubiec & Reinhart, 2013). The approach supports municipal decision-makers in operationalizing these opportunities within local planning processes.

Objectives

The primary aim of this study is to develop and validate a spatial methodology that can be replicated across diverse urban contexts to support climate-sensitive planning. Specifically, the research identifies urban areas with potential for carbon sequestration through targeted tree planting. In parallel, it aims to locate surfaces – rooftops, vacant lots, underutilized spaces – suitable for decentralized renewable energy production via solar photovoltaic systems. Central to the methodology is the *eco-energy balance* concept: residual emissions are offset by new carbon-sink green areas. This balance is pursued exclusively through the spatial reorganization and functional reuse of existing underutilized spaces, without requiring additional land consumption.

By calculating the spatial mismatches – *eco-energy deltas* – between energy demand/emissions and local ecological compensation capacities, the approach enables the formulation of practical and site-specific guidelines. These outputs can be integrated into urban and energy planning instruments, guiding cities toward net-zero objectives through more effective and place-based responses to the climate crisis.

Theoretical Framework

This proposal draws on interdisciplinary literature from climate change in cities and urban metabolism studies (Bai et al., 2018), nature-based solutions (Kabisch et al., 2017), and energy transitions at the local scale (Bridge et al., 2013). It also aligns with emerging concepts in urban resilience and spatial justice (Anguelovski et al., 2016), emphasizing both technical feasibility and equitable distribution of environmental benefits. Key component of the framework is the use of Geographic Information Systems (GIS) not just as a technical tool (Fistola, 2009) but as a platform for knowledge co-production, spatial reasoning, and support to multi-level governance (Geertman & Stillwell, 2009). This enhances the ability of local governments to make data-driven decisions grounded in their territorial specificities. The contribution tries to bridge the gap between mitigation and adaptation policies, proposing a dual methodology which spatially integrates, based on territorial features, carbon emissions reduction and ecosystem services and co-benefits.

Methodology

The methodological framework developed in this study is structured into five phases, aimed at identifying and evaluating the urban areas suitable for balancing emissions and renewable energy production.

1. The process begins building a geospatial database which integrates data from institutional sources – e.g. ISTAT and ISPRA – and open-source platforms like OpenStreetMap. It features data related to land use, vegetation, building typologies and infrastructure including layers on existing vegetation, rooftops, industrial zones, vacant land, and agricultural areas. Cadastral parcels are the primary unit of analysis.
2. Once established the spatial dataset, the carbon sequestration potential is mapped through the identification of urban areas with potential for new or increased tree canopy based on morphological, climatic and planning criteria. This involves indexing available open or unused land, prioritizing degraded areas next to high-emission zones (e.g. roads, dense residential areas). Therefore, the carbon sequestration potential is assessed through an estimation of CO_2 absorption capacity of the green infrastructure to be implemented in the area based on tree species, density, and growth projections.

3. The third phase focuses on mapping zones suitable for renewable energy production, specifically solar photovoltaic systems. These areas, conceptualized as *Power Hubs*, include a range of urban surfaces such as vacant urban land, rooftops of industrial buildings with flat and contiguous structures, agricultural land eligible for agrivoltaic systems, and residential or public buildings with flat or accessible rooftops. A key criterion is ensuring compatibility with current land uses and technical feasibility. The areas identified are key nodes for decentralized energy production, possibly contributing to community energy independence.
4. The fourth phase is the *Eco-Energy Balance Analysis*. The concept of *eco-energy deltas* is operationalized by developing a spatial model to estimate the CO_2 sequestration capacity of candidate areas and the solar energy production potential of *Power Hubs*. The difference between a given area's emissions/energy demand and its potential to offset it through carbon sequestration or local energy generation defines the energy delta characterizing the surplus or deficit zones. Performing these calculations at both municipal and sub-municipal scales offers a granular view of imbalances across the urban territory.
5. Finally, the results are synthesized into maps and planning guidelines, outputs designed to support planners in incorporating eco-energy balancing strategies into formal urban development instruments, such as zoning plans and climate action frameworks. The context-adaptable methodology offers a replicable model for guiding urban transitions through data-driven, spatially explicit interventions.

Preliminary Findings

The preliminary application of the proposed methodology to a large Mediterranean urban context – the city of Naples, Italy – produced several insights. First, the analysis revealed a considerable availability of degraded or underutilized areas with significant potential for arboreal interventions aimed at enhancing local carbon sequestration capacity. Second, the study identified an extensive surface area suitable for the installation of photovoltaic systems, particularly on flat rooftops of industrial buildings, an asset for decentralized energy generation often overlooked. Third, the spatial analysis highlighted notable mismatches between areas characterized by high energy demand and those offering the greatest potential for ecological or technological compensation – an imbalance especially pronounced in densely populated urban districts. These findings underscore the relevance of adopting a spatially differentiated approach to urban climate action. They lay the groundwork for the development of targeted compensation strategies and spatial energy justice policies, aimed at fostering more equitable, efficient, and territorially grounded responses to the dual challenge of decarbonization and energy transition.

Original Contribution and Practical Implications

This study advances a spatially integrated approach that connects ecological and energy planning within a coherent analytical and operational framework. It bridges urban decarbonization and ecosystem services through biophysical indicators and spatial planning instruments. Methodologically, it introduces a replicable GIS-based process that integrates cross-sectoral data to pinpoint opportunities for carbon sequestration and decentralized renewable generation across the urban fabric. Strategically, the model provides municipalities with tools to identify priority areas, quantify their potential contribution to *urban eco-energy balance*, and tests alternative scenarios for distributing mitigation and adaptation measures. The framework also supports adaptive planning, enabling cities to adjust strategies as energy demand, technologies, or social priorities evolve, while aligning with policy goals such as EU climate neutrality and the UN 2030 Agenda.

Limitations & Conclusion

The methodology identifies, quantifies, and maps local potential for carbon sinks and renewable energy, offering an evidence-based foundation for climate-resilient urban policies. Its performance depends on the availability and granularity of spatial data, public acceptance of interventions like agrivoltaics or large-scale tree planting, and the institutional capacity to embed new criteria within existing planning frameworks. Despite these challenges, the modular design and inherent scalability make it suitable for cities of any size. Future developments could incorporate socioeconomic and demographic layers to evaluate co-benefits and equity impacts, validate the framework across diverse international contexts – including the Global South – and create interactive digital platforms to visualize trade-offs and support participatory scenario planning. Such extensions would reinforce the model as a comprehensive decision-support system for urban climate governance.

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Cities, nature and care reflections on urban regeneration as a relational device in times of crisis

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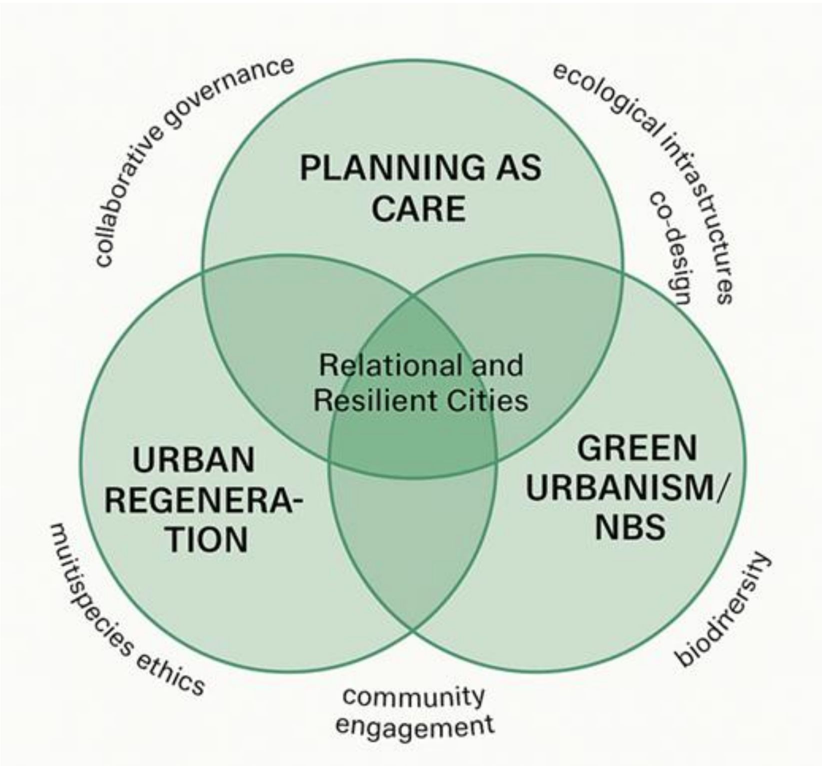
Highlights

- Planning as care: rethinking urban governance through relational ethics
- Urban regeneration as a strategic response to socio-environmental crises
- Integrating nature into the cities to advance ecological and spatial justice

Keywords

Urban Caring; Spatial Planning; Green Urbanism; Nature-Based Solutions; Ecosystem Services



Planning as care, urban regeneration, and green urbanism could provide a relationship perspective for a new integrated planning discipline

As a transformative ethos,
caring is a living technology with vital material implications
for human and non-human worlds.
(Bellacasa, 2011, p. 100)

Introduction

In recent years, the relationship between the relationship between cities and nature has gained increasing prominence in academic discourse and urban planning practices. The climate crisis, the COVID-19 pandemic, and global economic and social turbulence have highlighted the need to reconsider the connection between urban space, quality of life, and natural systems must be profoundly rethought. However, this is not merely a return to the notion of "nature in the city" in ecological terms: what is gradually emerging is a paradigm shift, in which the city is reimagined as a space of ecological, social, and symbolic relationships, and planning is increasingly understood as a practice of care [1].

This paper argues that two converging lines of research are consolidating in the literature. The first conceives urban and territorial planning as a form of care—not in the medical or welfare sense, but as an intentional practice of attention, maintenance, and enhancement of relationships among people, places, and ecological systems [9]. The second interprets urban regeneration—not expansion or densification—as the privileged tool to respond to a plurality of crises: environmental, social, economic, and symbolic.

Within these two theoretical frameworks, an integrated and multidisciplinary vision of planning is gradually emerging, in which environmental sustainability is no longer the sole guiding principle. On the contrary, there is a increasing imperative to associate sustainability with economic strategies and social innovation, reinterpreting concepts such as Nature-Based Solutions, Ecosystem Services [3], and the 2030 Agenda [10]. Finally, the importance of understanding care not as a unilateral act, but as a reciprocal and symmetrical relationship between urban actors, is particularly emphasized [2].

Planning as a Practice of Care

The notion of "care" has gained increasing relevance in the humanities, political theory, and urban studies, beginning with the seminal work of Tronto [9], Puig de la Bellacasa [1], and others who have extended its meaning beyond the domestic or medical sphere. In urban planning, care implies recognizing the city as a vulnerable, complex, and multispecies space, where territorial policies must engage with uncertainty, interdependence, and the co-production of values.

From this perspective, planning does not merely mean predicting and regulating but listening, accompanying, and facilitating. Planning as care acknowledges the plurality of urban actors—both human and non-human—and promotes inclusive and transformative processes. This approach is particularly relevant in medium and large cities, where spatial and social inequalities intersect with demands for renewed meaning and quality of urban life.

The concept of care is understood here in relational terms: there is no active subject who cares and passive subject who receives care, but rather a symmetrical relationship based on mutual responsibility. This is crucial for rethinking how planning tools are built, negotiated, and implemented. Planning should not only deal with the functional rationalization of space, but recognize territories as living systems, subject to regeneration, decline, and rebirth, which also involve collective imaginaries [1].

This orientation translates into practices of collaborative governance, participatory design, affective mapping of places, micro-regenerative interventions, and, above all, a new urban ethics that considers the well-being of people and ecosystems as co-essential goals.

Urban Regeneration in Times of Crisis

In parallel with the redefinition of care, urban regeneration is being reformulated as a central strategy to confront the multiple crises of our time. Unlike past models grounded in major infrastructure or continuous growth, regeneration is now conceived as a flexible, adaptive, and resilience-oriented approach, working with existing conditions, voids, marginalities, and territorial fragilities.

Urban regeneration is not merely a physical upgrading process, but an integrated set of interventions aimed at the social, economic, and ecological reactivation of places. In this sense, it is key to constructing cities capable of facing the challenges posed by ecological transition, deindustrialization, urban segregation, and social fragmentation [4].

Theoretically, urban regeneration intersects with the concepts of spatial justice, green and blue infrastructure, Nature-Based Solutions, and Ecosystem Services [5,6]. However, empirical experiences indicate that the effectiveness of ecologically inspired interventions depends on their capacity to integrate socio-economic and participatory components. Policies focusing exclusively on environmental sustainability risk producing "green gentrification" or exclusionary outcomes unless accompanied by strategies of social innovation.
Urban regeneration, understood as a systemic process, necessitates the combination of multidisciplinary competencies-urban planning, ecology, social economy, urban sociology-and the activation of networks among institutions, citizens, and economic and scientific stakeholders.
Green urbanism represents a normative and operational approach that incorporates ecological principles into urban design, planning, and governance. Beyond superficial greening, it fosters the rebalancing of urban metabolism, the development of biodiversity corridors, adaptive reuse, and climate-sensitive public space design. Within this paradigm, Nature-Based Solutions are not isolated interventions but integral elements of a broader ecological urbanism aimed at creating resilient, inclusive, and low-carbon cities.
In this perspective, technical innovation must be complemented by socially embedded green infrastructure that addresses urban heat, air quality, mental health, and community cohesion. Examples include the creation of urban forests in marginalized areas, implementation of water-sensitive green streets, and transformation of underutilized lots into productive landscapes all of which contribute to environmental justice and spatial equity.

Cities, Nature and Integrated Knowledge: Toward a New Epistemology
Recent urban experiences - particularly in medium-sized European cities - demonstrate that the complexity of contemporary urban challenges demands a profound epistemological rethinking. Planning models must be grounded in knowledge that is not solely technical but hybrid, co-produced by expert, local, affective, and symbolic actors. In this context, dichotomies between natural and artificial, urban and rural, human and non-human tend to blur, fostering a new conception of the urban as a relational ecosystem [8].
The city as cultural nature cannot be governed with linear or functionalist tools. Planning must evolve into a space of negotiation, care, and regeneration, capable of addressing environmental concerns while responding to needs for meaning, belonging, and justice. In this light, Nature-Based Solutions should not be seen merely as "green" technical devices, but as social catalysts that activate relationships, circular economies, educational processes, and forms of ecological citizenship [8].
The epistemological challenge, therefore, is to move from impact-mitigation planning to generative planning, supporting the emergence of new urban ecosystems as spaces of coexistence among humans, plants, animals, memories, and symbols.

The EUPOLIS Project in Palermo: A Case Study for the Definition of Performative Urban Standards
A concrete example of the theoretical reflections presented in this paper can be found in the European project EUPOLIS – "Planning healthier cities with nature-based solutions" – and in its experimental application in the city of Palermo. The project, funded by the Horizon 2020 programme and implemented in several European cities, aims to integrate Nature-Based Solutions (NBS) into urban planning, promoting public health and social cohesion through participatory and scientifically informed approaches.
In the case of Palermo, the initiative involved local institutions, research groups, civic associations, and citizens in the co-design of light tactical urbanism interventions. These aimed to regenerate marginal areas, improve the urban microclimate, and strengthen ecological and social relationships. The tools adopted—including multi-criteria analyses, urban fragility maps, and environmental and health monitoring devices—demonstrate how it is possible to move beyond the prescriptive approach of Ministerial Decree 1444/1968, which remains in force in Sicily under Regional Law 19/2020, and instead adopt adaptive and performative standards.
The EUPOLIS experience in Palermo thus serves as a significant laboratory for exploring how the Italian planning framework could be innovated. Rather than relying solely on dimensional thresholds, this case highlights the potential for establishing standards that consider the relational, ecosystemic, and socio-economic quality of public space. In particular, the project activated urban caring dynamics, involving multiple stakeholders in the management and maintenance of green spaces, and thereby suggesting a shift toward planning practices that integrate environmental and social values in a synergistic and transformative manner.
This study has outlined two emerging trajectories in contemporary urban and territorial scholarship: planning as a form of care and urban regeneration as a privileged tool in times of crisis. Both converge toward a

redefinition of the relationship between the relationship between cities and nature, grounded in a relational, multidisciplinary, and transformative paradigm.
Rather than being a mere metaphor, care is conceptualized as a theoretical and operational framework that redefines the objectives of planning: from functional regulation to the co-production of vital, inclusive, sustainable, and mutually caring urban environments. Urban regeneration emerges as the primary field of application of this paradigm, enabling interventions in the existing urban fabric that reactivate latent resources and rebuild fractured relationships.
These reflections contribute to the ongoing debate on how greening strategies, understood as relational and socio-ecological processes, may serve as catalysts for urban resilience and well-being. In line with the goals of the ENC conference and the Greenwork Project, this contribution underscores the need to embed green urbanism within regenerative and care-based urban policies.

Discussion

This contribution was enriched by integrating two critical observations raised by the reviewers. First, the theoretical framework was clarified by explicitly positioning green urbanism alongside planning as care and urban regeneration, forming a triadic structure that supports the proposed relational paradigm. Secondly, a concrete case study was introduced: the EUPOLIS project in Palermo, which illustrates how care-based planning and nature-based solutions can converge to define performative urban standards, particularly relevant in contexts still governed by rigid normative frameworks like Italy's Ministerial Decree 1444/1968. The Palermo case exemplifies a transition toward adaptive, participatory, and ecological planning instruments aligned with emerging European goals for urban resilience and environmental justice.

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Making cities green and sustainable through co-creation of Nature-based Solutions

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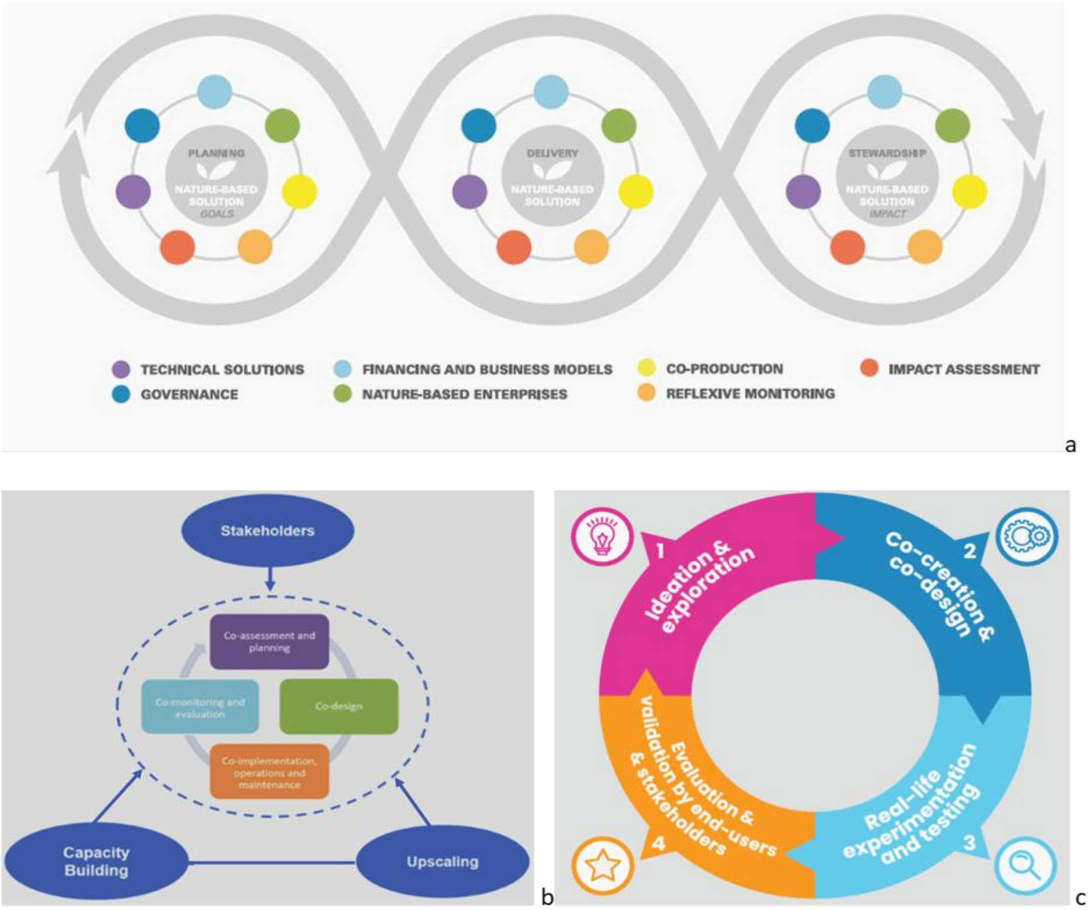
Highlights

- Approaches and principles developed to support the co-creation of NBS are presented
- Co-creation requires a clear understanding of stakeholder roles, expectations, benefits
- Key groups of barriers and enablers for successful NBS co-creation are revealed and discussed

Keywords

Nature-Based Solutions; Co-Creation; Sustainability; Resilience; Urban Environment



Co-creation approaches developed within: a) CONNECTING Nature, b) RECONECT; and c) EmpowerUs projects

Nature-based solutions (NBS) have gained significant traction across research, policy, and practice to advance urban sustainability, resilience, and spatial planning (Biodiversa+, 2024; EC, 2021). Defined as actions that protect, manage, or restore ecosystems while addressing societal challenges (IUCN, 2020), NBS offer multiple benefits for both people and nature. Among them are climate change mitigation and adaptation, biodiversity support, job creation, improved human health and quality of life, and many others (Adams et al., 2023; Dushkova and Haase, 2023; EC, 2021). As both a concept and practical approach, NBS bring together elements from ecosystem-based adaptation, mitigation, disaster risk reduction, ecological restoration, and blue-green infrastructure (Dushkova and Haase, 2020; IUCN, 2020). More recently, NBS have also been framed as tools for enabling transformative change by fostering community empowerment and participatory governance (Adams et al., 2023; Biodiversa+, 2024; Dushkova et al., 2025; Raymond et al., 2023).To further promote NBS, various policy instruments have been established: international and EU regulations (e.g. EU Water Framework Directive, Habitats Directive, Biodiversity Strategy, UN Paris Agreement), innovative financing mechanisms (e.g. European Investment Bank's program, Horizon Europe, Green Deal, LIFE+ programs), strategies, agendas, and plans (e.g. UN SDGs, EU National Adaptation Plans, Biodiversity plans). However, to better align these policy instruments with regional and local strategies, it is essential to incorporate social dimensions that reflect the perspectives of local communities and their specific contexts, including cultural norms, values, and behaviours. In the context of urban ecosystems, the recently enacted binding EU Nature Restoration Regulation moves away from strict quantitative targets, favouring a more adaptable strategy. This regulation requires member states to progressively expand urban green spaces until an adequate level is reached. Importantly, by promoting a fair and cross-society (multi-actor approach), the EU Nature Restoration Regulation highlights the value of co-creation for the success of nature restoration efforts. Local communities possess valuable local knowledge and have a direct interest in effective outcomes, making their participation key to long-term sustainability (Dushkova et al., 2025).

There is strong evidence that NBS are effective in addressing a wide array of socio-environmental challenges, such as climate change, biodiversity loss, environmental pollution, etc. (Adams et al., 2023; Biodiversa+, 2024; EC, 2021; IUCN, 2020). Various NBS initiatives (e.g. community gardens, green roofs, wetland restoration, and multifunctional protected areas) are proving capable of enhancing ecosystem services while supporting sustainable livelihoods and resilient communities (Dushkova and Haase, 2020, 2023; Raymond et al., 2023). Therefore, a noticeable shift is emerging in the NBS discourse – from "building in nature" to "building with nature" demonstrating a transition from traditional engineering toward approaches that integrate ecological functions and local knowledge (EC, 2021). This shift is supported by international reports (e.g. IUCN Global Standard for NBS, 2020) and handbooks (e.g. Handbook for NBS practitioners – EC, 2021), providing guidance for NBS planning, implementation, and impact evaluation.

Importantly, NBS require integration into local contexts and participatory processes to ensure their effectiveness and equitable impact. To address this, a variety of participatory methods and tools are necessary to actively engage community members in the entire process of NBS realization. In the last decade, various EC-funded projects focused on NBS have adopted co-creation as a core methodology, establishing their own frameworks and practical guides. Such projects as CONNECTING Nature, RECONECT, PHUSICOS, OPERANDUM, CLEVER Cities, Nature4Cities, NATURVATION, UNaLab, and others have proposed distinct sets of approaches and strategies for involving stakeholders throughout different phases of the NBS process, including guiding principles and tools for co-creation. However, research indicates that communities often lack the resources and capacities needed to effectively participate in local decision-making processes aiming at sustainability and resilience (Dushkova and Kuhlicke, 2024; Dushkova et al., 2025; van der Have et al., 2022). Thus, while participatory governance is increasingly promoted as essential for the effective implementation of sustainability initiatives, including NBS, various barriers still hinder meaningful community engagement. Based on a prior NBS project experience (e.g. CONNECTING Nature, RECONECT, EmpowerUs), this paper aims to: 1) demonstrate co-creation approaches and frameworks for NBS realization and their main features; and 2) critically discuss factors that hinder and enable effective community engagement and successful NBS co-creation.

All three projects centred on implementing and scaling up NBS and other sustainability solutions to address challenges related to climate change, biodiversity loss, the Blue-Green economy, and local sustainability. They promoted collaborative planning and stakeholder engagement, recognizing the value of co-creation by

involving local communities, policymakers, and experts throughout the design and implementation processes of NBS and other sustainable solutions. In these projects, co-creation is defined as a collaborative approach to planning, designing, implementing, monitoring, and evaluating NBS, where a broad range of local stakeholders are actively engaged in the entire NBS process from the very beginning. The projects established various methods and approaches for organizing co-creation (including capacity building) as well as for monitoring and evaluating its processes and outcomes. Moreover, they developed co-creation and knowledge co-production frameworks to successfully integrate scientific research and local knowledge, ensuring active community involvement (Dushkova and Haase, 2020, 2023; Dushkova and Kuhlicke, 2024; Dushkova et al., 2025; van der Have et al., 2022). The projects employed the Living Lab approach, generating new insights through collaborative processes that integrate research and development within real-world settings and involve multiple stakeholders in the planning, design, testing, and assessment of NBS. Although the number and names of co-creation phases vary across projects, several common features exist: NBS co-creation is a dynamic, multi-stage process that typically includes identifying local issues/challenges, analyzing the local context, developing future visions and scenarios, assessing potential sustainability impacts and outcomes, designing solutions and implementing them while tracking progress through monitoring and evaluation (Figure 1).
We conducted a context and document analysis of the project reports, meeting and workshop minutes, policy documents, and communication materials. Additionally, we used co-creation diaries as well as reflective monitoring and evaluation framework to identify and assess changes resulting from co-creation activities. It enabled the identification and critical assessment of specific barriers to NBS realization and ways to overcome them, based on the established co-creation approaches. Below, we provide a brief reflection on each of them:

1. *Shared understanding and capacity building.* A common understanding of NBS concept and approach, their benefits and long-term goals among stakeholders is vital. Capacity-building through training enhances the ability of facilitators and communities to implement NBS effectively. Regular stakeholder workshops, knowledge exchange platforms, and clear communication materials support this process.
2. *Political will and institutional support.* Limited political commitment, short-term policies, sectoral silos, centralized decision-making, and lack of inclusivity hinder NBS implementation. Tokenistic participation and bureaucratic complexity often reduce community trust and engagement. Fostering multi-level governance, embedding NBS into strategic policy frameworks, ensuring long-term commitments, and inclusive decision-making processes can counter these challenges.
3. *Resource availability.* Insufficient funding and human resources limit inclusive participation, leading to unequal representation in NBS decision-making. Land-use conflicts, dominance of grey infrastructure in planning, and slow returns further limit NBS uptake. To address them, various innovative financing mechanisms (e.g. public-private partnerships, grants, community-based funding models), flexible project timelines, and showcasing the cost-effectiveness and long-term economic benefits of NBS can attract and strengthen the investment.
4. *Stakeholder engagement and motivation.* Participatory processes are often time- and effort-consuming, which can cause stakeholder fatigue. Co-creation strategies based on a clear definition of stakeholder roles, expectations, and benefits, while considering inclusivity, transparency, legitimacy, trust-building, and flexible engagement, help maintain engagement. Building local champions and peer-to-peer learning also play a key role.
5. *Skills and expertise on NBS.* Stakeholders often lack the ecological and planning knowledge required to effectively realize NBS. Targeted education and accessible training modules, collaborations with academia, mentorship programs, and practical toolkits tailored to local contexts can build needed capacities.
6. *Social capital, trust, and ownership.* Weak networks and fragmented community efforts reduce co-creation efforts. Establishing local stakeholder groups (think-tanks) with NBS expertise, inclusive participation, transparent communication, conflict resolution mechanisms, and local stewardship initiatives can foster collaboration and trust.

The experience of the CONNECTING Nature, RECONECT, and EmpowerUs projects shows that inclusive, iterative, and locally grounded co-creation is key to maximizing NBS benefits and unlocking their full sustainability potential. While meaningful co-creation is essential to the success and legitimacy of NBS, structural and systemic constraints often hinder active community involvement and sustained commitment. Addressing these limitations requires targeted capacity-building, institutional reforms and systemic changes. Looking ahead, fostering truly transformative NBS needs moving beyond short-term pilot projects toward long-lasting governance shifts that institutionalize co-creation as a common practice. This includes embedding NBS into regulatory and planning frameworks, providing incentives for local engagement, and ensuring financial and technical support across all NBS phases. Moreover, building strong collaborative networks between scientists, practitioners, policymakers, and civil society is essential for knowledge co-production and shared learning. Co-creation plays an essential role in empowering communities through capacity building, better access to resources, building trust and a sense of ownership, thus allowing them to become not only recipients of solutions but active agents of change toward a more sustainable and resilient future.

Acknowledgments

The work was conducted within the European Union's Horizon 2020 research and innovation programme projects "CONNECTING Nature: COproductioN with NaturE for City Transitioning, INnovation and Governance" (grant agreement no. 730222, https://connectingnature.eu/) and "RECONECT: Nature-based solutions for hydro-meteorological risk reduction" (776866, http://www.reconect.eu/); and European Union's Horizon Europe programme project "EmpowerUs: Socio-economic Empowerment of coastal communities as users of the sea to ensure sustainable coastal development" (101059957, https://empowerus-project.eu/).

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How a neighborhood park can become a common ground for multispecies coexistence: the case of sorelle Mirabal garden in Milan

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Highlights

- Co-creation represents an effective approach to enhance the social acceptance of urban biodiversity
- Including multiple species in participatory processes helps recognizing non-humans as stake and rights holders
- Lengthy bureaucracy risks undermining the transformative potential of participatory approaches

Keywords

Urban Biodiversity; Multispecies; Co-Creation; Citizen Engagement; Social Monitoring

Some phases of the research: (from left to right) one of the co-creation workshops, the opening of the garden and the installation of the biodiversity sensors. Source: Luca Lazzarini and Asef Ayatollahi

Under conditions of a changing climate and mounting pressures on ecosystems, cities and their communities are increasingly dependent on a range of services and benefits that nature provides. In response to this, over the past decades local governments have implemented a growing number of biodiversity strategies and actions to address these climate and ecological pressures. A common objective of these efforts is to involve communities in recognizing the several benefits that nature offers in urban settings and harnessing them to improve quality of life. Although public participation is not always considered desirable by institutions due to the potential conflicts, associated risks, and the significant resources and time required for effective engagement [1], some co-creation methods have been tested to engage citizens and increase their awareness towards protecting and enhancing green spaces in urban areas [2; 3]. These approaches offer multiple benefits, including greater social acceptance of biodiversity and the generation of relational and social values that strengthen the connection between humans and nature [4; 5]. Notable examples of these approaches include the co-creation initiatives carried out in Milan, Hamburg, and London as part of the CLEVER Cities project (2018–2023), which explored the use of NBS in socially inclusive urban regeneration processes [6], or the Sharing Cities project (2016–2021) which developed collaborative design processes that employed co-design tools and methods to leverage digital technologies in addressing contemporary urban challenges [3].
As part of the research activities of the National Biodiversity Future Center (NBFC) [2022–2025] funded under the National Recovery and Resilience Plan, an urban living lab has been established in Milan to test co-creation methods for the redesign of a neighborhood park in the eastern periphery of the city, the Sorelle Mirabal Garden, with the goal of preserving and enhancing its biodiversity. The initiative was launched following a joint agreement between the Politecnico di Milano and the local Council of Milan (Municipio 3) in May 2023, centering on the ‘civic experimentation of urban biodiversity’, as stated in the municipal resolution approved by the local authority. The aim is to collaboratively safeguard and enrich the existing park’s biodiversity through participatory practices embedded in a living lab framework, fostering new knowledge and a renewed sensitivity toward nature conservation.
The Sorelle Mirabal Garden spans approximately two hectares and is located adjacent to a railway embankment, bordered by two elderly care facilities and surrounded by a mixed used urban fabric where new large-scale residential developments are being built. Once a wasteland and an illegal dumping site, the area was reclaimed in 2017 by a group of non-profit associations that secured the space through a public call for proposals. The associations restored the existing and planted new vegetation and transformed the site into a shared community garden. Since then, the garden has hosted numerous projects, including the co-design of a therapeutic park for elderly people, aimed at evaluating the cognitive and social benefits of urban nature [7]. In 2022, the loan-for-use agreement expired, resulting in the park’s closure to the public. Over the subsequent years, the vegetation initially restored by the local associations continued to grow spontaneously, turning the space into a valuable site for observing biodiversity dynamics. The park hosts a variety of trees, including mulberries and cherry trees, as well as spontaneous species like Acer negundo and invasive ones such as Ailanthus altissima [8]. It is also habitat to a diverse range of vascular plants, shrubs, birds, insects, and small mammals, the latter of which use the nearby railway as a corridor to access the Park.
This contribution aims to present the participatory methods tested for the redesign of the Mirabal garden, the results achieved so far, and the ongoing activity of biodiversity monitoring. The main research hypothesis underlying this contribution is that co-creation methodologies can serve as a relevant approach for local institutions to improve the social acceptance of biodiversity in cities and shape relational values that can catalyse local communities’ efforts toward nature preservation and enhancement. Moreover, the proposed co-creation framework differs from previous participatory models concerning green areas by incorporating the role of multiple species into the process, thereby recognizing non-human entities as stakeholders and rights holders. In fact, the integration of specific collaborative tools and techniques, such as participatory ecosystem services mapping or multispecies role-playing games in the co-creation process, can make a significant contribution in guiding local stakeholders to acknowledge multispecies dynamics and the multiple benefits of biodiversity in urban green areas.
The co-creation process took place between May and September 2024, has involved a group of 20-25 participants, mainly citizens living in the neighborhoods (Lambrate and Ortica) where the park is located, and was structured in four main workshops held in Milan.
In the first workshop, following a brief presentation of the main research objectives, participants were guided to develop an initial definition of urban biodiversity, explore its benefits through the concept of Ecosystem Services (ES) [9], and identify which of these benefits could be enhanced within the Mirabal Garden. Using a set of 28 cards divided into three categories, each representing a type of ecosystem service in urban areas—participants were invited to discuss the cards and select their top five ES with reference to the park. The most

frequently selected services included heat reduction through increased green coverage, improved social interaction among residents, reduction of anxiety and depression, and control of disease and sanitary risks. These preferences helped to prioritize specific ecosystem services in the park's redesign. Subsequently, participants were called to share their preliminary knowledge and expectations about the park, and this has served to establish collaborative vision, mission, and objectives of the park.

In the second workshop, a multispecies role-playing game was set up through the use of a set of cards representing a selection of animal and plant species which find their habitat in the park. Species were selected with the help of two local experts from the Natural History Museum and the Civic Aquarium of Milan who joined the workshop, providing relevant insights on local biodiversity. The decision to include not only desirable species but also non-native and even invasive species was driven by the aim of guiding citizens understanding the complexity of biodiversity dynamics in urban environments, where harsh competition between species is often observed. In line with this approach, each participant working in pairs received two cards (one featuring an animal and the other a plant) and was asked to complete two boards representing the seasonal and daily multispecies trajectories of the selected species. Each board contained blank fields to be filled in with information related to the species' needs (resources and habitats), potential interactions with other species, and the benefits and threats they pose to humans.

In the third workshop, the goal was to identify the design elements to be implemented in the park. Once again, a set of cards was prepared, featuring a selection of NBS drawn from existing catalogues, along with various types of urban furniture essential for the public use of the garden. The cards were laid out on the table, and participants were invited to collaboratively discuss and decide which elements could be introduced into the park, ensuring alignment with the vision, mission, and objectives established during the first workshop.

In the fourth and final workshop, a public presentation and discussion of the activities conducted in the previous months was organized with the participation of institutional representatives, academics and biodiversity experts within the Milano Green Week, a calendar of events about greening and sustainability promoted by the Municipality of Milan.

After a long preparation phase and some delays due to administrative issues, the park was finally inaugurated on May 7, 2025. One of its most distinctive traits resulting from the co-creation process and related to the vision of the park as a «multispecies, multifunctional, collaborative and inclusive garden», is a high-biodiversity area located in the western section of the garden, near the railway. This area is enclosed by a light and porous metal fence, with limited human access, allowing nature to flourish spontaneously. Thanks to its wide mesh, the fence allows small mammals to pass through and park visitors to observe natural dynamics. Its educational role is further enhanced by a series of informational panels installed along its length, which explain the ecological value of the area. Experts are monitoring several species in this habitat that were previously discussed during the workshop activities, such as the European green toad (Bufotes viridis), for which a dedicated pond was created and is now under continuous observation, and which became a sort of symbol of the park. Biodiversity monitoring is also supported by a range of sensors installed both in the high-biodiversity area and throughout the rest of the park. These sensors track key biodiversity indicators, including the abundance and types of pollinators, as well as the soil's carbon sequestration and water retention capacities.

While the process of biodiversity and social monitoring of the park is still ongoing, the results of the participatory pathway mainly relate to the creation of a common ground [10] that brought together a range of different stakeholders (local association representatives, citizens, experts and municipality officers), shaping a multispecies park where humans are called to coexist with and respect the non-human entities. Although citizen engagement was legitimized throughout the co-design activity, the process was constrained by several factors, including lengthy administrative procedures, and in particular limitations related to the public procurement of equipment, furniture and materials, which sometimes have restricted the imaginative and creative solutions developed by workshop participants during the co-creation phase.

Despite the local government's genuine commitment to promoting urban biodiversity, tensions arose when the area designated exclusively for non-human species was physically demarcated. At that point, there was an attempt to reduce its size, driven by concerns that the public reaction might be negative—especially given previous controversies in the city over reduced mowing of public lawns, a topic already prominent in public debate. Nevertheless, the first feedback emerging from park visitors highlight that no claim has been made to take possession of the protected area. Hence, the co-creation experience can be assumed as a relevant approach for investigating the social acceptance of the envisioned measures aiming at preserving and restoring urban biodiversity before their implementation.

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Between benefits and burdens: understanding the complex relationship with urban trees as Nature-based Solutions

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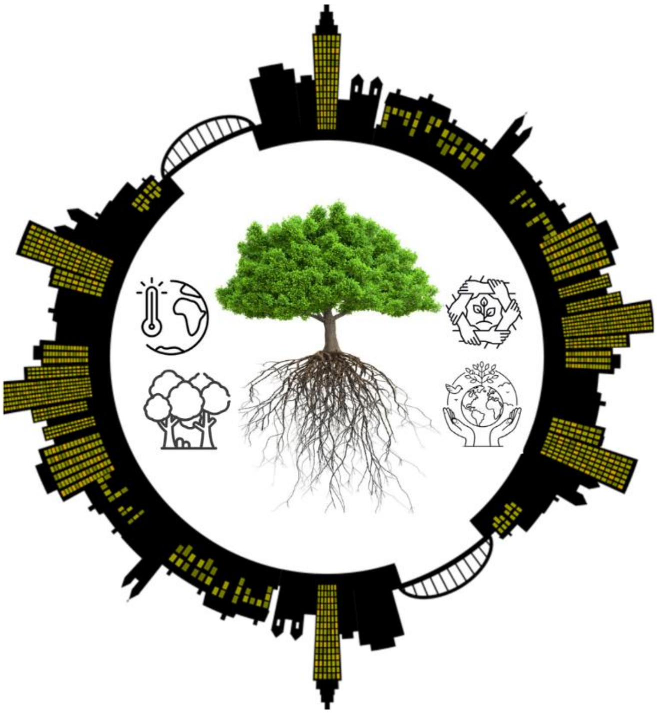
Highlights

- We examine various roles of urban trees, resulting in ambivalent human-tree relationships
- This ambivalence reflects deeper tensions between human needs and ecological priorities
- Participatory planning & governance, tolerant species, tree diversity help to address it

Keywords

Urban Trees; Nature-Based Solutions; Participation; Resilience; Sustainability



Ambivalence of urban trees

Trees and forests are vital components of urban green infrastructure (UGI) and nature-based solutions (NBS). They provide essential ecosystem services and have diverse meanings for urban communities. Numerous studies have emphasised their importance in supporting biodiversity, helping to adapt and mitigate climate change, and providing recreational, aesthetic, and cultural benefits [7, 8, 9]. Consequently, urban greening initiatives aimed at expanding tree canopy cover are gaining momentum globally. However, these benefits are under threat from climate change, pests, storms, droughts, fires, and inadequate planning. Urbanisation, pollution, and land use conflicts further intensify these pressures. Our previous research [3, 4, 5, 6, 10] has examined the ecological functions, social significance, and contributions of urban trees as part of UGI to social-ecological resilience. Building on them, the paper explores the ambivalence in human-nature relationships regarding urban trees, which is defined as a simultaneous sense of attraction and repulsion. It critically reflects on the ecological and social significance of trees, the origins of this ambivalence, and its implications for urban biodiversity and the use of trees as NBS.

Ecological roles and significance of urban trees within NBS and UGI

Urban trees, whether in forests, parks, on streets, or growing spontaneously on brownfield sites, are among the most visible and ecologically significant components of urban nature [5]. Due to their longevity, visibility, and structural prominence in urban landscapes, they are vital contributors to UGI and NBS, offering various ecosystem services such as climate regulation, air purification, recreation, and psychological well-being [4]. Along with providing shade and regulating the local climate, they play a vital role in supporting biodiversity by offering features such as cavities, bark textures, and layered canopies. These features are essential for a variety of species, including bark beetles, spiders, birds, and mammals [8] It helps create essential habitats for a wide range of species, e.g., invertebrates, birds, mammals, fungi, and lichens [7]. In addition to their own species richness, urban trees host a diverse array of associated organisms, thereby enhancing overall urban biodiversity [8]. Among them, oaks stand out as biodiversity hotspots, hosting the greatest variety of insects and fungal species of any tree in Central Europe.

While native species, such as oaks, play a crucial role in supporting biodiversity, urban environments also host a mix of native and non-native trees. In Central Europe, some of them (e.g., *Acer negundo, Ailanthus altissima, Fraxinus pennsylvanica, Pinus strobus, Populus canadensis, Robinia pseudoacacia, and Quercus rubra*) are considered invasive. However, assessing their ecological roles is complicated by increasing climate change and the relatively recent establishment of urban settlements [4].

Historically, trees have played a central role in urban landscape design and have been planted in squares, courtyards, or gardens. From the 19th century onwards, following the removal of city walls, trees became a key feature of large recreational parks, initially in the Global North and later in the Global South. In Central Europe, research on urban trees, their ecosystem services, and community involvement in greening initiatives is among the earliest and most advanced in the world.

Trees also serve as navigational and aesthetic landmarks and focal points in landscape design. As integral elements of urban green infrastructure (UGI), they play a key role in participatory greening strategies and adaptive planning under NBS frameworks [4, 7, 6].

Understanding ambivalence in the context of urban trees

As densely populated centres with extensive infrastructure, cities pose challenges to urban trees. High surface sealing and complex underground systems, in particular, limit tree growth and landscape continuity. Large, mature trees often impede urban development projects, resulting in their removal, while young trees planted in new residential areas take decades to replace lost habitats [9]. This dynamic exemplifies the ambivalent relationship between humans and trees.

Although UGI and NBS are increasingly recognized as crucial for sustainability and resilience, urban development still prioritizes grey infrastructure, leaving trees confined to small and fragmented green spaces [5,4]. Combined with air and noise pollution, this harms both human and ecosystem health [1], while also deepening citizen disconnection from nature and reducing accessibility to green space. Furthermore, increased climate change intensifies urban heat, disproportionately affecting vulnerable populations [5].

Urban trees remain vital NBS for cooling cities and mitigating climate impacts. Therefore, preserving tree diversity and habitats is essential for building resilience against climate-related stresses and pests in expanding urban areas [7]. Yet this need often clashes with competing demands for urban land (e.g., prioritizing grey infrastructure leading to limited spaces for trees and their fragmentation), illustrating the ambivalence that shapes human-nature relationships in cities.

Unveiling urban tree ambivalence through NBS: implications for research and practice

Globally, urban planners are increasingly recognising the importance of urban trees. Consequently, various targeted strategies have been developed to maintain and increase the urban tree population. Notable initiatives include New York's MillionTreesNYC project, Greening Melbourne, Tokyo's Green Belt Project, Reinventing Paris, and London's Urban Forest Plan. They aim to improve air quality, reduce urban heat, and enhance city livability by planting trees and encouraging community involvement. Leipzig's ongoing Tree Strong City campaign is a prime example of citizen involvement through tree sponsorship, promoting biodiversity and fostering a stronger connection between humans and nature [4]. However, conflicts such as the illegal removal of trees illustrate ambivalence towards urban trees. Our research reveals that this ambivalence mainly arises from competing urban needs, such as the need for space for grey infrastructure versus the need for space for trees. Below, we summarize various approaches to addressing the complexity of the relationship between trees and humans (Figure 1):

a) *Balancing people and nature interests.* Sustainable urban planning requires mediating between human needs and ecological well-being through strategies such as ecological zoning, land sparing and sharing, and giving rights to people and nature. Furthermore, balancing low-allergy species in parks with diverse species elsewhere supports human health and biodiversity.
b) *Adapting to climate change through heat- and drought-tolerant species.* Climate change introduces additional complexity to urban tree management, which requires tree species that can withstand higher temperatures and prolonged drought conditions. However, prioritizing climate-resilient species can reduce tree diversity. Thus, balancing resilience and diversity is key to creating sustainable urban trees and forests.
c) *Integrating spatial strategies for urban biodiversity.* To effectively protect urban biodiversity while accommodating city growth, spatial strategies should balance green space isolation and connectivity. Enhancing connectivity through UGI allows species movement and genetic exchange, while isolated patches serve as refuges for sensitive habitats. Additionally, the "go spontaneously" approach allows urban wastelands and brownfields to naturally regenerate and increase biodiversity. Combining planned green infrastructure with natural regeneration supports multifunctional and adaptive urban environments.
d) *Harnessing co-creation and citizen engagement*. Urban human-nature ambivalence can be leveraged for sustainable coexistence between people and trees through co-creation, involving diverse stakeholders in planning and implementing trees as NBS. This approach fosters direct interactions with urban trees via planting campaigns, sponsorships, and care initiatives, strengthening social connection and stewardship. Crowdfunding complements these efforts by financing and promoting urban greening projects, mobilizing community support. Though co-creation may involve conflicts, it offers opportunities for learning and collective problem-solving [4]. Integrating conflict research in urban planning could empower stakeholders, increase motivation, and improve the design of biodiversity-focused solutions in cities [1,6].

Ambivalence in human-nature relationships highlights the need for fresh, systematic, and comprehensive approaches to nature conservation, spanning science, practice, and policy. Such approaches should openly and inclusively address the diverse and sometimes conflicting dynamics between humans and nature. Recognising this ambivalence enables effective integration of scientific knowledge with practical tree planting and management through co-creation strategies, thereby enhancing urban sustainability and resilience. Specifically, the strategies outlined above help to resolve this dualism by systematically linking ecological science, urban practice, and governance. *Balancing people-nature interests* translates ecological knowledge into spatial planning and policy tools that mediate competing land-use demands. *Adapting to climate change with heat-, drought- and pest-tolerant species* bridges scientific research on species selection with applied arboriculture and long-term management guidelines for practitioners, including *rethinking invasive species*. *Integrating spatial strategies for urban biodiversity* operationalises landscape ecology insights into concrete planning practice and policy regulations, ensuring that connectivity, resilience, and multifunctionality are embedded in urban design. Finally, *harnessing co-creation and citizen engagement* establishes participatory governance models that bring together policymakers, scientists, practitioners, and communities, thereby institutionalising inclusive and adaptive approaches. Taken together, these strategies provide innovative, systematic, and comprehensive ways of aligning science, practice, and policy to address the urgent need for nature conservation within cities.

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Promote a new human and social development through the defence of climate and nature

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Highlights

- Research explores how nature shapes lives, societies, and economies
- A framework translates net zero and resilience goals into concrete action
- Climate action engages citizens, policymakers, researchers, and financiers

Keywords

Environment; Nature-based Solutions; Resilience; Ecosystem; Sustainable Development

The choice of this figure represents the purpose of our contribute in matter of sostenibility environment regards to Agenda 2030. That underlines an approach on nature conditopns on our lives,societies and economies

Our field of research regards the nature conditions regard our lives, societies, and economies and is fundamental to achieving our 2030 Agenda. Addressing the nature crisis is essential to eradicating and preventing poverty, reducing inequalities, and protecting human rights. Nature is a positive source of solutions and hope: a nature-positive transition is central to tackling planetary crises such as climate change. This contribution comes from an analisys of the matter and offers, from a certain point of wiew, the possibility to operationalize the opportunity to advance the SDGs through nature. It will help decision-makers and practitioners recognize programming options and make the case for investing in nature to achieve development outcomes. It comprises key facts, figures and talking points about nature through five different practice lenses: 1) Nature for Food Security 2) Nature for Water Security. 3) Nature for Climate Action. 4) Nature for Gender Equality and least but not least 5) Nature for Peace.

This is a full resource and call to action that will expand to cover more practices. In the last years EU has introduced in the research the definition of *"Nature based solutions"* as tool for a sustainable, social and economic development. In 2022, the fifth ONU Assembly adopted fourteen resolutions and in the same direction was the Sharm el-Sheikh Plan and the Kunming-Montreal Global Biodiversity Framework, to build a world living in harmony with climate and nature by 2050.

Climate change is much more than an environmental issue and presents enormous social and economic conseguences at the global, regional, and local levels. For these reason we must analyze the root causes, developing targeted assessments of the risks and costs of climate change in Europe. This idea has to lead the political community in order to support long-term climate action involving stakeholders: local population (with regular consultations and interviews), policy makers at european,regional,local levels, researchers, financial organizations, and industrial sectors.

By building predictive case-studies in economic sectors (agriculture, forestry, energy, and infrastructure), it will be possible to assess the effect of local climate impacts on the emergence of “socio-economic hotspots” and calculate costs in order to formulate policy for more effective responses.

Finally, with the creation of an open-source web archive, it will be possible for community at all level (official and no) to have tools for understanding to implement appropriate strategies in agreement with human beings and nature.

The purpose of our contribution is to present a framework designed to help agrifood companies strengthen the resilience of their supply chains to climate risks while reducing emissions, in alignment with the Nationally Determined Contributions and National Adaptation Plans of the countries where they source, produce, buy, and sell products.

At its core, this framework helps businesses move beyond high-level climate commitments and translate net zero and resilience goals into concrete actions that align with national priorities.

The framework comprises four key steps: *1. Build management commitment for climate action in supply chains; 2. Implement climate adaptation strategies in supply chains; 3. Reduce supply chain greenhouse gas emissions through targeted mitigation actions; and 4. Track, evaluate, and disclose progress to ensure continuous improvement.*

All that we can observe conduct towards a model of sustainable development that is how we must live today if we want a better tomorrow, by meeting present needs without compromising the chances of future generations to meet their needs.

The survival of our societies and our shared planet depends on a more sustainable world!

It’s a bit of a juggling act. Three different balls must be kept in the air at once: economic growth, social inclusion, and environmental protection. If one or two fall to the ground, the act is over. An economy might grow rapidly, for instance – but only for so long if most people remain poor and all the natural resources are used up. Where development is sustainable, everyone has access to decent work, quality health care and education. Natural resource use avoids pollution and permanent losses to the environment. Public policy choices ensure that no one is left behind due to disadvantages or discrimination. If you want to understand why sustainable development is so important in real-world terms, just look around.

On average globally, people live longer lives with higher incomes. But a lot of development is *unsustainable.* It has taken us to climate change. environmental destruction. Conflict. Poverty and hunger. Vast inequalities and social instability. Unsustainable development happens when people pursue immediate rewards without thinking about harms to other people or the planet. Often, short-term gains are overshadowed by longer-term costs. That’s the case when someone cuts down an entire forest to turn a quick profit – even if an ecosystem collapses, endangered species die off and local communities are left at permanent risk of devastating floods.

In 2025, United Nations Member States translated their vision of sustainable development into a blueprint for achieving it: the 2030 Agenda for Sustainable Development. Its 17 Sustainable Development Goals —with ambitious targets to achieve by 2030— cover the three dimensions of sustainable development: the economy, social development and the environment. However, halfway to our 2030 deadline, the climate crisis, a weak global economy, conflicts and the lingering impact of COVID-19 have put the Goals in jeopardy.

According to the UN SDGs Report 2023: Special Edition, the number of people living in extreme poverty in 2020 rose to 724 million, and now gender equality is some 300 years away. The Intergovernmental Panel on Climate Change (IPCC) warns that without more robust policies across all sectors, the world is likely to surpass the critical 1.5°C tipping point by 2035. It is not too late to reset efforts to reach them, however. To advance the sustainable development agenda, governments are integrating the Goals into national plans. However, a fundamental shift is needed to put the world on a better path.

The SDG Summit, on 18-19 September 2023, has been a defining moment for world leaders to renew their commitments and deliver the breakthroughs that our world desperately needs. The Summit will be an opportunity to review progress and gaps in achieving the Goals and will seek to provide high-level political guidance on transformative, accelerated actions to reach the Goals by their 2030 endpoint.

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How much can urban roads be depaved to accommodate Nature-based Solutions? Exploring possibilities in old towns

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Highlights

- The amount of existing green open spaces, in old towns, is often limited
- Planning green spaces in old cities is a challenge as ambitious as necessary
- In old cities, every small transformation opportunity must be caught

Keywords

Old Towns; Nature-Based Solutions; Adaptation; Urban Risks; High Density

Land Transformability map

Introduction

Most of the world's cities face several challenges posed by climate change, such as urban heat islands and pluvial floods. The high exposure to natural risks is often due to a scarce green spaces endowment and the high incidence of impermeable surfaces resulting in high degree of impervious surfaces.

To cope with these issues, Nature-based Solutions (NbS) stand out as adaptable and multifunctional-engineered green solutions inspired by nature in a way to meet climate resilient transformation [1], while providing many social benefits [2;3;4]. The basic idea behind the concept is that using components that mimic natural processes in the built environment can generate a wide number of benefits in cities, and produce equal, safe and liveable urban environment. These solutions contribute to carbon storage and sequestration, air and water purification, mitigation of urban heat island effects, and reduction of storm water runoff. They encompass a broad spectrum of elements, including green roofs and walls, street trees, rain gardens, vegetated swales, storm water planter boxes, and permeable pavements [5].

Despite the growing NbS implementation in urban environments, it remains unclear how—and to what extent—these strategies can be applied within particular urban contexts [6]. Indeed, the complexity of some urban morphologies may complicate NbS implementation strategies [7]. For this reason, in cities, the distribution of NbS is often uneven, creating grey gaps, and this is particularly the case of urban dense contexts, old towns and historic centres which are characterised by morphological fabrics and road systems that are often intricate and limited in size, and pose unique challenges to integrating nature-based interventions [8]. Historic city centres typically face structural weaknesses, including limited accessibility, outdated housing stock, scarce green space, and heightened exposure to natural hazards. These vulnerabilities have led to contrasting dynamics: on one hand, deprivation and abandonment of entire sections of historic centres [9]; on the other, gentrification processes that threaten the heritage by disrupting its long-term cycles of use and maintenance. Thus, the dense morphology and compact form of old towns pose obstacles for implementing NbS, particularly due to the difficulty in identifying suitable spaces that meet spatial and technical requirements [10]. Therefore, regenerating old towns through the dual approach of integrating nature-based solutions in urban streets and preserving their usability by public transportation and private cars and pedestrians is a necessary challenge. Such strategies aim to enhance quality of life, safety, and liveability in these complex urban fabrics.

In this perspective, this study proposes a methodology for the green transformation of urban roads in old towns, helping to locate new NbS in public open spaces, and road sections specifically. Indeed, operating on public owned land typically it is easier then imagining strategies of private owned land transformation, which implies negotiations with individual landowners. Actions on private land are mainly driven by market considerations, while those on public land have fewer obstacles, provided they are politically agreed upon. However, in extremely dense contexts such as historic centres, where open spaces are a precious resource, finding enough space to imagine green adaptation strategies is a challenge, as ambitious as necessary.

The aim of this work is to develop a method for spatially locating NbS in available areas for their installation in the historic centre.

Materials and Methods

The methodology, here proposed, involved 4 phases: 1. classification of public open spaces; 2. association of dimensional and qualitative attributes; 3. definition of minimum dimensional parameters; 4. location and quantification of possible green transformations. All phases were performed by QGIS software.

1. Public open spaces were classified into two categories: squares and roads. The polygons of the squares used in this study are obtained from QGIS Quick OpenStreetMap (OSM) plug-in. The roads have been manually drawn by photo-interpretation of the recent orthophotos. Borders of patches have been matched to vector topographic map features (streets, walls, property borders, etc).
2. Two attributes were associated with the roads: the first one concerns their dimensional characteristics and the second one is a qualitative attribute relating to the type of road. The road section data was derived using the "Oriented minimum bounding box" tool, which calculates the minimum area rotated rectangle for each feature in the input layer. To derive the road geometric feature data with an adequate confidence level of approximation, the road polygons were previously trimmed at every intersection and for each road curvature. This is how the total road section from building to building is obtained, including traffic lanes, roadside parking spaces and pedestrian sidewalks. The width attribute of the oriented minimum bounding box was, then, merged with the road polygons using the tool "Join Attributes by Nearest". In

addition to the width attribute, each road polygon was associated with the street type attribute, based on the OSM roads classification (primary, secondary, tertiary, residential, pedestrian and service). Thus, there was a slight offset between the map data and the open Street map data, so the OSM roads were moved and their position corrected manually, in order to minimise errors during the attribute association phase between layers.

3. Minimum road cross-section widths were defined for each of the OSM road categories in order to ensure normal private or public vehicular traffic. The value of the minimum road cross-sections was obtained by combining the following road components differently: a. bus lane = 3 m; b. driveway/car parking lane = 2.8 m; c. sidewalks in areas with high pedestrian traffic = 1.8 m; d. sidewalks in areas with normal pedestrian traffic = 1.5 m.
   Taking into account the different hierarchy of OSM roads, the minimum road width allowing vehicular traffic was assessed individually for each category. For primary roads this minimum width was estimated to be 15 m (=a+3b+2c); secondary roads have an estimated minimum width of 12.2 m (=a+2b+2c); tertiary roads have an estimated minimum width of 8.6 m (=2b+2d); finally, residential roads have an estimated minimum width of 4.3 m (=b+d). Squares and roads classified as pedestrian have been considered fully transformable, while service roads are considered non-transformable because they are internal access for specific urban functions.
4. If the roads in each category have a smaller actual width than the estimated width, then they are considered non-transformable. Otherwise, the difference between the actual width and the estimated width is the potentially transformable portion. Each road section contributes a different measure depending on the available area for the installation of greenery (Figure 1).

Table 1 Distribution of categories of streets and squares for transformation (area and percentage)

Type of public open space	Total area [m²]	Depaving area [m²]	Depaving area [%]
Pedestrian road	11,510	11,510	100
Primary road	5,355	1,501	28
Secondary road	61,643	24,438	40
Tertiary road	21,378	7,936	37
Residential road	112,005	66,424	59
Squares	45,839	45,839	100

Results

In this work, the study area is given by an urban portion of the historic centre of the city of Catania, a municipality on the eastern coast of Sicily, Italy. The case study covers an area of 1,032,770 m2 and it is characterised by a complex morphological structure. The city of Catania was rebuilt after the earthquake in 1693 on its own original site. So, it is the result of pre- and post-reconstruction historical stratifications, that have resulted in an articulated urban morphology, made up of minute road network, very high levels of density and a general lack of open spaces.

The results show that the least transformable roads are primary ones, with only 28% of the surface area potentially available for depaving (Table 1), followed by tertiary roads with 37%, secondary roads with 40% and finally residential roads with 59%. These results are clearly affected by the choice of the minimum section value, which considered the area needed strictly for the transit of cars and pedestrians, giving less importance to roadside parking, which is present, in the case study, in almost all roads. Moreover, the depaving results, as shown in Table 1, do not take into account the current green areas, which in any case have little incidence as they are very limited. However, this methodology can be implemented, considering the existing green components and assessing the real availability of space and the real increase in permeable surface area.

Conclusion and discussions

The proposed methodology shows some advantages. First, the global OSM data coverage allows to extend the methodology to further comparisons using homogeneous data sets. Secondly, the use of open-source data (OSM) and data management through QGIS basic tools, makes the methodology easily replicable. However,

the lack of some local road data related to the specific case study, implied the manual editing to build it on the topographic map base in order to derive geometric characteristics.
Nevertheless, the proposed methodology presents some limitations. Operating on the complex context of the historic centre, both roads and squares could be subjected to transformation constraints due to the presence of pavements to be protected and preserved. Therefore, depaving interventions should be evaluated individually in relation to the effective transformation opportunities according to heritage conservation policies.
The method proposed in this study could support local decision-making processes, based on the assessment of spatial availability of urban roads for NbS allocation in dense cities and old towns. This is an extremely relevant issue for cities strongly affected by urban heat islands and stormwater runoff and flooding phenomena, characterised by very low levels of greenery, and that have not yet experienced clear and effective climate change risk adaptation strategies.

Acknowledgement

This research is part of the project "Nature for sustainable cities: planning cost-effective and just solutions for urban issues (NatSolis)" (2022ZLE8HC) funded under the PRIN 2022 Program by Italian Ministry of Education and Research and European Union - Next Generation EU.

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Coupling CFD and ML to optimize volumetric stormwater green infrastructure

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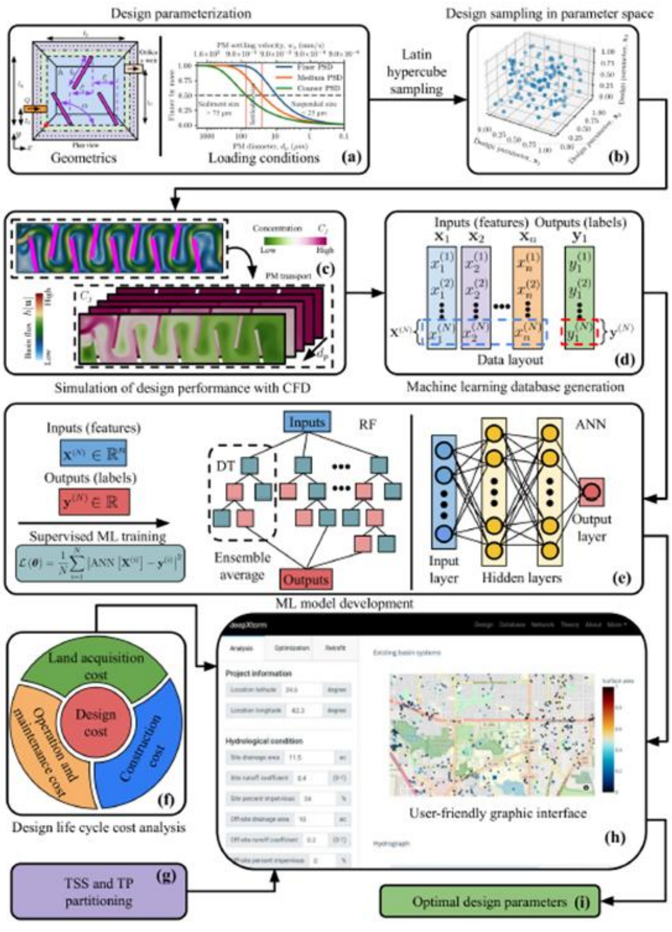
Highlights

- Residence time (RT) is a common metric for volume-based stormwater control
- Yet, RT is agnostic to hydrodynamic, geometry, chemical-particle interactions
- CFD-ML optimizes treatment and economics (10x lower) compared to RT

Keywords

Computational Fluid Dynamics, Machine Learning, Unit Operations and Processes, Urban Drainage, Urban Retrofits



A flowchart of the methodology for the CFD-ML DeepXtorm model

Introduction

As a common unit operation and process (UOP) within urban drainage (stormwater) management systems, volumetric-based green infrastructure (as known as wet basins, ponds, and clarification basins for at-grade applications or as tanks/tunnels below-grade) are widely implemented for hydrologic control and constituent (PM and chemical) load reduction from urban drainage [1]. Despite ubiquitous applications, optimizing the cost-benefit of basin planning/design or needed retrofits of such units is often not considered in practice. As a result, initial planning/design yield high costs (i.e., total cost of design includes land acquisition costs, operation and maintenance of vegetation costs, and construction costs) from hundreds of thousands to tens of million US dollars (USD) per unit. Many of these volume-based units are impaired because of inadequate design/analysis tools such as residence time (RT) indices that only provide presumptive guidance for treatment, lack of regular maintenance or through the non-stationarity (increasing over time) loadings from further imperviousness in urban land uses. Retrofits, if even feasible, yield even higher costs, noting that RT-based solutions require increased unit volume and surface area in constrained urban areas. The high cost of such RT-based solutions imposes substantial financial burden for stakeholders. Existing models such as RT-based models [2] and continuous stirred tank reactor (CSTR) (embedded in many existing tools such as the Stormwater Management Model [SWMM]) [3], a common and comprehensive hydrologic model, are lower-fidelity sub-models. Many critical physics and chemical mechanisms that influence the treatment performance are either significantly simplified or not considered. For example, in the RT-based model, the influence of geometrics, hydrodynamics, constituent chemistry/partitioning, particle diameter/density and particle size distributions (PSD) and biological uptake are not considered. Consequently, the RT-based model does not capture the dependence of treatment performance on the detailed design and constitutive loadings. Hence, such models cannot provide design or retrofit cost-benefit optimization. Optimized design/retrofit can reduce the cost at a given level of benefit for this common volumetric green infrastructure system that is shown to be a context-sensitive green aesthetic solution in urban areas. Stakeholders significantly benefit from optimizing green infrastructure design that becomes a context-sensitive urban recreational amenity [4]. Studies demonstrate computational fluid dynamics (CFD) improves and guides design while reducing costs [4], [5] with even greater reductions when CFD is coupled with machine learning (ML) optimization algorithms for a given level of treatment. The objectives of this study are (1) to introduce the DeepXtorm model; (2) to synthesize and elucidate the DeepXtorm model and methods as compared to existing models (e.g., SWMM, RT, and CIR) focused on design; (3) to compare the design cost-benefit generated by existing methods and DeepXtorm for a wide range of design conditions.

Methodology

CFD-ML DeepXtorm model:

Turbulent flow dynamics coupled with particulate matter (PM) (and PM partitioned chemicals, in this case total phosphorus, TP is illustrated) transport and biological uptake in volumetric-based green infrastructure are governed by a set of partial differential equations (PDEs), the Navier-Stokes equations [5]. These PDEs are the tools and benchmarks in the CFD-ML model. Table 1 provides a flowchart of the DeepXtorm process.

Residence time [RT], capacity-inflow ratio [CIR] and Storm Water Management [SWMM] models:

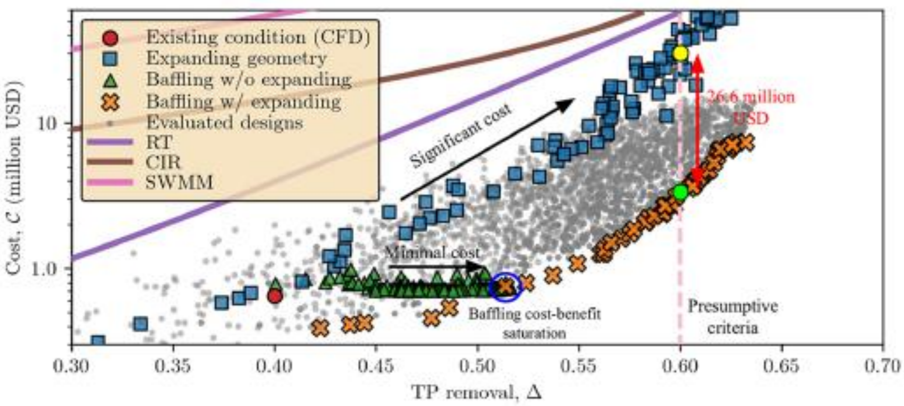
In development of RT-based models and SWMM, basin turbulence dynamics, PM constitutive properties, chemical partitioning and the Navier-Stokes PDEs are not considered. PM (as total suspended solids, TSS) removal (and PM-associated TP removal) is assumed to be only a function of RT through regression to field samples and RT for stormwater basins [2]. As the precursor of the RT-based model developing the capacity-inflow ratio [CIR] model is not significantly different from the RT-based model. The CIR is used as the regression input variable instead of RT and is based on a field samples of agricultural basins [6].

Case study

Results from an existing impaired volumetric green infrastructure UOP system providing biological/physical/chemical treatment in Naples, Florida USA are illustrated. The unit has a surface area at normal pool of 1.33 hectares with a mean wet season flow rate of 0.1 m^3/s. The mean depth is 3 meters and the length to width ratio is 6:1. Details of the Naples case study conditions are provided in [4] and [5].

Results and Discussion

Fig. 2 illustrates an example of the economics required through the methods described herein to upgrade this UOP for a typical 40% TP removal to achieve 60% TP removal through a constrained retrofit. In this example, the site condition with a mean wet season flowrate of 0.1 m^3/s is based on 12-month field monitoring at APF in Naples, Florida. Three retrofitting approaches are examined and compared: (1) expanding the geometry/volume, (2) intra-basin vegetated gabion (baffling) as biological trickling filters without geometric expansion; keeping the same surface area and volume, and (3) intra-basin baffling with geometric expansion. Since RT, CIR, and SWMM are agnostic to geometrics, internal baffling, and hydrodynamics, as well as constitutive loadings, these methods do not optimize retrofit design. Relations between the cost and TP removal produced by RT, CIR, and SWMM (CSTR) methods are still plotted for reference with respect to DeepXtorm optimization schemes. In the first approach, the system is scaled up by expanding the bulk geometry. As illustrated by the blue square marker in Fig. 2, as the system bulk geometry increases, design cost and TP removal increase. However, the cost with this expanding geometry increases at an exponential rate with respect to a linear increase in TP removal, yielding significantly higher retrofit costs. In the second approach, internal baffles are configured (considering non-linear interactions of baffle placement and turbulent transport) by DeepXtorm for improving TP removal, while bulk volume remains unchanged. Because baffling has substantially lower costs than geometric expansion, treatment is improved by 12% at minimal cost, as indicated by the green triangle markers in Fig. 2. In the third approach of baffling with some basin expansion, the basin is retrofitted by configuring internal baffles as well as expanding the basin geometry, as illustrated by the yellow cross markers in Fig. 2. With such a combination of baffling and geometric expansion, performance is further enhanced, overcoming limitations of only baffling. Meanwhile, compared to the approach of only expanding basin geometry without baffling, this combined baffling and expansion approach yields significantly lower costs. As shown by the yellow circle marker and green circle marker, the combination of the baffling and expansion can reduce the retrofitting cost by 26.6 million USD for this single typically-sized volumetric green infrastructure unit of which there are over 15,000 in Florida.



Retrofit design economics to achieve 60% TP removal with DeepXtorm vs. RT, CIR, SWMM

Conclusions and Future Work

Compared to existing tools (RT, CIR and black-box software tools), DeepXtorm provides a more robust and significantly improved cost-effective design. Optimized design produced by DeepXtorm yields much lower cost than existing tools with respect to a range of presumptive or regulatory design criteria. The improved cost-benefit from DeepXtorm is provided by the constrained non-linear optimization and CFD-ML engine, which allows DeepXtorm to efficiently explore the design parameter space that no current model can accomplish. Beyond the research applications, future work is the creation of a web-based user-friendly application interface for designing any type of green or nature-based solutions and can be readily expanded to wastewater treatment.

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Integrated green infrastructure for stormwater management of impervious paved systems

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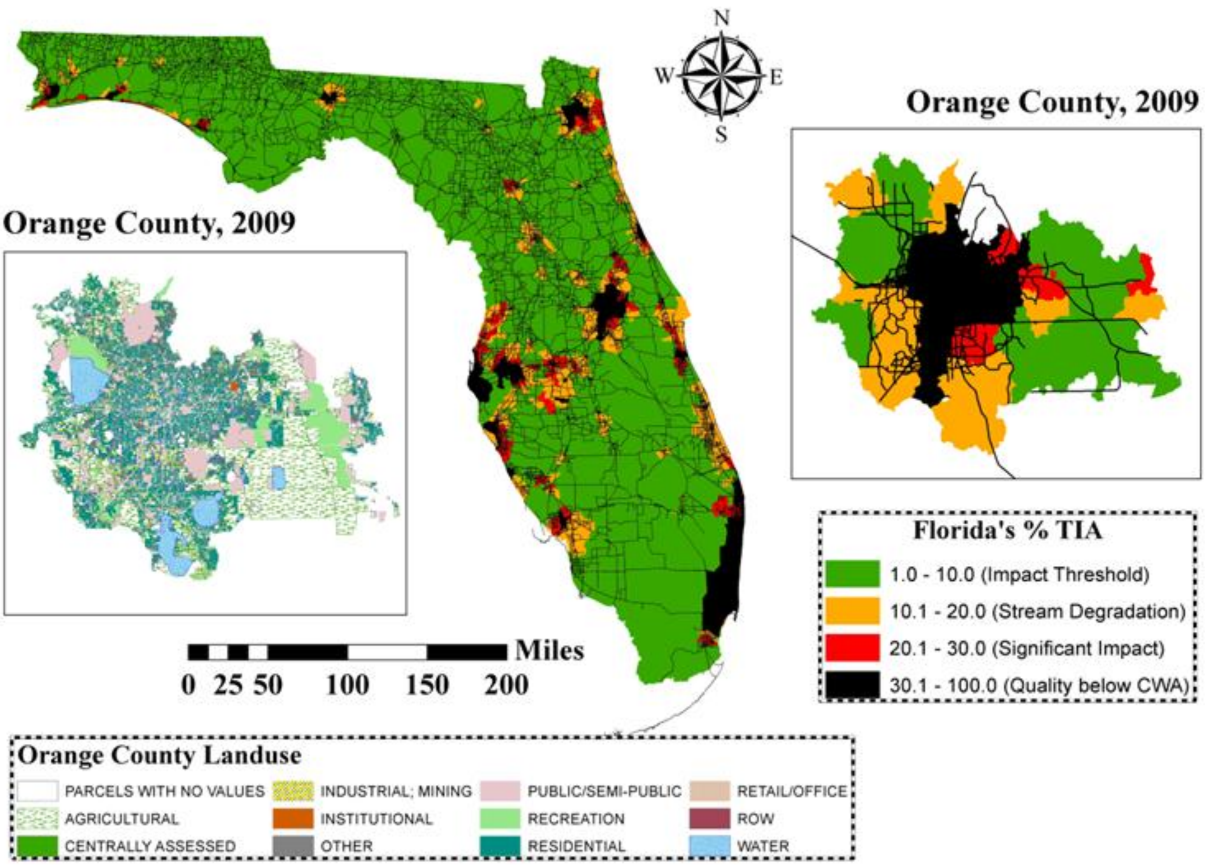
Highlights

- Pavement and traffic are anthropogenic drivers of water cycle degradation
- Integration of pervious pavement and biofiltration provides load reduction
- Integration reduces stormwater treatment costs and provides vegetated amenities

Keywords

Computational Fluid Dynamics, Machine Learning, Unit Operations and Processes, Urban Drainage, Urban Retrofits



Total Impervious Area (TIA) in Florida and Orange County land uses (inset maps). As the %TIA increases, deleterious impacts from the altered water cycle and chemicals/particulate matter (PM) washoff increases. Above 30% TIA, the water chemistry in Florida urban and highway drainage does not meet Clean Water Act (CWA) discharge requirements [3]. 1.0 miles = 1.61 kilometers

Introduction

Over the last century, Florida has experienced rapid population growth. From 1960 to 2000, the population increase in the United States averaged 1.1 percent each year while the State of Florida experienced a growth rate of 3.0 percent each year during the same period of time [1]. As of 1960, 1.2 million acres of land in Florida were urbanized. By 2000, approximately 6 million acres (1 acre = 0.4046 hectares) in Florida had been converted for urban land uses. Between 2000 and 2024, nearly 3.0 million more acres of land were converted for urban land uses. For example, Orange County alone will convert 125,000 acres to urban land uses during this period [2]. Figure 1 illustrates total impervious area (TIA) across Florida and, for example, the current land uses and TIA in Orange County. Commensurate with this growth are increases in wastewater and stormwater reuse in Florida, in part for irrigation. By 2020 Florida reclaimed approximately 5 billion liters per day of tertiary-treated wastewater for non-potable uses, such as urban/suburban irrigation.

Background: Urban Site and Rainfall-Runoff Loading Information

The study site is in Gainesville, FL on the University of Florida campus. The road and parking surfaces are impervious asphalt, while the sidewalks are constructed of impervious concrete. Historical rainfall time series data were utilized to characterize precipitation loadings for the site design. Hourly data from the Gainesville Regional Airport (GNV) station with continuous recording data, was utilized. The dry season occurs between October and May and the wet season between June and September. Based on the number and frequency of events from these data, the mean number of events on an annual basis for Gainesville, FL is 152 events and the long-term annual rainfall depth is 1300 mm [3].

The design required representative hydrologic, chemical and PM load characterization. Rainfall-runoff data were collected and analyzed for 15 storms. Of the 15 storms examined, both mass limited (first-order washoff) events and flow limited events (zero-order washoff) were observed. Varying chemical and PM granulometry generate variable partitioning, distribution across the PM particle size distribution (PSD) and therefore different washoff behavior; with PM exhibiting mass limited transport (first flush) while dissolved species preferentially exhibiting flow limited transport. Data were collected for total phosphorus (TP), phosphate, total nitrogen (TN), nitrate, ammonia, and PM fractions (sediment, > 75 microns, settleable and suspended, < ~25 microns) for the 15 storms. For brevity in this document rainfall and runoff loadings are detailed in [1].

Objectives

The primary objective was to combine the benefits of green infrastructure as a combination of cementitious permeable pavement, CPP), biofiltration, native vegetation, hydrologic restoration, and denitrification to manage hydrologic, chemical and PM load control for stormwater. This management through re-design of the existing infrastructure condition was designed/modeled/monitored to create a passive low impact development (LID) system that met pre-development “pristine” load conditions. Design alternatives were evaluated based on hydrologic restoration, removal of nutrient loads and PM with costs that are compared to typical Florida BMPs and also to conventional design and construction for impervious surface parking systems. The design intent was to provide indirect reuse of runoff though evapo-transpiration, infiltration and recharge capacity while meeting load reduction goals.

Methodology

Light Detection and Ranging (LIDAR) data was obtained and added to the data set, providing the outlying area's existing topography. Survey and LIDAR data were used to create a Triangulated Irregular Network (TIN) surface of the site. With the 3D surface model slope vectors of the existing surfaces were determined. ArcGIS as a geographic information system was chosen providing several project requirements: an industry standard with a large user base, ability to import geospatial data from AutoCAD with ability for analysis of geospatial data, export of shape files and export to the USEPA stormwater management model (SWMM) [2]. ArcGIS was used to delineate subcatchments for SWMM, calibrated with existing site data. USEPA SWMM 5 was chosen for unsteady continuous modeling providing hydrologic and hydraulic routing. The watershed was modeled with 89 subcatchments comprised of varying hydrologic functional units (HFUs) and properties. The United States Geological Survey (USGS) VS2D numerical model was used to further examine and solve variably-saturated, 2-D flow problems for biofiltration and permeable pavement [2].

Results

By using the same historical rainfall, chemical and PM loading data, but varying design element combinations of a BAR and various LIR (permeable pavement as a linear infiltration reactor) widths in the contaminant transport and fate models and economic analyses, a series of efficiency indices and load evaluations were created. Design elaborations were used for comparisons to the loads generated from the pre-development “pristine” catchment. Design options were compared to "pristine" (pre-developed): Design Option (No LIR, BAR); Design Option (2 ft LIR, BAR); Design Option (4 ft LIR, BAR); and Design Option (All CPP, BAR). All options included a vegetated biofiltration area reactor, BAR). 1.0 feet = 0.3048 meters.

There is a strong correlation between the extended LIR widths and decrease of phosphorus, nitrogen and PM (as TSS) loadings. By expanding the LIR width to 6 feet, the design is capable of treating all runoff loads down to levels lower than pristine conditions and achieving a 20-year design life with regular pavement cleaning. This design life is based on in-situ testing of CPP and an LIR at another site; referenced for brevity of this document [2]. Other design options did not meet pristine conditions for all pollutants and had a shorter design life.

Conclusions

Ultimately, if any pavement area, a commercial or retail parking area or a highway/roadway system, is to be constructed or retrofitted using a BAR/LIR system, the area should drain to regularly spaced engineered treatment biofiltration areas similar to the BAR, where infiltration, evapo-transpiration, storage and treatment can occur with upstream treatment facilitated by engineered cementitious permeable pavement, CPP in this case deployed with an amphoteric admixture for phosphorus adsorption. With such hydrologic communication, a target level of hydrologic restoration and load reduction can be achieved; with benefits to components of the hydrologic cycle; and ultimately provide indirect reuse of stormwater through local recharge. Such benefits include reductions in pollutant loads and concentrations with reduced thermal loads. Further benefits provide source area control of PM loads before such loads are transported to conveyance systems [4]. Design components such as the BAR also provide beneficial aesthetic with context-friendly landscape as an amenity in an otherwise hot expanse of asphalt pavement. Additionally, CPP eliminates the deleterious environmental and thermal impacts of asphaltic binders while providing beneficial alkalinity to the infiltrated runoff. Results illustrate that the cost of such green infrastructure and LID is on par with conventional construction, even before the costs of pollutant and runoff load reduction are included. When load reduction costs are accounted for the system construction costs are lower; and costs per unit load of nutrient treated are lower than current mean Florida BMP costs. This study has illustrated the benefits of matching green infrastructure design elements to target specific pollutants based on pollutant-specific chemistry and known unit operation and process (UOP) mechanisms. Results are also quantitative and illustrate that LID or sustainable urban drainage practices and designs can be quantified; removing such practices from the category of "black-box" systems. For example the bounding clay layer design element within the BAR allows for denitrification utilizing the natural consortium of microbes in runoff and kinetics that allow denitrification within 48 hours. At the same time, a simple modification of CPP as a filtration medium with an aluminum oxide admixture provides an interface for the removal of phosphorus that would otherwise produce rapid breakthrough from a stand-alone BAR design element. The use of engineered CPP or media systems with oxides provide significant benefits compared to many bio-filtration media or friable media substrates such as perlite that have been shown to leach pollutants. The current combination of native soil and local vegetation as part of the proposed system design, combined with CPP and a clay bounding layer meets project objectives (and State of Florida requirements) for no-net load increase of phosphorus, nitrogen, PM (as TSS) and volume of runoff. The combined system of a BAR and LIR with CPP has the additional benefit of providing a more comfortable urban environment for humans and local ecology, minimizing the local heat island impacts, and allowing more evaporation and phyto-pumping, and reduced overall energy utilization.

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The URBioPark project: a multidisciplinary framework for urban biodiversity and public health

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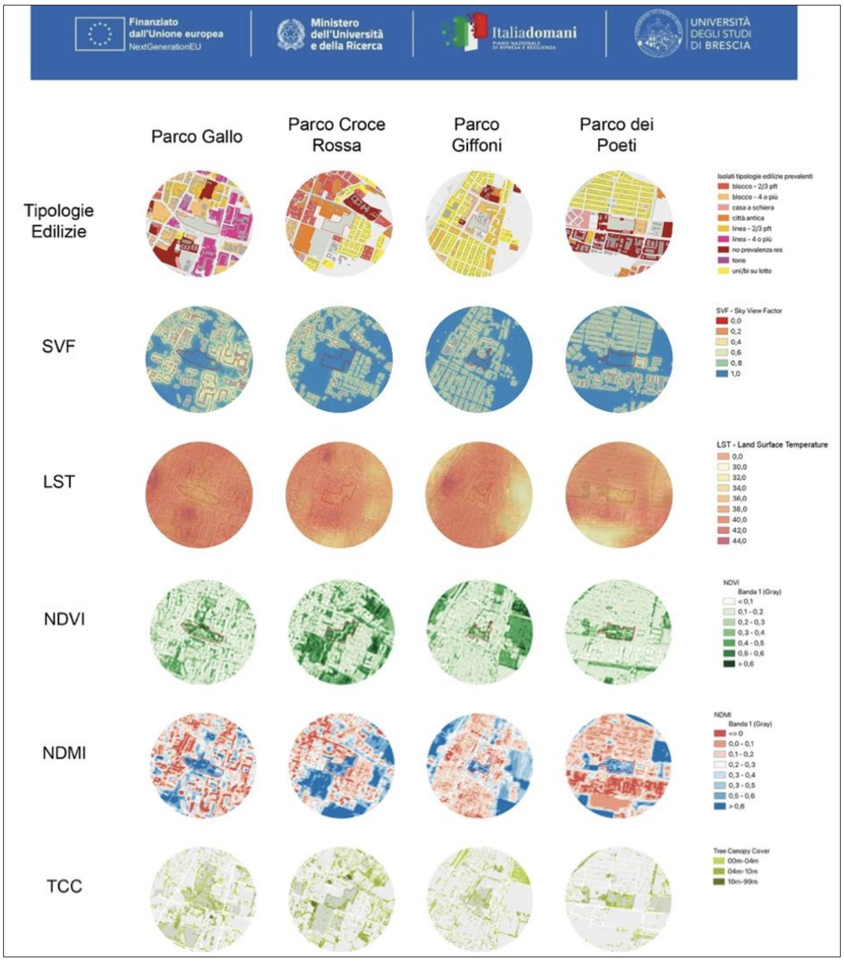
Highlights

- Urban biodiversity promotes health equity and resilience
- GIS links chronic disease data and biodiversity
- Participatory methods enrich spatial planning

Keywords

Urban Biodiversity; Public Health; Nature-Based Solutions; GIS, Urban Planning



Analysis of the urban fabric surrounding urban parks within a 500-meter buffer zone. Comparison of indices: Building Typologies, Sky View Factor (SVF), Land Surface Temperature (LST); Normalized Difference Vegetation Index (NDVI), Normalized Difference Moisture Index (NDMI), and Tree Canopy Cover. Source: Author's own elaboration

Cities face increasingly urgent challenges linked to climate change, biodiversity loss, pollution, and public health inequities. In this context, innovative and integrated strategies are essential to ensure environmental and social sustainability for present and future generations. Urban green spaces, biodiversity, and Nature-based Solutions (NBS) play a central role in this transformation. According to the World Health Organization, health is a prerequisite for sustainable urban development [1]. Recent research highlights the connection between urban biodiversity and human health, showing that exposure to biodiverse green spaces benefits both physical and mental well-being. Aerts et al. [2] illustrate how green infrastructure, biodiversity, and ecosystem services interact to support human health. Sandifer et al. [3] emphasize the multifaceted nature of these benefits, while studies by Maas et al. [4] and Carrus et al. [5] link the presence of greenery to a reduced incidence of chronic diseases and improved psychological well-being. Conversely, Haahtela [6] points to a higher risk of inflammatory conditions associated with biodiversity loss. Moreover, access to green spaces contributes to reducing socio-economic disparities in health and to lowering public healthcare costs [7].

In response to these complex challenges, the URBioPark project was launched. Funded in 2022 under the PRIN (Research Projects of Significant National Interest) programme and supported by Next Generation EU resources, the project brings together the Universities of Brescia, Verona, and Padua, along with the Italian National Research Council (CNR). URBioPark aims to develop a practical, interdisciplinary model that integrates urban biodiversity, public health, and spatial planning. It investigates how biodiversity in urban parks affects human well-being, while also defining indicators, identifying practical actions to monitor, conserve, and enhance biodiversity, promoting citizen participation, and producing tools and guidelines to support governance and planning processes.

The project applies a multidisciplinary and phased methodology to explore the interrelations between biodiversity in urban parks and public health. It integrates geospatial analysis, ecological field surveys, public health data, and citizen science tools. Four pilot parks in Brescia—Parco Gallo, Parco Giffoni, Parco Croce Rossa, and Parco dei Poeti—were selected based on vegetation structure, accessibility, tree cover, and urban context. Around each park, 250m and 500m buffer zones were defined for spatial and socio-demographic analysis.

Each site was analysed using satellite and GIS-derived indicators such as Land Surface Temperature (LST), Sky View Factor (SVF), Tree Canopy Cover (TCC), Normalized Difference Vegetation Index (NDVI), and Normalized Difference Moisture Index (NDMI). These indicators were used to evaluate the ecological conditions and microclimatic performance of green spaces. Preliminary results show that parks with denser tree cover exhibited lower surface temperatures and higher NDMI values, suggesting better environmental conditions and reduced water stress.

To assess potential health correlations, aggregated epidemiological data from the Local Health Protection Agency (ATS Brescia) were analysed for residents within the buffer zones. Chronic disease prevalence, including cardiovascular and metabolic conditions, was compared to citywide averages using Standardized Prevalence Ratios (SPR). Although the project is still ongoing and most findings are not yet statistically significant, preliminary analyses suggest a potential trend: in some areas, such as the 500-meter buffer around Parco Giffoni, the prevalence of chronic diseases is up to 6% higher than the citywide average, potentially correlating with lower vegetation cover.

Sociodemographic analysis suggests possible health inequalities, as areas with a higher proportion of socioeconomically disadvantaged groups may exhibit both slightly lower vegetation indices and modestly elevated disease rates. For instance, in the area near Parco Gallo, the share of foreign residents (29.3%) exceeds the city average (19.9%), and some indicators point to lower ecological quality and slightly higher prevalence of chronic conditions—although not statistically significant.

In addition to quantitative analyses, the project incorporates community engagement through surveys and a discrete choice experiment involving 500 residents. This tool estimates the perceived value of urban ecosystem services and evaluates citizens' willingness to invest in specific biodiversity-oriented interventions. Preliminary findings from the survey indicate public interest in greener and healthier cities, with many participants—especially those living near more biodiverse parks—expressing a willingness to support biodiversity-oriented interventions.

These are preliminary elaborations based on the first phase of the project, which focused on spatial analysis, socio-demographic mapping, and health data integration. A second phase—currently ongoing—includes field

sampling of vegetation and soil biodiversity, and microbial and eco-physiological assessments, which will enable the definition of specific urban biodiversity indicators.
The expected outcomes of URBioPark include a replicable GIS-based model that combines ecological and health indicators to inform urban planning. Outputs will comprise a set of biodiversity metrics tailored to urban contexts, technical guidelines for municipalities, and strategic recommendations for integrating biodiversity into regulatory tools such as Strategic Environmental Assessment (SEA) and masterplans.
Ultimately, URBioPark aims to build a governance model that connects health, urban planning, and ecology, promoting equity, resilience, and environmental justice. By scaling this model to other urban areas, the project offers a blueprint for cities seeking to improve health outcomes through biodiversity-sensitive design and participatory planning practices.

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Topic B

Urban microclimate and outdoor spaces

Greenery systems for the improvement of outdoor comfort in urban built environment with artificial ground depression. A case study in Sicily

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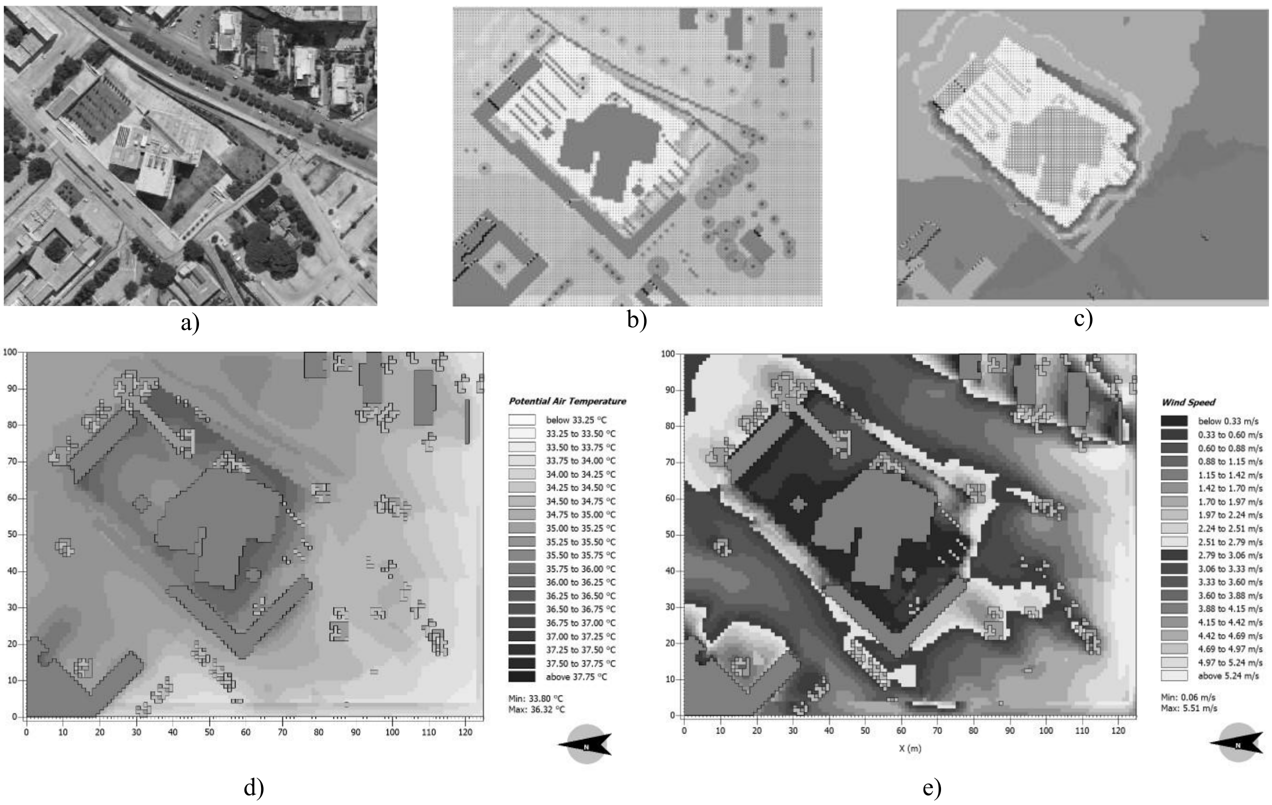
Highlights

- The terrain and buildings were modelled using high-resolution DTM and municipal shapefiles
- Baseline simulations confirmed critical thermal zones inside the ground depression
- Vegetation can further reduce wind speed in ground depression

Keywords

Greenery Systems; CFD Simulations; Artificial Ground Depression



a) aerial view of the analysed area at building scale; b) ENVI-met model with building and vegetation of scenario 1; c) ENVI-met model in which the darkest colours are the highest height of the terrain and the white ones area near to zero height. d) air temperature map of scenario 1 at 14:00 of 16 August; e) wind speed map of scenario 1 14:00 of 16 August

Introduction

Rising temperatures caused by climate change have pushed countries around the world to establish agreements aimed at reducing greenhouse gas emissions, encouraging sustainable forest management, and increasing the use of energy from renewable sources. To keep global warming below 1.5°C above pre-industrial levels, the Paris Agreement mandates that participating nations to review their national energy, and climate plans every five years. Recently, the United States of America officially withdrew from the Paris Agreement for the second time, a position that could alter the global political direction on efforts of reduce effects of climate change. To reduce greenhouse gas emissions and mitigate the effects of Urban Heat Islands, greenery systems can be implemented in urban contexts [1]. Greenery systems can improve both outdoor and indoor comfort within the built environment. Actually, he positive effects of greenery systems - such as trees, green corridors, green walls, and green roofs - have already been confirmed by several studies carried out in different climatic zones [1–5].

Methodology

A multi-scale methodology -already tested in another works - has been used to analyse a particular area located in the campus of the University of Palermo. To evaluate the thermofluidic process and the effects of greenery systems a well know CFD software (ENVI-met ®) has been used to analyse both microclimate urban scale and building scale [1], considering the specific climatic conditions (Csa a hot-summer Mediterranean climate according to the Köppen-Geiger classification). The analyses have been focused on the area of the Department of Architecture that consists in a main building located within an artificial ground depression at the lower point of 39 m above sea level (m.a.s.l.). It has four floors and totally its height reaches approximately 22 m. A secondary lower building is positioned along a side of the ground depression. It has two floors and totally its height reaches approximately 7 m. The streets outside the ground depression are between 47 and 51 m.a.s.l.
The weather data was obtained from the weather station of the University of Palermo located near the analysed area, inside the campus [6].
Based on the increasing trend of temperatures registered and published by Copernicus [7] this work used the available weather data of the 2024, instead of using an average weather data of a wider range of years than can usually goes from 5 to 10 years (as it can be found in literature). Simulations have been carried out considering 24 hours, by selecting the hottest and the coldest day of the year, which corresponded to 16 August 2024 and 24 December 2024. These weather data have been used as input for the urban scale simulations.
Urban scale simulations aimed to evaluate the effects of urban morphology by considering building surfaces, existing vegetation, and thermal and wind flows. The analysed area measures 500x500 m and it was modelled using a grid of 100x100x30 cells, with each cubic element measuring 10x10x5 m. The modelling process was carried out using the QGIS software, where it is possible to set up the area, the surfaces, the buildings, and the vegetation; the model has been exported by using ENVI-met plugin®. The terrain was modelled using the Digital Terrain Model (DTM) of the Sicily Region, which has a resolution of 1 m and derived from LIDAR scanning conducted in 2008 [8]. The buildings were modelled using open data shapefiles of the Municipality of Palermo to obtain building shapes and their heights [9]. Adjustments have been carried out to overcome inaccuracies found in the shapefiles The results obtained from these simulations - regarding air temperature, relative humidity, wind speed, and wind direction - were subsequently used as input data for the building scale simulations.
Building scale modelling was carried out over an area measuring 200x250 m, using a grid of 100x125x40 cells, with each element measuring 2x2x2 m. In front of the main entrance of the building there are cylindrical deciduous trees (Populus nigra). Based on the results of the baseline scenario, critical zones were identified, and three scenarios were proposed and evaluated to improve outdoor thermal comfort. In the first scenario, vegetation was enhanced with additional shrubs and trees. In the second scenario, artificial ponds were added. The third scenario considered a green wall installed on the façade of the lower building. A fourth scenario evaluated the condition in which the trees did not exist, as was in the past. This scenario was assessed to determine whether the introduction of these threes had a significant effect on comfort.

Results and discussion

The results obtained from the building scale simulations of the baseline scenario confirmed that the artificial ground depression contains several critical thermal zones. The lowest wind speeds were observed along the borders inside the artificial ground depression, and it also corresponded to the highest temperatures recorded in the baseline scenario. The peak temperature was registered at 14:00 (16 August 2024) in all scenarios. Several points were selected – along the area – to quantify and to assess the effects of each proposed intervention compared to the baseline.

Scenario 1, which involved enhancing vegetation, showed temperature reductions ranging from 0.05 °C to 0.4 °C, with the magnitude of reduction depending on the distance from the implemented vegetation.

Scenario 2, which included artificial ponds, demonstrated temperature reductions between 0.1 °C and 0.6 C, also varying with distance from the ponds.

As expected, Scenario 3, which implemented a green wall, registered the highest temperature reduction near the intervention area, although this reduction was not significant, ranging from 0.05 °C to 0.1 °C.

Scenario 4 has confirmed that the introduction of threes reduced the temperature ranging from 0.05 °C to 0.3°C.

The localized proposed interventions demonstrated that the beneficial effects on the improvement of the outdoor thermal comfort were limited. This is primarily due to the site's topography: the artificial ground depression negatively affects natural ventilation. In some zones of the area the wind speed is close to zero. Since the presence of vegetation usually reduces the wind speed, in the case of a ground depression area it can negatively affect zones located farther. Traditional greenery systems, such as those applied in this study, have not shown significant effects on improving outdoor comfort. Therefore, the sole traditional greenery interventions are not able to sufficiently improve outdoor comfort, and further strategies have to be considered in alternative or in a complementary way in order to enhance natural ventilation and mitigate the thermal conditions.

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Effectiveness of pocket green spaces within the built environment in Mediterranean historic city centers in improving urban microclimate: a case study in Rome

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Highlights

- Pocket Parks in historic city centers are considered towards heat stress reduction
- In field experiments are carried out to assess temperatures in parks and streets
- Cool materials, greenery, water and shade are effective to lower temperatures in PPs

Keywords

Pocket Parks; Historic City Center; Mediterranean Region; Greenery; Cool Materials

Pocket Parks along the path (1), (2) and (3) Colosseum, and (4) Via Eudossiana,; thermographic image (left) and corresponding plain image (right)

Introduction

Cities are facing increasingly exacerbated climate change-related challenges, such as more frequent and stronger heatwaves, as well as extreme pluvial events and droughts. While these challenges intensify, the exposure of urban population to such events grows, as the world population is increasingly moving towards cities.

With respect to heat stress, cities are already affected by Urban Heat Island Effect (UHIE) [1], which causes higher temperatures in urban areas as compared to suburban areas, up to around +10 °C. It has been demonstrated that the UHIE further increase the risk and frequency of heatwaves [2], demonstrating how heat stress in cities is a paramount challenge, especially in the Mediterranean Region.

Among the causes of UHIE, there are the accumulation of heat within the built components (roads, buildings) of cities, the reduction and modification in ventilation due to increased rugosity in cities, the anthropogenic heat release, and the reduced evapotranspiration from green and blue components that are increasingly lacking within neighborhoods [3]. With respect to the latter, soil sealing is increasing faster than population grows, thus reducing green areas, grass and trees, as well as water elements such as ponds, defined Nature-based solution (NBS), and negatively impacting the cycle of natural, permeable soil [4].

Big urban parks, constituting an effective NBS, are able to reduce urban temperatures, but are localized services that are not equally distributed in close proximity to each neighborhood, thus benefitting in an unequal manner urban population [5]. The advantages of NBS are not limited to the improvement of urban microclimate, but also deal with (i) humans' need for contact with nature, benefiting both physical and psychological health and wellbeing; (ii) contribution to pluvial runoff reduction and rainwater harvesting [6]; (iii) conservation of biodiversity in cities.

While medium- big-sized parks are difficult to insert in consolidated cities, historic city centers present even higher challenges in implementing more diffuse and distributed NBS that are enjoyable for all people. In this panorama, we propose to tap on the potential of pocket parks (PPs), i.e., small-sized parks that can be easily inserted within densely built urban areas, with different extent of complexity [7]. Such PPs have demonstrated to possess the capacity to slightly improve urban microclimate, while greatly improving overall comfort for their users [8,9], as well as also being able to reduce and manage pluvial runoff [10]. Previous studies focused on contexts where PPs are already well-developed, while are limited for historic urban areas. We aim to fill this gap and to respond to the following research question (RQ): are pocket parks effective in mitigating heat stress in historic city centers in the Mediterranean region?

Methodology

To respond to the RQ, we conduct in field experiment in a relevant and significant case study for historic city centers in the Mediterranean region, in this case considering Rome city center. We conducted, along a studied path that crosses several typologies of PPs, characterized by different materials and morphologies, two climate walks during summer 2024, in different times of the day (morning and afternoon). The studied path has been selected to account for the maximum crossing of NBS around the University Campus in the city center of Rome, favoring those smaller green areas that also provided views on the historic monuments. Along this path, we measured surface temperatures with a thermal camera and used a portable microclimate monitoring station to measure air temperature, solar radiation, relative humidity, wind speed and direction in the PPs and close by streets. The use of the two tools together allowed us to jointly measure microclimate features and analyze in depth the temperatures of urban surfaces, as the two are linked, thus allowing a deeper comprehension of the effect of different materials and construction elements, as well as NBS, on the microclimate.

Results

Results demonstrated that such PPs are able to mitigate heat stress if consciously designed. Indeed, the analysis shows the fundamental role of shading (either from trees or urban shades from buildings) in all the analyzed PPs (Figg. 1, 2, 3). Also the materials constituting the paving and the envelope of the buildings heavily impact temperatures, where cool materials (cool gravels) maintain lower temperatures than darker materials (such as sanpietrini or asphalt). Greenery shows to be effective especially under the form of trees, projecting shade, but also green grass proved effective in maintaining lower surface temperatures (-10°C) even with respect to cool materials (-5 °C).

Water elements within the parks also proved fundamental in reducing surface temperatures, thanks to water flowing (Fig. 3). Bare, dry soil or dry grass are ineffective in reducing temperatures, on the contrary they display high surface temperatures.

Conclusions

PPs demonstrated the capacity to provide small areas of respite from heat stress, even in very simple typologies (Fig. 4), when consciously designed with respect to surrounding urban morphology, materials, greenery choice and shade. Based on the above results, we contend that even in the historic city center it would be possible to include small PPs, in line with traditional materials and surrounding built environment, and also the view of surrounding historic heritage should be considered and emphasize to further tap on the beneficial effects of the integration of the small NBS within the historic context, highlighting not only the contact with nature but also the cultural identity of the location, and contributing to an enriching and diffuse comfort perception both physical and psychological.

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Recovery tools for particulate matter in traffic-dominated urban microclimates benefits human health, ecology and sustainability

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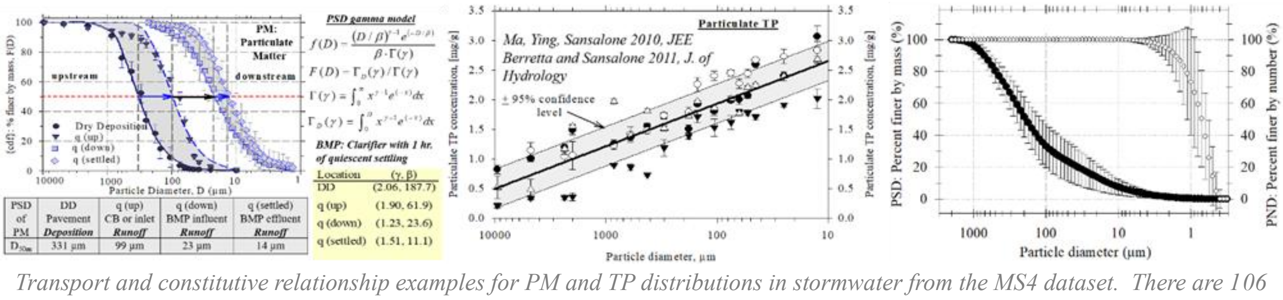
Highlights

- Urban microclimate PM/pollutants directly impact human health and comfort
- Maintenance recover far greater PM/pollutant loads than structural treatment
- Maintenance benefits to microclimates are economic, sustainable and ecological

Keywords

Urban Water; Cardiovascular Inflammation; Human Health; Particle Size Distribution (PSD); Pavement Cleaning



Transport and constitutive relationship examples for PM and TP distributions in stormwater from the MS4 dataset. There are 106 mm in 1.0 meters and [mg/g] is the mass of TP per dry mass of PM. The PSD is modelled as a cumulative gamma (G) distribution function (cdf) which is a physically-based two-parameter model where g and b are the shape and scaling parameters of the model and x is the increment of particle size (diameter). The shape parameter represents the size-heterodispersivity and the scaling parameter represents an index of the median size tendency of the PSD

Introduction

An uncomfortable legacy for constructed urban environments is that urban drainage (rainfall-runoff) transports greater annual loads of particulate matter (PM), metals, organics and chemical oxygen demand (COD) than untreated domestic wastewater discharges from the human population of that same urban environment [1]. Yet, that legacy is chronic and has intensified with increasing urban traffic, pavement area and urban populations. This legacy has further expanded to include heat island effects [2], endocrine disrupting compounds (EDCs) and micro-plastics which are now ubiquitous in the urban near-surface atmosphere and in urban drainage. PM is the major source and sink of these chemicals. Within urban microclimate and ecology that humans have constructed and now dominates, these impacts, particularly driven by the interaction of vehicular traffic and impervious pavement generate spatially distributed loads of reactive and mobile PM and chemicals that have direct effects on human health and the comfort of outdoor spaces. Structural treatment systems such as "best management practices" (BMPs) receiving point loadings have not mitigated these loads and are not economically or ecologically sustainable.

In contrast, implementation of maintenance tools to recover traffic-generated PM, debris, litter, plastics and chemicals, before these constituents interact with urban drainage generated from impervious pavement surfaces, significantly reduces pollutant loads that impair urban microclimates and urban receiving waters. In short, *maintenance matters* and quantifying load recovery from maintenance tools and activities is beneficial for all human and ecological stakeholders. Furthermore, maintenance practices are one to two orders of magnitude more economical than structural treatment systems. The hypothesis that maintenance matters is quantifiable. While this knowledge may be considered controversial or "outside-the-box" of conventional practices, the knowledge and database given herein represents a defensible, generalizable and implementable foundation to build the allocation of load reduction credits based on quantifiable maintenance operations for any municipality and urban microclimate. These maintenance practices/tools/operations remove accreted PM that includes gross solids (detritus), litter, and associated chemicals from the urban microclimate inventory. This PM is transported to, thru, or stored in urban drainage management system networks [3]. This PM is a source and sink of chemicals that result from the interaction and imposition of anthropogenic/biogenic activities and urban infrastructure design practices/materials on the hydrologic cycle. This study illustrates a Florida-based metric for PM, total nitrogen (TN) and total phosphorus (TP) which are highly regulated in Florida and can serve as indices for the transport or recovery of metals. This study was designed to provide load credits to municipalities for quantifiable maintenance practices and is used in their regulatory basin management action plans (BMAPs) for nutrients and PM.

Methodology

To establish nutrient loads and the credits for quantifiable recovery, fourteen (14) MS4s (municipal separate storm sewer systems) across Florida actively participated in the creation of a knowledge base of PM inventory within or on urban hydrologic functional units (HFUs) across Florida. For each of eleven (11) MS4s, PM samples were obtained under conditions where there was no known reclaimed wastewater impacting the HFUs and land use locations of the samples. Samples were "granular" particulate-phase with a particle size distribution (PSD) ranging from clay-size to gravel and included biogenic solids and urban detritus as shown later in Figure 1. Moisture content varied as a function of HFU and sampling location. For the 11 MS4s twenty-seven (27) samples from three hydrologic functional units (HFU) were obtained. HFUs consisted of a planned variety of BMPs most frequently maintained by the MS4, paved area street sweepings (SS), and cleaning of catch basins (CBs). HFUs were sampled for three land uses: highway (H), commercial (C) and residential (R). For each sampling matrix category, three independent locations were utilized. In the remaining three MS4s, the same matrix of 27 samples was also taken as well as 27 paired samples from inside areas where reclaimed water was used. In total, four hundred and fifty-nine (459) samples were recovered and analyzed for nutrients. Data and subsequent results were developed and categorized in terms of HFU and land use for nitrogen (N, as total nitrogen: TN), phosphorus (P, as total phosphorus: TP) and PM. Samples taken by each MS4 were transported to the University of Florida (UF) laboratories, in coolers and with a chain-of-custody. Samples remained refrigerated until analyses were conducted. Detailed methods are presented elsewhere [4].

Results and Discussion

Table 1 summarizes Florida-based results; results consistently indicates that the metrics of TN and TP are log-normally distributed. This observation is important for allocation of load credits by Florida to MS4s because the results are not represented by a singular concentration [mg/dry kg of PM] but by log-normal distributions.

Table 1. Florida-based PM phosphorus and nitrogen concentration mean, median and standard deviation values for each HFU, independent of land use. The underlying frequency distributions are not shown for brevity

	TP [mg/kg]			TN [mg/kg]		
	Mean	**Median**	**St. Dev.**	**Mean**	**Median**	**St. Dev.**
Street Sweeping (SS)	512.5	361.0	599.9	1012.2	563.0	1422.2
Catch Basin (CB)	552.2	416.8	481.8	1729.1	679.1	2601.6
BMP	647.1	363.9	728.9	2648.1	898.5	3983.1

A goal of this study was also to quantify the valorization of urban PM recovery for the purpose of nutrient management through the comparison of maintenance practices in comparison to common and standard urban structural treatment systems. The economic analysis and full dataset cannot be captured in this extended abstract but is detailed elsewhere [4] Raje and Sansalone 2022. A comparison of the costs ($/lb) for BMPs and maintenance practices are shown in Table 2.

Chemicals partition to and distribute across a PSD. Therefore, physical-chemical constituent relationships for PM transport, partitioning/distribution of TP (as an illustration) and particle size distribution (PSD) vs. particle number distribution (PND) are illustrated in Figure 1. The left plot illustrates the change in the PSD from traffic-generated dry deposition of PM from the interaction of tires and pavement, vehicular part abrasion and exhaust PM noting that the coarser PM that remains on the pavement and is not transported in traffic-generated turbulence or runoff is abraded by traffic to finer mobile and bio-available $PM_{2.5}$. The center plot illustrates the gravimetric relationship between TP and PM particle size – if PM particle size can be tracked in a numerical model, the fate of TP can be (and is) assessed. The right plot provides both gravimetric (PSD) and number distributions of PM noting that the number distribution of particles is dominated by $PM_{2.5}$ and smaller.

Table 2. Comparison of structural BMPs vs. maintenance costs ($/lb) for PM, TP and TN. For BMPs, separation and recovery are required, while only recovery is required for maintenance practices

Separation and/or Recovery Method	Median Cost ($/lb)		
	TN	**TP**	**PM**
BMP Treatment Train (structural)	935	32,600	26
FL Database for BMPs (structural BMPs)	1,900	10,500	41
Screened Hydrodynamic Separator (structural)	3,730 (1,280 - 14,860)	9,210 (3,170 - 36,680)	4 (1 - 13)
Baffled Hydrodynamic Separator (structural)	3,020 (1,280 - 14,860)	7,450 (3,170 - 36,680)	3 (1 - 13)
Street Sweeping (maintenance)	165	257	0.10
Catch Basin Cleaning (maintenance)	1,016	1,656	0.70

PM not recovered from pavement sweeping is eventually abraded towards $PM_{2.5}$. Chronic human inhalation of traffic-generated PM in urban outdoor (and indoor spaces) spaces (such as outdoor dining and pedestrian walking/cycling/running – providing recreation and comfort) proximate to motor vehicle movement has been shown to impact cardiovascular inflammation and oxidative stress, increased blood pressure, atherosclerosis, plaque instability, arrhythmias, blood clotting and worsening heart failure [5].

Conclusions and future work:

With respect to the costs of recovery for PM, TP or TN, Table 2 illustrates the economy of tools such as street sweeping as compared to other maintenance practices but in particular to structural BMPs. Results of this study as illustrated in Table 2 indicate that street sweeping (cleaning) practices using a variety of existing technologies across Florida is significantly more economical than BMPs for PM, TP and TN. These technologies are also used throughout Italy but load recovery is not quantified, nor load credits provided for any contaminant to the best knowledge of the authors. The non-sustainable cost of BMPs to provide the equivalent load credits can be discerned from the results in Table 2. Results of this study are currently used across the State of Florida to provide load credits for nutrients that amount to tens of millions of USD annually for Florida MS4s. Future research is needed to examine the optimization of maintenance practices for load recovery given the significant potential of modern computational and machine learning tools to further optimize maintenance practices. The framework of this study can be readily extended to other urban contaminants with the appropriate databases. While load recovery by maintenance does not obviate the need for hydrologic/hydraulic management by hydrologic control systems, load recovery by street sweeping upstream of such systems benefits these systems and receiving water since the loads do not have to be subsequently recovered. In conclusion, common maintenance tools to recover PM from traffic-dominated urban microclimates benefits human health, ecology and sustainability

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Light in urban parks: balancing humans' needs, nature's health, and sustainability goals

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Highlights

- Intermediate CCTs and light levels enhance urban park appeal and safety sense
- Proper spectral power distribution must be selected to preserve ecosystems
- Using innovative smart systems reduces energy consumption and light pollution

Keywords

Lighting In Urban Parks; Ecosystem Preservation; Light Pollution Reduction; Intrusive Lighting; Citizens' Safety And Security.

Dos and don'ts in the lighting design for urban parks

Introduction

The growth of global population, coupled with increasingly dense urbanisation, presents a significant challenge to environmental sustainability and human well-being. Air and water contamination, noise and light pollution rise as urban centres expand to accommodate a growing populace. Moreover, being accustomed to living indoors for almost the whole day, people lose connection with nature, consequently suffering from increased levels of stress and depression, reduced immune defences, and loss of creativity and cognitive abilities. Nature-Based Solutions are a promising approach in response to these pressing problems and are currently implemented at various scales within a city, from the micro-level of individual buildings (e.g., green roofs and walls) to the macro-level of urban landscapes (e.g., urban parks).

In particular, urban parks create pleasant views in contrast to drab concrete and brick surfaces, sequester carbon, and reduce the urban heat island effect, contributing to climate change adaptation and mitigation [1]. Green areas in cities also enhance biodiversity and provide spaces for recreation and social cohesion, contributing to reconstituting the crucial human-nature connection.

In this context, light is fundamental. It shapes the appearance of urban parks during nighttime, making the space visible and driving its use after sunset; it helps in guaranteeing public security; it affects people's perception, influencing their psychological state. However, it can also have negative impacts, generally referred to as light pollution.

The goal of this contribution is to highlight benefits of good lighting in urban parks, and possible negative impacts due to poor design. The analysis is performed by discussing the results of previous relevant studies, finally driving simple design suggestions.

Benefits of good lighting

Lighting guarantees park visibility at night. For this reason, the choice of light levels and light patterns is essential. It should consider the space typology, the activities that can be carried out in the park during nighttime, and possible users' specific needs, to create inclusive environments. In this respect, Lis et al. [2] found that while able-bodied individuals prioritise path lighting over surrounding lighting, wheelchair-bound people consider well-illuminated surroundings critical for safety, allowing them to see potential threats earlier.

Moreover, lighting is fundamental for public security. Indeed, proper illumination helps prevent accidents by making obstacles, uneven surfaces, steps, and other potential hazards clearly visible, reducing the risk of trips, falls, and collisions. In addition, good visibility makes it harder for potential criminals to operate, as they are more likely to be seen by other people or surveillance cameras, reducing the risk of aggression, theft, and vandalism.

Lighting also defines the aesthetic quality of the space, influencing people's psychological state. For example, research [3] found that correlated color temperature (CCT) equal to 6500 K and high light levels (illuminance around 10 lx) are associated with nervousness, while CCT equal to 2500 K and high light levels make people less motivated to explore the park. Overall, CCT equal to 4500 K and intermediate light levels (illuminance around 6 lx) are associated with positive feelings, while low light levels (illuminance around 2 lx) negatively influence safety perception. Indeed, people naturally feel more vulnerable in dark areas, while light instils a sense of security and comfort, encouraging people to use urban parks even during the night [4].

Negative effects of improper lighting

Light can have negative effects, i.e., light pollution, caused by excessive and improper use of artificial light at night. It manifests in many forms, reported below.

Skyglow is due to light sent upward and scattered in the atmosphere, which results in the typical haze that prevents people from seeing stars.

Intrusive light occurs when sources are designed and placed such that light falls where it is not intended or needed, for example, inside private houses. This effect can be risky for people, leading to the disruption of the natural circadian rhythm, i.e., the numerous processes, including hormone production and sleep-wake cycles, that regulate physiological and behavioural aspects over a roughly 24-hour cycle. Prolonged or consistent exposure to intrusive electric light during night hours has been linked to a range of more severe health outcomes. Indeed, improper light exposure can cause metabolic disorders, sleep disturbances, reduced sleep quality, increased sleep onset latency, and consequently excessive sleepiness, fatigue, and impaired cognitive

functions during daytime, compromised immune function, and an increased susceptibility to mood disorders, including anxiety and depression [5].
Similarly, animals' and plants' behavioural disorders can occur because of excessive and poorly designed electric lighting. It can: Cause disorientation in migratory birds, increasing the risk of collisions and reducing migration amplitude; affect plant germination, growth, flowering, tissue repair, leaf retention, and bud break; influence how organisms select their habitats, with some species avoiding illuminated areas and others being attracted, in turn disrupting interactions between animals and plants (e.g., pollination and seed dispersal) crucial for ecosystem services and the food supply chain [6]. The lighting factors affecting living beings' responses are several (timing of light exposure, spatial pattern, intensity), but the spectral power distribution (SPD) is surely crucial. For example, Rodriguez et al. [7] underlined that lamp technology and spectrum affect the mortality and fatality rate of some bird species, and registered a mortality rate equal to 47%, 29% and 24% for metal halide, LED, and high-pressure sodium lamps, respectively. Brehm et al. [8] revealed that many moths were attracted by light sources characterized by higher energy concentration in short wavelengths. Cashmore et al. [9] found that the plant phytochromes system is more sensitive to long wavelengths in the visible field (660 nm - 720 nm), whereas the animal phototropin and cryptochromes are more sensitive to ultraviolet radiation.

Design suggestions

Based on the above observations, light for urban parks must be designed according to the following criteria, schematically represented in the figure:

1. Guaranteeing human safety, appraisal, and wellness

Light levels and CCT should ensure adequate visibility without appearing too bright or creating uncomfortable atmospheres. Intermediate light levels and CCT balance safety, security, and appreciation of the space. Additionally, since vegetation can shade luminaires and reduce light levels, lighting fixture placement should be designed in coordination with greenery.

2. Controlling skyglow and intrusive lighting

The choice of luminaires' photometry is fundamental to preventing skyglow and intrusive lighting. In this sense, the use of full cutoff luminaires avoids light from spilling upwards into the night sky and entering private spaces.

3. Preserving the ecosystem

Lighting systems should be conceived considering all the ecological players, not only humans. Ideally, ad-hoc spectra not harmful for people, animals, and plants could be designed using multichannel LEDs. However, this is a tricky challenge since the spectral sensitivity to radiation varies among living species. Time by time, it would be necessary a deep analysis to identify the proper lighting conditions to safeguard the specific ecosystem. In this line, the concept of "light ecological function zoning" is interesting. It consists in classifying green areas according to the similarities and differences of living species to limit negative effects on them. This design concept was adopted in the planning and design of lighting in the Zhaomushan Forest Park in Chongqing, where the entire park was divided into three areas (lighting area, lighting control area and prohibited lighting area) according to both the distribution of ecological resources and visual needs, each lit based on different criteria [6].

Moreover, besides these considerations, the energy costs for urban park lighting must not be neglected. Surely, energy-efficient sources, like LEDs, allow for reducing energy consumption and carbon emissions and provide high flexibility in terms of control and regulation. Moreover, smart adaptive systems are crucial to optimise energy use; they allow adjusting light output according to use and occupancy, considering traffic due to pedestrians, cyclists, cars, and public means of transportation. They use microcontrollers, sensors, dimmers, and remote modules to connect all the street luminaires in a grid, efficiently managing them, collecting environmental data, detecting possible problems to improve management activities, and tracking consumption. Another valuable energy-saving option is to power lighting systems through renewable energies. In [10] it is demonstrated that in urban parks, they can provide several services (charging small electronics, production of hot water, heating, and cooling), including lighting, thanks to different design approaches, ranging from the use of solar-powered LEDs to the integration of photovoltaics in urban furniture, to provide electricity used to power lighting fixtures.

Conclusions

Developing proper lighting for urban parks is a complex challenge that must balance human needs and environmental preservation. Although pioneering projects, such as the Zhaomushan Forest Park in Chongqing (China), the Pineda Platja in Vila-seca (Spain), the Nallibaana Route in Oulu (Finland), and the Smart City in Lonato del Garda (Italy), demonstrate that it is possible to integrate ecological considerations into lighting design, these examples are still limited. Therefore, this article has stressed benefits of good lighting and possible negative impacts due to poor design, since it is essential to raise public awareness on the topic to drive the necessary behavioural and policy changes that will lead to widespread and informed strategies for the design and management of urban park lighting.

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Integrating climate adaptation and heritage values in Aachen: a climate-legibility assessment for historic urban areas

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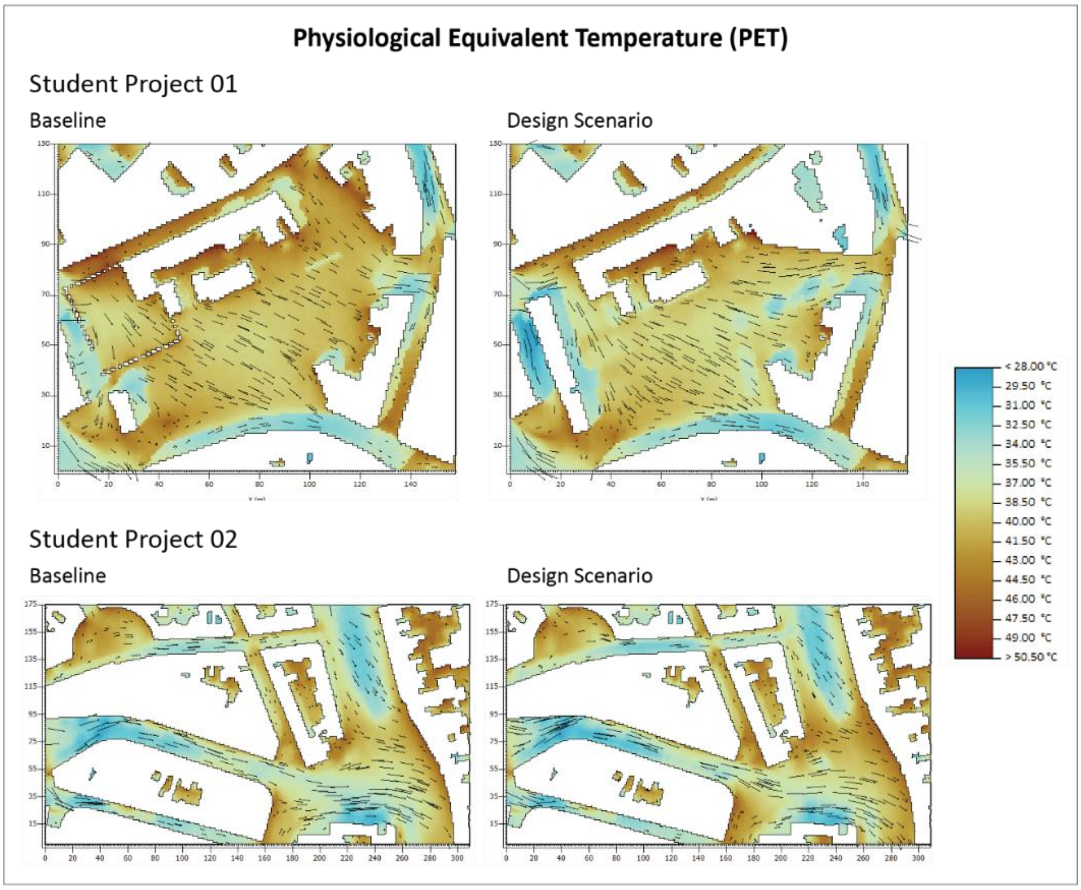
Highlights

- Framework bridges climate design with urban heritage preservation
- Six urban legibility dimensions assess spatially anchored heritage
- ENVI-met modelling applied to the urban heritage context

Keywords

Urban Legibility; Envi-Met; Blue-Green Infrastructure; Nature-Based Solutions; Climate Adaptation



PET Results of Student Projects

Historic and heritage-rich urban areas are particularly vulnerable to the effects of climate change and increasingly frequent natural disasters. This is not only due to the inherent fragility of their traditional urban fabric, but also because the historical layouts and materials in these areas may become functionally obsolete under new climatic conditions, demanding substantial investment to address climate-related issues [1]. Traditional city centres often exhibit dense layouts of stone, brick, and paving materials that store heat, while narrow streets limit airflow. Scarce vegetation exacerbates thermal stress, leading to high daytime heat and slow nighttime cooling. Rising global temperatures intensify these effects, posing risks to heritage assets and to public health, particularly for elderly residents and tourists unaccustomed to extreme heat. In pedestrian areas of historic city centres, high heat levels can result in heat exhaustion, diminished outdoor activity, and a decline in life quality during summer months.

Maintaining thermal comfort in heritage areas is essential not only for health and safety but also for conserving sociocultural vitality. Historic squares, markets, and streets are important public realms where community and cultural heritage are expressed. Favourable outdoor microclimates attract people and sustain vibrancy, while poor thermal conditions deter use. Yet, preservation efforts have often prioritized aesthetics and building protection over climate adaptation [2]. This imbalance is beginning to shift as cities recognize the need for microclimatic interventions in heritage context.

Nature-based solutions (NBS) and blue-green infrastructure have emerged as key strategies for climate adaptation. However, their implementation in historic districts presents unique challenges. Space for new greenery is limited, and modifications must respect heritage regulations and aesthetics. Interventions may face resistance if perceived as intrusive to cherished vistas [3] or architectural coherence. An assessment of NBS in the urban heritage context[4] identified two weaknesses: a lack of scientific guidance tailored to heritage contexts and underdeveloped tools for quantitatively assessing performance in historic settings. Consequently, city authorities often struggle to measure the benefits of adaptation, leading to cautious or minimal action [5]. However, projects suggest that with careful planning, NBS can harmonize with heritage preservation, provided that environmental functionality and cultural significance are balanced [4].

A core principle advocated by ICOMOS is that adaptation efforts must consider heritage values[6]. The European Union's adaptation strategy further stresses the importance of "smarter adaptation" by 2050[7], relying on robust data and advanced modelling tools, such as ENVI-met microclimate models. Built on that, this research investigates how climate adaptation strategies can be integrated into historic and heritage-rich urban areas to improve human thermal comfort while preserving spatial legibility. The central question is how interventions interact with historic morphology and how success can be evaluated in both climatic and heritage terms. The study develops a framework combining qualitative and quantitative approaches: (a) a legibility-based analysis of spatially anchored urban heritage and (b) microclimate modelling using the Physiologically Equivalent Temperature (PET) as the key indicator. The methodology proposes the assessment of six legibility dimensions derived from Lynch (1960)[8]: Urban morphology (street patterns, block forms, spatial layout); Architectural character and built fabric (styles, materials, coherence); Landmarks and monuments (anchors of orientation and identity); Spatial setting (open spaces, natural features, framing context); Functional and social identity (land use, cultural practices, activities); and Historical continuity and temporal layers (visible traces of past periods).

Together, these six dimensions define how a place "tells its story" through space [8]. In this initial phase, the analysis is conducted from a normative expert perspective, drawing on Lynch's legibility criteria and expert guidance on urban heritage preservation [1,6,9]. These sources provide criteria for assessing the relevance of spatial elements in historic environments and are used as a basis for evaluating the compatibility of climate adaptation strategies with the preservation of urban legibility.

The evaluation is made by the application of the following legibility thresholds to case studies: Preservation Essential (continuity required), Preservation Preferred (minimal change), Adaptive Flexibility (selective transformation permitted), Transformation Welcome (reimagining encouraged), and Open for Reconfiguration (reinvention tolerated). Design outcomes are classified as Enhanced, Stable, Fragmented, or Lost depending on alignment with thresholds. The objective is to achieve Stable or Enhanced legibility. This method highlights that in historic and heritage-rich urban spaces, not all legibility dimensions carry equal preservation imperatives; some demand continuity, while others can accommodate change. For planners, this provides a structured way to balance adaptation with cultural identity.

On the quantitative side, ENVI-met simulations are used to assess adaptation measures under a typical hot summer day scenario. PET is applied as the key indicator of outdoor thermal comfort. Successful outcomes are defined as achieving PET ≤34 °C or a reduction ≥4 °C compared to baseline in at least 60% of grid points for public spaces, and at least 50% of grid points for pedestrian nodes. Along main routes, a mean PET reduction of ≥2 °C is targeted. PET 34 °C represents the upper bound of moderate heat stress, so staying below this value or achieving a 4 °C drop indicates substantial improvement.

To operationalize the framework, the historic city of Aachen, Germany, was selected, as it clearly illustrates the challenge of advancing climate adaptation while safeguarding a deeply layered historic fabric. The city's form and identity developed over two millennia in a shallow basin, the "Aachener Talkessel," carved by brooks (small springs) and hot springs that sustained its historic bath culture. Although many buildings were lost during World War II, the Roman orthogonal grid, the Carolingian axis, and medieval radial routes remain legible, despite some post-war widening and realignment. The city's high degree of sealed surfaces, dense building masses, and narrow street canyons, features that were either retained or exacerbated by post-1950 redevelopment decisions prioritizing traffic infrastructure, coupled with brooks confined to culverts between 1820 and 1908 [10], collectively intensify climate risks.

In Summer 2025, as part of the UROP program (Undergraduate Research Opportunities Program) at RWTH Aachen University, two visiting students from the University of Waterloo developed conceptual adaptation design projects for areas within Aachen's historic city centre and used ENVI-met models for microclimate analysis (fig. 01). These projects were used to illustrate the application of the framework:

- Student Project 01 – Büchel Area: An empty block was redesigned as a biodiversity meadow with new trees, gardens, and infill. Dimensions open to change (architecture, social identity, spatial setting) were transformed, while historical continuity was maintained. Simulations showed localized cooling (PET reduction >4 °C) but still reaching 35 °C, and path/node targets were unmet.
- Student Project 02 – Kaiserplatz Area: Measures such as permeable paving, raingardens, bioswales, and stream daylighting enhanced legibility in water heritage and spatial setting. However, no node or path targets were met in simulations.

The results indicate that successful adaptation in heritage areas requires aligning interventions with dimensions open for change while intensifying cooling at key nodes and paths. Preservation alone is insufficient: adaptation must deliver both legibility resonance and tangible thermal benefits.

The proposed integrated method for linking spatial legibility analysis with microclimate modelling offers a novel framework for evaluating climate adaptation in historic districts. It enables planners to assess how adaptation strategies align with heritage-spatial contexts and to balance heritage continuity with climate adaptation. By bridging climate-responsive design and legibility preservation, the research demonstrates that preserving the past should not conflict with preparing for the future.

While the current research phase operationalizes the framework, future work should expand perspectives through the inclusion of residents, visitors and tourists on the legibility analysis, and expand the framework to include aspects from diverse cities. Furthermore, adjusting PET thresholds for other climate zones will allow broader applicability. Ultimately, this research seeks to contribute to the development of tools for designing adaptation strategies that keep historic urban areas both legible and liveable, as well as support in the planning process of such spaces.

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A decision support system to promote effective solutions for climate change adaptation and energy saving in urban open spaces

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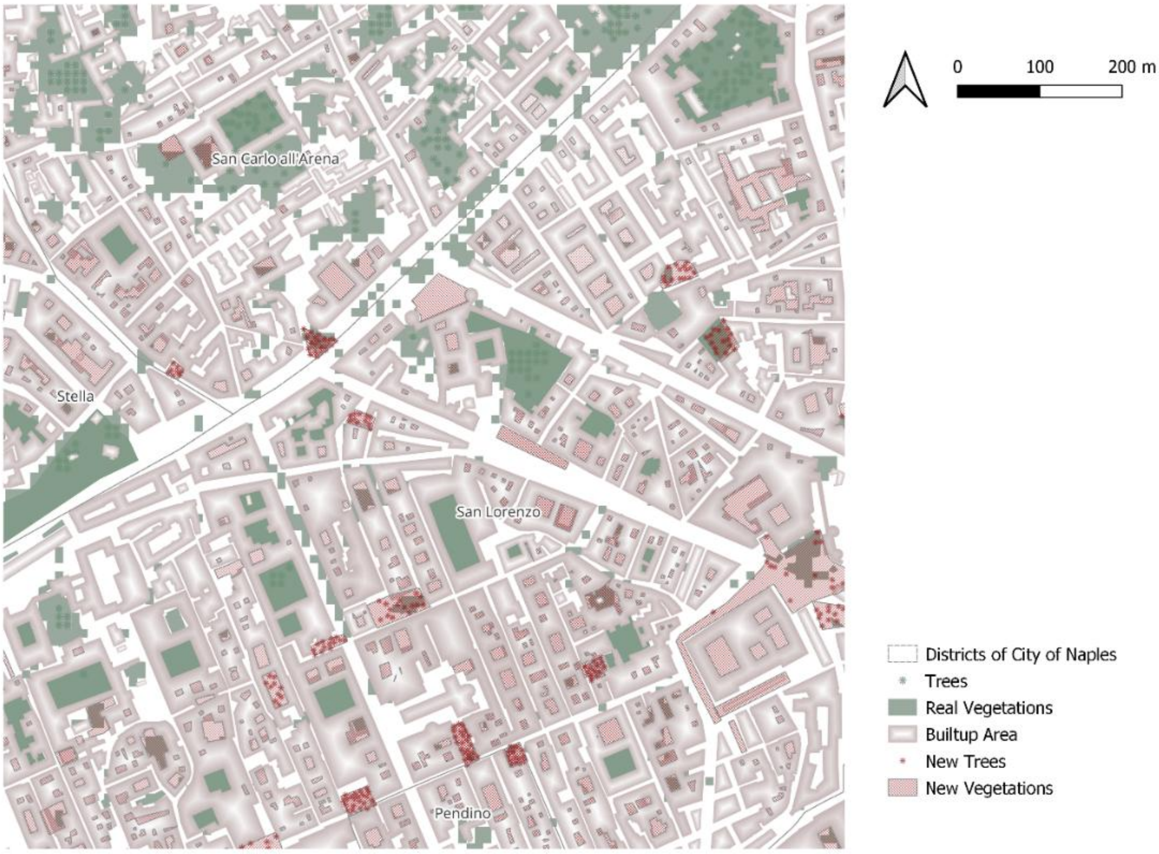
Highlights

- Measuring air temperature reduction due to open space greening
- Classifying urban fabrics based on urban and micro-climate characteristics
- Defining climate change adaptation interventions for urban open spaces

Keywords

Urban Planning; Climate Change Adaptation; Energy Consumption; Green Open Spaces; Microclimatic Simulation.



Real Scenario and Priority Scenario

Cities have been facing increasingly complex challenges related to the frequency of heat waves and the growing energy demand for space cooling, due to the intensifying effects of climate change. In this context, green open spaces represent one of the most effective strategies for urban adaptation, contributing to microclimate regulation and reducing energy consumption too. The scientific literature has developed numerous methodologies to quantify the impact of green and blue areas on the urban microclimate, making extensive use of simulation software such as ENVI-met, SOLWEIG and RayMan, often integrated with GIS tools [1-2]. ENVI-met is the most widely used software for detailed simulations, due to its capability to construct three-dimensional grids at a high-resolution scale and incorporate advanced vegetation parameters. Compared to other tools, ENVI-met stands out for its ability to model complex environments and variable conditions, while RayMan is faster but less accurate, and SOLWEIG is more suitable for large open spaces [2]. Furthermore, the use of biometeorological indices such as UTCI, PET and PAT allows for the assessment of perceived thermal comfort [3].

Thanks to its computational abilities, ENVI-met allowed us to simulate climate change adaptation interventions at the urban scale, by measuring the amount and the extent of the microclimatic benefits deriving from their implementation and depending on the relationships between the urban context and the open spaces. In fact, the main goal of this work is to provide local policy-makers with a set of greening transformations of open spaces (built and unbuilt) that efficiently improve thermo-hygrometric conditions (temperature reduction) of high-densely built cities and contribute to the reduction of energy consumption, based on the nexus between urban characteristics (physical, functional, socio-economic, micro-climatic) and open space features. Planting new trees, increasing the water and the permeable surfaces within squares, courtyards, parking areas, and also along streets, are among the suggested interventions that result in raising efficiently the thermal comfort of open spaces and their stratified urban context surroundings [4]. The work is part of a national research project “Definition of a guidelines handbook to implement climate neutrality by improving ecosystem service effectiveness in rural and urban areas” CUP E53D23018970001 funded by EU in the NextGenerationEU Plan through the Italian “Bando Prin 2022-D.D. 1409 del 14-09-2022”.

The last version 5.7.1 of ENVI-met is used, as it introduces important innovations compared to previous versions, including an updated interface and direct integration with QGIS, facilitating the spatial analysis, and elaborates the numerous input data also at urban scale that, at the best knowledge of the authors, lacks in experimental studies.

The methodology is based on interconnected phases providing knowledge and operational outputs:

1. The classification of the different parts of the city based on the interactions between the physical, socio-economic, micro-climatic and geomorphological characteristics of the urban contexts where open spaces are located and these last ones;
2. the building of a database to collect and compare international case studies of climate change adaptation interventions;
3. the definition of the layers and simulation grid dimension to be integrated into the ENVI-met model by QGIS;
4. the definition of micro-climate simulation scenarios according to the different urban contexts where open spaces are located and the possible greening interventions to implement;
5. the analysis and interpretation of the results.

It is worth noting that one of the most demanding steps is the definition of the spatial resolution of the grid. After an initial test at 3x3x3 meters (length, width and height of each cell of the simulation grid), which would have allowed a high level of detail but was impractical for the entire urban area due to excessive calculation times, a resolution of 99x99x3 meters has been chosen. This choice can represent an acceptable compromise because the primary objective of this work is to measure the thermal interactions between the different urban assets where open spaces are distributed and the micro-climate, to propose suitable greening interventions. Furthermore, the application to a large scale, like the urban one, represents an innovation in this kind of study that has required particular attention to balance computational time with the accuracy and utility of the output. We detail the procedure for defining an appropriate grid resolution that is coarse enough to be computationally feasible for a large domain, yet fine enough to capture the critical interactions between urban surfaces, vegetation, and the micro-climate.

Once the dimensional and resolution specifications of the simulation area are defined, a sensitivity analysis is performed to quantify the potential of urban greening interventions (Figure 1). By comparing the current state

scenario with an optimal one where all available open spaces were converted to green areas, we were able to measure the full extent of microclimatic improvements. This approach serves as a crucial benchmark, establishing the maximum possible mitigation effect of green infrastructure at the city scale. The results of this analysis validate the effectiveness of our proposed strategies, providing urban planners with data on the potential thermal benefits, helping to prioritize interventions in the most sensitive areas.
The applications is developed in the city of Naples (southern Italy), due to its high building density, reduced presence of urban greenery, vulnerability to extreme summer heat phenomena, and its morphological complexity. If on one side the urban characteristics have been easily collected from consolidated national and international databases (i.e. ISTAT for socio-economic data, Urban Atlas for land uses), on the other side the meteorological data have been retrieved from the historical archive of ilMeteo.it, chosen for its accessibility and the possibility of quickly obtaining time series for the day selected as representative. July 31, 2024, identified as the hottest day of the year, with a reference time set at 2:00 p.m., has minimum and maximum air temperatures of 25 °C and 34 °C, respectively, and relative humidity values ranging from a minimum of 20% to a maximum of 74%. This kind of data allows to test the methodology, intending to integrate more accurate data in next studies. The duration of the simulation is set at six hours, covering the middle of the day.
About other setting simulation parameters, it is worth noting that the 3D vegetation introduced is represented using ENVI-met library parameters of type 01SLSM (spherical tree, medium, sparse canopy, diameter of 15 m), while surfaces were simulated as lawn or permeable paving, with predefined static values.
About simulated scenarios, the baseline scenario based on the city's current state is built by using municipal layers and satellite data to map the distribution of trees, courtyards, and both permeable and impermeable surfaces. The optimal scenario envisions a comprehensive transformation where all open spaces larger than 55m² are converted into permeable surfaces with 50 cm high grass, and new trees are planted in squares. This represents a full-scale greening effort across the entire city. In contrast, the priority scenario focuses on more targeted interventions in specific areas identified as having high thermal and social vulnerability. These zones were pinpointed using a priority index calculated from data in the PAESC (Economic Impact of Flooding, Hospitalization Costs for Heat-Related Illnesses, Heatwave Mortality Rate) and energy consumption data.
By comparing the outcomes, our results demonstrate that the effects of the optimal case (the city-wide greening transformation) are significantly more efficient than those achieved by only addressing priority areas. This underscores the need for a holistic greening strategy that extends throughout the entire city, rather than being limited to just a few key locations. The Potential Air Temperature in the best-case scenario is reduced by up to 0.9 °C; the PET shows localized decreases of up to –5 °C in central neighborhoods such as Pendino and San Lorenzo; the UTCI shows an average decrease of –1.5 °C; and the Mean Radiant Temperature shows significant decreases, even exceeding –10 °C, in squares and streets where new trees are planted. While a reduction of less than one degree in PAT may seem negligible, it should be noted that it occurs on the hottest day and at the hottest time of the year and on an urban scale: such an improvement has significant implications for perceived comfort, for reducing the heat waves' health risks and for limiting energy consumption.
These results should be interpreted cautiously and considering some limitations. ENVI-met is mainly designed for building-scale analysis and applying it to the municipal scale of Naples naturally raises methodological questions. Nevertheless, the work has demonstrated that even at a broad level, the model can produce plausible differences aligned with international literature, which reports PET reductions of between -3 °C and -7 °C in scenarios of widespread afforestation [5]. The outputs verify the validity of the proposed greening measures at the urban scale and offer urban planners practical guidelines for lowering air temperatures and promoting energy saving, based on interactions between urban features and open space characteristics.
Future studies can address the analysis of smaller districts with finer resolutions, integrating certified meteorological data, extending the duration of simulations, and including detailed parameters on materials, albedo, and tree species.

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Evaluating climate regulation benefits and social perception of an urban park in northern Italy

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Highlights

- Qualitative and quantitative approaches to evaluate the benefits provided by a park
- simulation of different design scenarios that provide microclimatic regulation
- Assessment's results provide useful results for guiding future design choices

Keywords

Microclimate Regulation; Temperature Measurements; Thermal Comfort; Ecosystem Services Assessment; Social Perceptions

Study area – Raster (1x1m) of the 4 land cover scenarios for F. Parri Park and photos taken during the site visit (June 2025)

The high concentration of people living in urban areas is increasingly exposed to the urban heat island (UHI) effect, caused by the excess heat stored and later released by the built environment. Interventions aimed at containing and mitigating this phenomenon are essential to make urban areas more liveable. Renaturalizing portions of land, designing public spaces with tree planting, removing impervious surfaces, and increasing green areas are all planning actions that significantly contribute to the reduction of UHI, improving microclimatic comfort conditions in urban spaces [1.2].
The concept of nature-based solutions (NBSs) encompasses a wide range of interventions for the management, conservation, restoration, and sustainable use of natural, modified, or constructed ecosystems. These solutions can address one or more challenges of contemporary urban systems thanks to the benefits provided by ecosystem services. Restoring biodiversity, reducing the heat island effect, improving air and water quality, and mitigating flooding due to extreme weather events are just a few of the ecological benefits that can be achieved through the integration of green-blue infrastructures and NBSs [3]. Understanding and quantifying the benefits of microclimate regulation ecosystem services, developing different project scenarios, and comparing the distribution of benefits to support the environment and communities represent a fundamental phase in planning processes. This allows for the identification of design alternatives that maximize benefits for local communities.
This contribution combines several qualitative and quantitative approaches to assess the benefits offered by a specific nature-based solution (NBS), an urban park, both for the environment and for the community that uses the area. The case study presented is Ferruccio Parri Park in Cuneo, chosen for its design that takes hydrological processes into account: a previously buried water source has been reopened and an open channel feeds a surface-flow wetland. An infiltration trench regulates the runoff from rainwater, which is conveyed to an underground storage tank. The water can be reused to irrigate the park's vegetation, which features various species of shrubs, shade trees, fruit trees and open lawns, chosen for their climatic adaptability, growth rate and and maintenance needs.
From a methodological perspective, after identifying the case study, the research combines various qualitative and quantitative methods to assess the benefits provided by the park. Microclimatic benefits were evaluated through a fine-scale application of the InVEST Urban Cooling model, which simulates the contribution of vegetation and water to temperature reduction. Four transformation scenarios of the area were compared.
The first scenario refers to the area before the park's construction, characterized by extensive unmanaged grassland. The second scenario represents the design phase, including the planting of vegetation. The project also includes two blue infrastructure elements: one with fountains and water play features, and another more naturalistic, a 920 m² pond with hydrophilic vegetation. The third scenario simulates the park ten years after planting, with mature vegetation. Finally, the fourth scenario hypothesizes a pond surface twice as large as the actual design, to consider specifically, the contribution of evaporation from waterbodies on temperatures reduction.

Results from InVEST Urban Cooling model, empirical measurements and social perception
The temperature data simulated by the model Invest Urban Cooling were compared with the actual temperature data recorded during the days of 21 and 22 June 2025. Temperature, relative humidity, dew point, wet bulb and absolute humidity data were recorded with a thermos-hygrometer (Testo 605I) for three-time intervals: 8-9 a.m., 2-3 p.m., 7-8 p.m. Data were collected at three points within the park, near the lake, under the dense tree canopy and on a well-watered and maintained lawn. A measurement was made in a highly impermeable area outside the park. The measurements were carried out in shaded conditions, and the instrument was placed at 15 cm from the ground surface, to measure the data close to the surfaces by subjecting the instrument to similar conditions for all measurements. The temperature data measured in band 14-15 were compared with temperature data simulated with the Invest Urban Cooling model. The model simulates temperatures for different land covers from a user-built land use land cover raster. The model requires other input data such as evapotranspiration, albedo, crop coefficient that the user must indicate for each land cover class [4]. The model also requires reference temperatures in the urban area, and in the suburban area, to consider the intensity of the urban heat island, given by the difference between the two temperatures. For the Parri Park in Cuneo, the temperatures refer to the maxima recorded in June 2024 by two stations of the Arpa Piemonte meteorological network, the Dronero station for temperature in the rural area and the Cuneo cascina Vecchia station for the urban area [5].

The table below collects the data measured and simulated by the InVEST model:

Land cover class	Time	Temperature 25/06/21	Temperature 25/06/22	InVEST simulated temperature June 2020
Point near water	13:57	30.4	29.3	30.01
Grassland	14:02	33	29.8	30.01
Shadow	14:15	27.3	26.6	29.99
Urbanised area	14:37	32.3	32.5	30.12

The temperatures measured by the invest model compared to those measured in the field are flattened and overestimated especially for the natural surfaces, e.g. the temperature *"shadow"* measured by the model is 29.99 C° with an average deviation of more than 3 degrees, compared to the temperatures measured in shade on 21 and 22 June. The simulated temperature *"point near the water"* is unchanged compared to that simulated for *"grassland"* 30.01 C°, while the real measured temperatures show significant microclimatic differences between the temperatures measured at different points in the park, highlighting the contribution of the water in reducing the temperature, phenomenon recorded on both day of measurement campaign. The only case in which the model shows good consistency with the measured data is *"urbanisation area"*, where the simulated temperature exceeds 30 C°, in accordance with what was observed in the field measurement, with temperatures of 32.3 and 32.5 C°. In general, the model simplifies the microclimate of the park by underestimating the real mitigation effects of the different surfaces, permeable, vegetation cover and water. The simulated delta of variation is only 0.10°, flattening the values of the different land cover classes to minimal and almost negligible differences. In contrast, the in-situ measurements show substantial temperature differences between the various surfaces, testifying to the complexity of the park's microclimate.

In addition to the quantitative evaluation, the methodology also includes a qualitative component, in order to understand the benefits perceived by the community, surveys, semi-structured interviews, viewpoints, and perceptions regarding the transformed space and perceived temperature within the park were collected. Questionnaires were administered to park users during the measurement campaigns to obtain user perceptions consistent with the recorded climate data, twenty are the people that answered at the digital survey made on ArcGIS survey 123.

The survey aims to gather the views and opinions of park users on two main topics: the perceived microclimate and sensations experienced by users within the park, and the role of water in providing benefits and the perception of the natural pond. Sixty-eight percent of participants perceive the park as cooler, breezier, and more comfortable climatically than the surrounding urbanised areas, but in general, there is a lack of shade. In fact, 53% say that there is less shade within the park than in the surrounding urbanised areas, 36% say there is more, and 10% say there is the same amount. Currently, the trees are not at their maximum growth, so the shade generated by the new plantings is not dense and compact. This is reflected in the responses of those who say that there is less shade inside the park than in the surrounding areas characterized by the presence of mature trees. Furthermore, the most shaded area is the north-west of the park, bordering the road and cycle path, where a row of existing trees, together with the recently planted ones, generate dense and uniform shade. Regard to the second macro-theme of the survey, 58% of users stated that the presence of the pond in the park is quite pleasant, and 79% of respondents would have liked to see a larger body of water. The 90% of users stated that the pond can be beneficial to people or the environment. Among the benefits listed, the most recognized by respondents were aesthetic, cultural, recreational, and psychological well-being (17 respondents), followed by increased biodiversity (13 respondents), microclimate regulation (6 respondents), and water regulation (2 respondents). Each user could select one or more benefits.

The combination of qualitative and quantitative assessment provides useful results for guiding future design choices at both the project and urban scale. Interventions relating to the park could be aimed at planting more trees in order to increase tree density where possible, while pergolas and temporary structures could be designed for the paths most exposed to the sun while waiting for the existing trees to grow. Considering the morphology of the park area and the presence of a water source, the creation of another wetland could be considered. These interventions would improve the microclimatic performance of the park, in line with the opinions and preferences of the community.

Acknowledgements
This research was developed as part of the project "Nature for sustainable cities: planning cost-effective and just solutions for urban issues", PRIN 2022, funded by European Union, Next Generation EU.

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Enhancing urban ecosystem service assessment through a vegetation structure index

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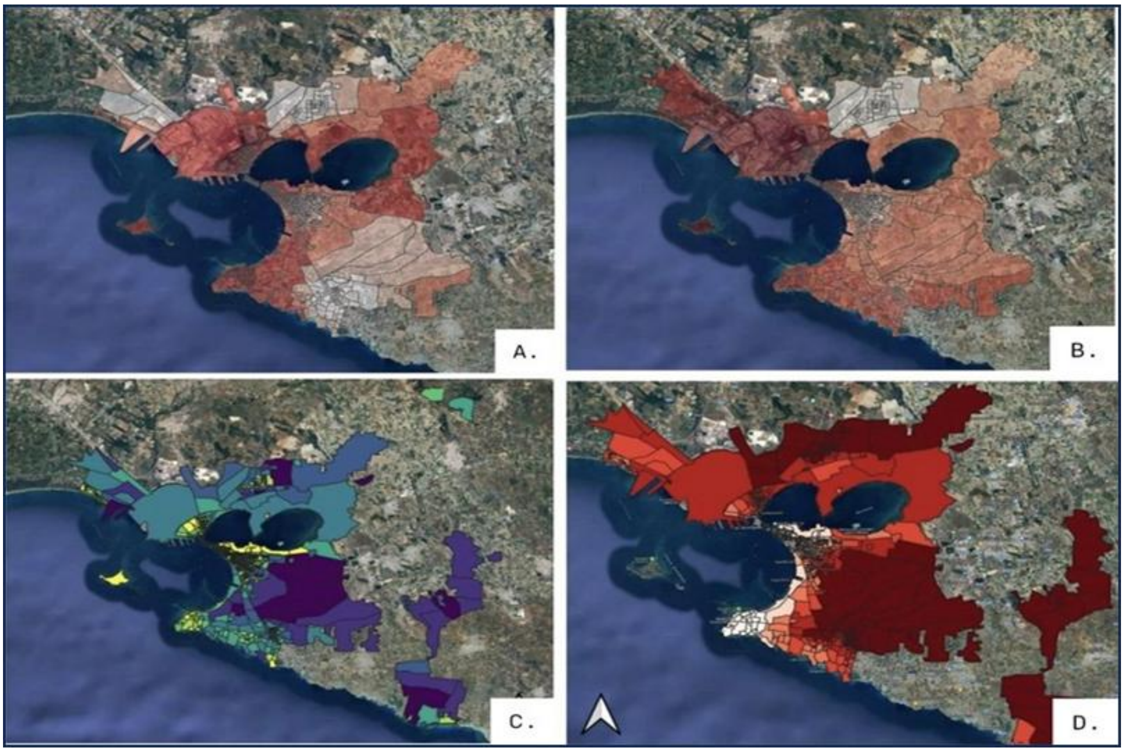
Highlights

- A new index estimates green volume using satellite-calibrated LiDAR data
- Structural vegetation metrics support better ecosystem service assessments
- Applicable in Mediterranean cities where LiDAR is not always available

Keywords

Urban Vegetation; Ecosystem Services; Lidar; Remote Sensing; Green Infrastructure



Comparison of spatial indicators in the urban area of Taranto (Italy); A. PM2.5 concentration map; B. PM10 concentration map; C. Canopy Height Model (CHM) derived from LiDAR; D. Land Surface Temperature (LST); The maps illustrate spatial relationships between air quality, vegetation structure, and urban heat, supporting the need for volumetric green assessment in ecosystem service modeling.

The increasing focus on urban green infrastructure is becoming essential for tackling climate change, enhancing environmental quality, and boosting public health. This growing interest has sparked a deeper look into how we monitor, map, and evaluate these crucial green spaces. Urban vegetation offers a plethora of ecosystem services, such as regulating temperature, capturing carbon, filtering air pollutants, reducing noise, and even improving mental health. These benefits are closely tied to the three-dimensional structure of the vegetation itself. Factors such as canopy height, density, and biomass not only play a role in ecological functions but also greatly affect how urban residents experience the advantages of green infrastructure, influencing their comfort, air quality, and overall well-being. It is vital for urban planners, architects, engineers, and policymakers to integrate the concept of urban forests into their strategies to foster sustainable cities.

Even though the ecological significance of these three-dimensional features is clear, traditional assessments of urban vegetation often rely on two-dimensional spectral indicators, especially the Normalized Difference Vegetation Index (NDVI), derived from high-resolution satellite images. While these indices are popular for their ease of use and accessibility, they often struggle to differentiate between vegetated areas with distinct functional traits, such as grasslands, shrubs, and tree canopies. This oversight can lead to inaccuracies in mapping urban green spaces and evaluating the ecosystem services they provide, resulting in overestimations or underestimations.

Recently, airborne LiDAR (Light Detection and Ranging) has become a game-changer for accurately analyzing the vertical structure of vegetation. By generating detailed 3D point clouds, LiDAR gives researchers an opportunity to explore urban greenery in ways that traditional methods cannot match.

LiDAR datasets create intricate 3D point clouds that help derive important metrics, such as canopy height models (CHMs), vegetation density, and biomass proxies. However, access to LiDAR data remains a challenge due to high acquisition costs, the need for specialized processing, and the irregular nature of data collection efforts. As a result, many urban areas, especially those with limited resources or data availability, continue to depend primarily on satellite data.

This study seeks to bridge that crucial data accessibility gap by introducing a method for creating a synthetic vegetation structure index. The index is derived from satellite spectral data and statistically calibrated with high-resolution LiDAR measurements. The aim is to enhance the estimation of volumetric vegetation properties, ultimately enabling more reliable and spatially explicit assessments of ecosystem services in urban settings where LiDAR data are not easily accessible. This approach is especially relevant for Mediterranean urban areas, where the combination of dense built environments, sparse vegetation, and high climate stress presents unique challenges for ecological planning and climate adaptation.

This research is based on the assumption that vegetation structural characteristics, although not directly measurable through satellite imagery, can be inferred through the combined analysis of spectral indices, contextual land cover information, and statistical modeling. Satellite-derived variables such as NDVI, EVI (Enhanced Vegetation Index), GNDVI (Green NDVI), and spectral bands in the red, green, and near-infrared ranges serve as predictors in a model trained using LiDAR-derived metrics. Through spatial alignment of datasets and the use of statistically representative sampling units (e.g., grid cells or vegetated patches), regression models or machine learning algorithms are developed to approximate structural indicators such as average canopy height, vegetation volume, and biomass density.

To ensure methodological robustness, the model is initially developed and calibrated in a Mediterranean urban area for which recent LiDAR data and high-resolution satellite imagery are available. Validation is then conducted by applying the model to a second urban area, using historical LiDAR data and satellite images from the same time period. This dual application allows for testing the model's generalizability in both temporal and spatial dimensions, as well as performing sensitivity analyses related to urban morphology, vegetation type, and data resolution. The resulting synthetic index offers a scalable and transferable solution, suitable for integration into urban monitoring platforms, GIS-based planning tools, and environmental impact assessment workflows.

This research extends beyond the technical domain by engaging with broader issues such as urban justice, environmental equity, and the digital representation of space. While the index does not directly estimate socio-economic disparities, it provides spatially explicit indicators of vegetation structure whose uneven distribution often mirrors socio-economic patterns, such as differential exposure to heat, pollution, and access to restorative environments. In this way, the index offers an environmental perspective that can be integrated with socio-demographic data in interdisciplinary analyses.

Additionally, this synthetic index significantly contributes to how we interpret and design digital representations of urban nature. Unlike traditional vegetation indices that focus mainly on quantity, this tool introduces a qualitative perspective based on the spatial arrangement of greenery. In this way, the index functions not only as a measurement tool but also as a representational strategy, helping to reveal the often-overlooked vertical aspects of urban green spaces and making them more understandable to planners, designers, and decision-makers.

From a practical standpoint, the synthetic index serves as a bridge between high-precision remote sensing and everyday urban analysis. It is designed as a cost-effective and replicable method that has been calibrated in one Mediterranean city and validated in a second, using temporally matched LiDAR and satellite datasets. Its application could support several areas of urban planning, including climate resilience strategies, environmental justice assessments, landscape architecture, and public health initiatives.

In summary, the synthetic vegetation structure index marks a significant step forward in the three-dimensional analysis of urban green spaces. It provides an accessible and precise tool for incorporating the functional aspects of vegetation into assessment and planning processes, supporting urban strategies that prioritize sustainability, equity, and resilience.

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When solar meets green: toward resilient, sustainable, and smart urban landscapes

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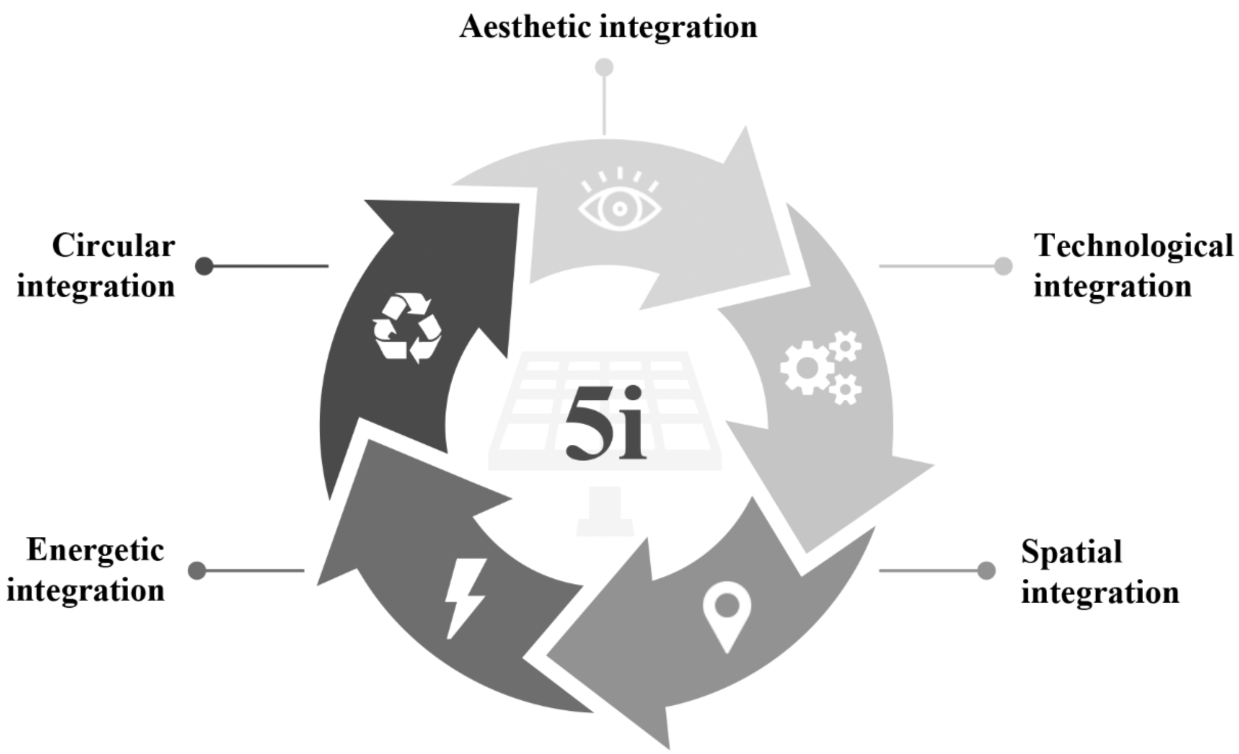
Highlights

- Integration of PV systems and NBS for resilient and sustainable cities
- A multidimensional evaluation framework based on 5 key dimensions is proposed
- PV technology and urban greenery are not antagonistic but synergistic allies

Keywords

Integrated Photovoltaics (IPV); Nature-Based Solutions (NBS); Urban Sustainability; Synergy Nature–PV Technology; Energy Efficiency.



The five "i" dimensions of smart photovoltaic integration

Introduction

Contemporary cities face intertwined environmental, social, and energy-related challenges of critical complexity. Accelerated urbanization, indiscriminate land consumption, surface impermeabilization, and population concentration strongly affect both urban quality and inhabitants' well-being. Urban areas are among the environmental systems with the highest climate impact, with visible consequences such as rising urban temperatures (heat island effect), deteriorating air quality, biodiversity loss, and increasing extreme weather events [1]. In response to these challenges, Nature-Based Solutions (NBS) are emerging as fundamental design and strategic tools for ecological and resilient urban regeneration. The NBS concept is grounded in the use of solutions inspired by natural processes to address environmental challenges while enhancing health, social cohesion, and quality of life [2]. Urban greening interventions, green infrastructure, green roofs and walls, and urban agriculture are examples of how vegetation can help mitigate the effects of climate change by promoting natural cooling, CO_2 absorption, stormwater management, and air pollution reduction [3].

However, alongside these approaches, another critical challenge is the high energy demand of the building sector [4]. Achieving the ecological transition and climate neutrality by 2050 requires a radical transformation of the existing building stock. In this context, photovoltaic (PV) technologies represent a strategic driver for energy self-sufficiency, distributed generation, and electrification of consumption. Nonetheless, these technologies are often perceived as incompatible with urban greenery, seen by part of the public as visually intrusive elements that disrupt both the built and natural landscapes [5]. Ground-mounted PV parks are frequently criticized for their visual impact and extensive land use [6]. This apparent dichotomy between technology and nature risks hindering the adoption of integrated strategies, whereas a systemic and multidisciplinary vision holds the key to overcoming this impasse. A rethinking of design logics is thus required: coordinated approaches must integrate greening and renewable energy interventions as complementary components of a new urban ecology, where energy efficiency, microclimatic comfort, and biodiversity coexist synergistically. Within the landscape of solar technologies, Integrated Photovoltaics (IPV) is gaining relevance. Building-Integrated Photovoltaics (BIPV) replace building envelope components (roofs, façades, external elements), providing energy generation alongside protective, aesthetic, and structural functions [7]. This transforms sun-exposed building surfaces into a sustainable energy source, avoids further land consumption, and improves landscape acceptance, even in sensitive contexts [8]. Alongside BIPV, other IPV applications include photovoltaic urban furniture (canopies, bus stops, solar charging stations for electric vehicles) and agrivoltaics (APV), which reconcile energy production with land conservation. APV represents a beneficial coexistence between photovoltaics and vegetation, offering shading, microclimate regulation, reduced evapotranspiration, protection from extreme weather, and biodiversity restoration [9]. In peri-urban and urban areas, this approach can regenerate degraded fringes and enable sustainable landscapes.

This study explores the synergistic potential of NBS and photovoltaic technologies, focusing on IPV, and emphasizes how context-aware integration can foster sustainable, resilient, high-quality urban environments. Table 1 compares NBS solutions, conventional PV solutions, and integrated NBS-IPV strategies, underscoring the added value of multidisciplinary approaches across performance categories.

Table 1. Comparison of NBS-only, conventional PV-only, and synergistic interventions

Intervention type	**Performance levels**			
	CO_2 reduction	**Microclimatic comfort**	**Energy production**	**Aesthetic value**
NBS	High	High	None	High
PV	Medium	Low	High	Low
NBS + IPV	High	High	High	High

In this light, a photovoltaic integration model is proposed, based on five key dimensions—aesthetic, technological, spatial, energetic, and circular—to guide the design and planning of harmonious interactions between nature and technology. The underlying vision is one of dynamic balance, where greenery and photovoltaics not only coexist but mutually enhance one another.

Methodology

This study combines a review of scientific literature with selected case studies to explore and assess the potential of IPV and NBS within contemporary urban contexts. Unlike conventional PV, IPV systems are defined by specific boundary conditions and installation types, requiring high-quality design that integrates technological, aesthetic, and contextual aspects. However, the literature still lacks contributions offering a unified vision of all these factors for design purposes [10]. The study promotes a holistic approach over the prevailing reductionist tendency to analyze aspects or issues in isolation, which risks underutilizing the potential of IPV and leading to suboptimal results. To address this gap in knowledge, a multidimensional assessment framework has been developed, structured around five domains of integration: aesthetic, technological, spatial, energetic, circular. Each dimension encompasses qualitative criteria and corresponding assessment methods that support the harmonization of photovoltaic systems with the urban context, contributing to an operational and holistic model for design purposes. The proposed five-dimensional model (5i), illustrated in Figure 1 and formalized in Table 2, constitutes an original interpretative framework for guiding integrated interventions through an interdisciplinary, sustainability-oriented approach.

Table 2. The five dimensions of integration (5i) with qualitative criteria and corresponding assessment methods and indicators

Dimension	Qualitative criteria/Key aspects	Assessment methods and measurable indicators
Aesthetic integration	Harmonization with architecture and landscape, visual appeal, social acceptance	Visual impact, heritage compatibility, skyline impact, color/texture matching
Technological integration	Compatibility with technical and regulatory requirements of the host context	Compliance with fire and wind performance standards, mechanical resistance tests, waterproofing and ventilation certifications
Spatial integration	Multifunctionality, accessibility, synergy with NBS	Land-use efficiency, density of functions, spatial distribution, green space ratio, building typology and PV system configuration
Energetic integration	Contribution to energy self-sufficiency, adaptability	Annual energy yield, specific yield, performance ratio, demand coverage, CO_2 avoided
Circular integration	Evaluation over the full life cycle in a circular economy perspective	Life Cycle Assessment and Life Cycle Costing Analysis (life cycle-based indicators), Circularity Assessment (circularity indicators)

The proposed indicators—intended as illustrative examples and not exhaustive—combine standardized, widely recognized metrics with evaluation methodologies employed in architectural and landscape studies. While the latter are not always strictly numerical, they represent established approaches for assessing qualitative dimensions. This reflects both the multidisciplinary nature of the 5i framework and the current state of the literature, where some dimensions remain less codified in quantitative terms than others.

Results and Discussion

To ensure photovoltaics are not perceived as alien elements in the urban context but recognized as valuable resources, it is necessary to adopt best practices guiding their integration across five key dimensions (5i):

1. Aesthetic integration: concerns the visual and perceptual quality of the photovoltaic system, ensuring harmony with architectural language and context. This can be achieved through colored, semi-transparent, or custom-textured modules and patterns referencing local elements. Assessment must consider both building and urban landscape scales, including visibility, impact on built heritage, and the skyline.
2. Technological integration: refers to technical and regulatory compatibility between the photovoltaic system and the host context—be it a building, greenhouse, urban furniture, or urban garden. It involves selecting components (modules, substructures, inverters, wiring, etc.) that ensure mechanical resistance, appropriate fire and wind behavior, waterproofing, ventilation, maintainability, and other performance requirements. A technologically integrated system does not compromise the performance of the host context but rather enhances its functionality and quality.
3. Spatial integration: relates to placement and configuration of the photovoltaic system in relation to form, function, and morphology of the surrounding context. Depending on the building typology (residential, commercial, industrial), integration may occur at the base, main volume, upper termination, or roof. At the broader urban scale, PV can be incorporated into furniture, gardens, and greenhouses, fostering synergies with NBS and multifunctional spaces.
4. Energetic integration: evaluates system energy performance by optimizing orientation, tilt angle, shading, ventilation, and cell technology. Well-designed systems maximize output and energy self-sufficiency. In agrivoltaics, elevated and angled panels can both produce electricity and support crop growth by lowering soil temperature and reducing water demand.
5. Circular integration: assesses systems from a life-cycle and circular economy perspective. This involves selecting recyclable materials, implementing design strategies for disassembly, managing end-of-life

components intelligently, minimizing waste, and utilizing methods such as LCA, LCCA, and CA. The adoption of life cycle-based and circularity-based indicators enables the evaluation of impacts throughout the system's life cycle, encouraging more sustainable and responsible design choices.

As introduced in Table 2 and elaborated in this section, the 5i constitute a structured framework. Although conceptually established, it still requires empirical validation through real-world case studies. Addressing this gap demands a paradigm shift in design thinking, moving away from sequential, specialized approaches toward a multidisciplinary and synergistic model in which architects, engineers, agronomists, urban planners, and designers collaborate from the earliest stages. Only through a shared vision can adopted solutions simultaneously meet multiple requirements.

Conclusions

The integration of photovoltaic technologies with NBS represents one of the most ambitious and promising challenges for the sustainable design of future cities. As demonstrated, photovoltaics and greenery are not competing systems but complementary tools that, if designed and implemented in a coordinated and context-sensitive manner, can jointly advance the energy transition and ecological regeneration of urban environments. The proposed 5i framework—encompassing aesthetic, technological, spatial, energetic, and circular dimensions—provides a structured, operational tool for design practice. It enables the systematic evaluation of trade-offs and synergies between renewable energy systems and green infrastructure, supporting decisions that address multiple performance criteria. By offering a multidimensional perspective, the framework overcomes the limits of single-aspect evaluations and enhances the capacity to deliver context-aware, high-performance interventions. At an urban scale, the 5i model can guide interventions that optimize energy efficiency, microclimatic comfort, biodiversity, and aesthetic integration, serving as a reference for regeneration policies and planning strategies. While currently conceptual, its application in full-scale projects and pilot studies could enhance integrated planning and demonstrate the practical value of combining NBS and IPV. Translating this vision into widespread practice requires enhanced interdisciplinary collaboration—across architecture, engineering, agronomy, landscape design, and environmental sciences—and investment in experimentation, thereby enabling urban transformation aligned with European climate neutrality goals.

Ultimately, the 5i framework offers a pathway toward smart, resilient, and sustainable cities, where technological innovation and NBS coexist synergistically, addressing environmental challenges while fostering livable, high-quality urban environments.

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Designing for well-being: a multi-disciplinary framework for urban regeneration through biophilia and community engagement

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Highlights

- Embodied sensory experience in urban greenery fosters well-being
- The biophilic approach creates resilient, healthy and poetic environments
- The active City-Nature community strengthens social bonds and belonging

Keywords

Biophilic Urbanism, Restorative Cities, Community Engagement, Sensoriality, Co-Design

Sensory design experiences in Matera (Source: Urban Green Shapes)

Introduction

Accelerated and often unplanned global urbanization has led to densely populated cities vulnerable to a growing range of risks, including pollution and climate, health, and social crises. In this context, urban resilience emerges as a strategic imperative, demanding innovative approaches that transcend traditional infrastructural solutions. This work explores the transformative role of integrating nature into urban environments, proposing design strategies based on sensory design, biophilia, and biophilic design to contribute to the creation of inclusive atmospheres and resilient, healthy, and livable cities. Within a multidisciplinary theoretical framework, we argue how participatory design, environmental psychology, and communication are fundamental pillars for constructing social innovation projects centered on holistic and sustainable urban resilience. The experience cited is that of "URGES, Urban Green Shapes," completed in Matera at the end of 2024, where the authors were responsible for the participatory design unit.
The relationship between humans and nature is profound, as postulated by Edward O. Wilson's biophilia hypothesis (1984) [1], which describes an innate human tendency to connect with life and vital processes. This connection, often eroded in urban settings, is crucial for psychophysical well-being. Biophilic design, developed by Stephen Kellert [2], translates this hypothesis into principles applicable to the design of built spaces. It's not merely about adding greenery, but about meaningfully integrating natural elements and processes, thereby improving health and social connectivity [3]. Biophilic urbanism and the concept of green cities serve as paradigms for rethinking the city not just as a place of coexistence between humans and nature, but as an integrated ecosystem where nature is essential. This approach, updated and integrated into the conceptualization of restorative cities [4], is not a luxury but a necessity for addressing urban resilience challenges. Research has shown that exposure to nature reduces stress, improves cognitive functions, and promotes health recovery processes, highlighting the potential of biophilic design as a therapeutic and preventive tool in urban planning.

Integrating Design and Environmental Psychological Approaches

Climate change is causing severe consequences for human health, both physical and mental, leading to the emergence of new forms of psychological distress. These include solastalgia, an anguish that affects those who witness the degradation of their living environment caused by environmental disaster, and eco-anxiety, a chronic psychological distress resulting from concern for the environment's future and impending ecological threats.
Therefore, a key emerging theme is the mitigation of eco-anxiety and the improvement of quality of life through green (and blue) solutions. Simple exposure to nature has been shown to reduce cortisol levels (the stress hormone) and improve heart rate variability, indicating physiological relaxation. Ulrich's Stress Reduction Theory (SRT) (1983) proposes that nature induces positive affective responses and reduces physiological stress activation [5], while Kaplan and Kaplan's Attention Restoration Theory (ART) (1989) suggests that natural environments facilitate recovery from mental fatigue and enhance attentional capacity [6]. These mechanisms provide foundational knowledge for designers, empowering them to create projects and atmospheres that counteract eco-anxiety, fostering a deeper connection with a broader, more resilient environment.
The presence of nature in cities improves air and water quality, enriches daily experience, and offers opportunities for play, socialization, learning, and sensory contact. Groups of trees planted in high-density residential areas attract more people to green spaces, encourage social interactions crucial for personal and collective well-being, and promote physical activity. From a mental health perspective, nature improves mood and cognitive function. In disadvantaged communities, the presence of common outdoor spaces contributes to social cohesion, and the perceived quantity of open space and vegetation is associated with lower crime rates and a greater sense of safety.
Thus, designers are called upon to trigger virtuous mechanisms for creating atmospheres of well-being and participation, starting from the sensory experiences they can design for residents and for their immersion in a city-nature.

Participatory practices in the URGES project in Matera

Nature-Based Solutions (NBS) are "solutions that are inspired and supported by nature, which use or enhance natural features and processes to address social, economic and environmental challenges in an efficient and adaptive manner, providing multiple benefits" [7]. In urban contexts, NBS, such as green roofs, green walls, urban parks, rain gardens, and urban forests, offer a myriad of benefits. The "dose of nature" required for these restorative and instorative benefits is an active area of research, but it's clear that even brief exposures can have significant positive effects [8].

The URGES (Urban Green Shapes) project was precisely such a project, studying a wide range of factors from heat island mitigation and reduction of domestic energy consumption to stormwater management and fostering a sense of community belonging. Funded by POR FESR Basilicata 14-20, URGES implemented a pilot prototype of vertical and horizontal greening forms on a public housing building in Matera. The authors of this contribution co-designed a series of workshops, "Poetically Inhabiting the City", to facilitate resident participation and engage them in discussions to imagine a community that would later adopt the developing green area. Green solutions cannot be top-down impositions; their effectiveness and resilience depend on the acceptance, care, and appropriation by local communities [9]. Involving citizens in the design and management phases of urban green spaces is a matter of social justice and a pragmatic strategy to ensure their durability and functionality. The methodology for the URGES project was based on a bottom-up approach, creating a multidisciplinary process. This integrated the expertise of various professionals—architects, engineers, agronomists, and environmental psychologists—with the active participation of residents and stakeholders. The initial phase involved a preliminary analysis to explore the context and collect both qualitative and quantitative data. This was followed by a central phase of community activation and engagement, which was facilitated by the "Poetically Inhabiting the City" workshops. During the subsequent co-design phase, the contributions from citizens were translated by the design team into concrete proposals, such as the extension of green spaces on horizontal surfaces.

In the URGES process, participants experimented with perceptual positions different from the ordinary, meaning they experienced the world with all their senses. This involved itineraries composed of neighborhood walks and performative artistic activities, moments of poetic reflection, and sensory games—for example, by foregoing the visual channel (with blindfolds) and activating other senses like hearing and smell (fig. 1). There were also field visits during which small groups of residents guided experts through areas of interest, bringing forth stories, questions, reflections, and perceptions. Neighborhood and building block parties were also organized. Furthermore, interviews with key figures were conducted to compile a mosaic of perspectives and information, along with focus groups and meetings with administrations, designers, and UNIBAS faculty-researchers and foreign partners. Communities with strong social ties and a shared sense of place are better equipped to face shocks and stresses, both environmental and social, and to recover more quickly. Valuing local traditions and narratives linked to green spaces can strengthen the sense of belonging, transforming simple green spaces into meaningful and vital places for urban life and reinforcing place attachment [10].

The project is now in an evaluation and monitoring phase to verify its effectiveness and use. The main results of this process were both tangible and intangible. Tangible results included concrete green infrastructure proposals and the creation of new central hubs within the neighborhood. Intangible results included building trust and social cohesion, the re-appropriation of spaces, and the creation of both territorial and personal identity. The project also led to an improvement in well-being and place perception. However, some obstacles and critical issues were also identified, including distrust, disinterest, disaffection, and resignation to the status quo, as well as an excessive bureaucratization of processes that hinders concrete actions. Short timelines, unkept promises, and working groups where responsibilities are overly dispersed do not work effectively. The main challenges are then linked to measuring impact: what should be measured? The intangible, cultural outcomes of participatory design, such as strengthening communities or improving social cohesion, can elude traditional metrics. Moreover, these results sometimes germinate over immeasurable periods, like many socio-cultural actions. It's like planting a seed without knowing exactly how, when, or if it will take root. For the future, considerations include the need for long-term commitment and continuity in resident engagement processes, the adoption of non-invasive, trust-based approaches, and the ability to value people over physical structures.

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Multicriterial framework for technical, ecological, economical, and social indicators of green walls in urban environments: the case study of the University Campus in Palermo

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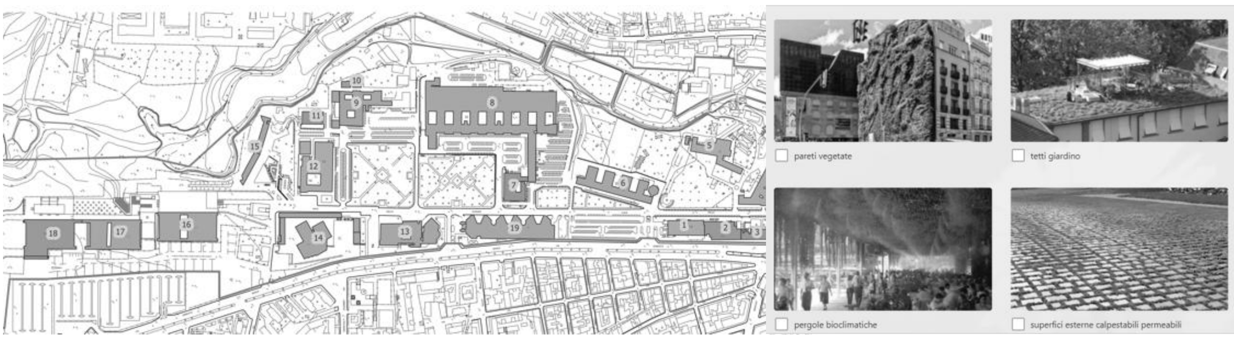
Highlights

- Multidimensional Evaluation Framework to assess the feasibility of green walls in urban environments
- Application to a Case Study for identifying optimal sites for pilot greening projects and demonstrating and validating its practical relevance
- Contribution to Sustainable Urban Planning and technical development: greening scalable solutions for climate adaptation and urban sustainability

Keywords

Multicriterial Framework; Green Walls; Urban Resilience and Sustainable Cities; Technical Methodology Feasibility; Transformability Index; Greening application



Mapping of campus buildings and users' preferences for greening strategies@Author2025

Introduction

Urban environments around the world are increasingly confronted with severe challenges arising from climate change, environmental degradation, air pollution, the urban heat island effect, and a marked decline in urban biodiversity. These complex and interlinked issues threaten not only ecological balance but also public health, social cohesion, and long-term sustainability. In this context, nature-based solutions (NBS) have gained prominence as adaptive strategies that harness natural processes to enhance urban resilience and liveability. Among these, green walls, also referred to as vertical gardens, have emerged as a promising intervention capable of transforming otherwise inert urban surfaces into active, multifunctional ecological assets.

Green walls offer a suite of environmental, aesthetic, and socio-economic benefits. They contribute to air purification, thermal regulation, noise mitigation, and biodiversity restoration, while also enhancing the aesthetic quality of the built environment and promote indoor and outdoor comfort. Furthermore, they can serve educational and symbolic functions, promoting environmental awareness and fostering a renewed connection between urban dwellers and nature [1]. However, despite the growing recognition of their potential, the implementation of green walls remains limited and fragmented, often hampered by a lack of holistic planning, unclear evaluation criteria, and insufficient integration across technical, ecological, economic, and social domains.

This study aims to address these gaps by proposing a comprehensive and adaptable feasibility assessment framework for green wall implementation [2]. The framework integrates both structural and technical feasibility indicators (e.g., façade orientation, accessibility, load-bearing capacity) and microclimatic performance criteria (e.g., reduction of surface and ambient temperature, improvement of air quality, enhancement of biodiversity), combined with economic and social dimensions. It is grounded in a multidisciplinary analysis and focused on the specific application within the urban context of the University of Palermo Campus, which comprises twenty distinct buildings with varying typological and contextual characteristics. The framework aspires to assist architects, planners, and decision-makers in systematically evaluating green wall initiatives, ensuring their viability, microclimatic effectiveness, and long-term sustainability.

Objectives

The primary objective of this study is to develop and operationalize a holistic multicriteria framework for assessing the feasibility of green walls in urban environments. This framework seeks to merge and integrate diverse indicators [3] derived from literature review, case study analysis, survey of the building for technical features; and expert consultation and evaluation, allowing for a multidimensional understanding of green wall performance and potential.

Specifically, the study pursues the following goals:

- To identify and classify the main technical, ecological, economic, and social factors that influence the success of green wall application;
- To develop a composite evaluation index that quantifies and integrates these factors in a consistent and replicable methodology;
- To apply the framework to the case of the University of Palermo Campus, analysing the feasibility of green wall implementation across its twenty buildings;
- To give a tool to technical department for greening application to facilitate the application of green walls on buildings;
- To promote a culture of interdisciplinary planning that recognizes green walls as tools not only for environmental improvement but also for public and social engagement and urban regeneration.

Ultimately, the framework aims to facilitate evidence-based decision-making and support urban policies aligned with the broader goals of climate adaptation, ecological restoration, and sustainable development [4].

Methodology

The methodological approach adopted in this study is structured around five sequential phases:

- Literature review and case study analysis;
- Indicator development;
- Composite index construction;
- Pilot application: University of Palermo Campus;
- Tool for greening walls application.

A comprehensive review of international academic literature, technical reports, and green infrastructure guidelines was conducted to identify best practices, success factors, indexes and performance metrics for green wall systems. These case studies offered empirical insights into diverse implementation strategies, design models, and operational frameworks [5]. The study defines a four-pillar structure based on indexes that were found selected, extract and used to develop a selected strategy based on evaluating green wall feasibility:

1. Technical Viability – including structural and technical capacity of building façades, microclimatic compatibility, irrigation and drainage systems, native plant selection, and maintenance logistics [6].
2. Ecological Benefits & human health – encompassing air quality improvement, biodiversity support, microclimate regulation (particularly temperature and humidity), and water retention capabilities.
3. Economic Evaluation – assessing initial investment, maintenance costs, lifecycle performance, energy savings, and potential impact on real estate value [6].
4. Social Acceptance – considering factors such as public perception, aesthetic integration, educational opportunities, and stakeholder engagement.

Each indicator was associated with measurable criteria: quantitative values (e.g., simulated temperature reduction, percentage energy savings) or qualitative scales (e.g., stakeholder perception, visual integration). A multi-criteria decision analysis (MCDA) approach was then applied: quantitative indicators were normalized on a comparable scale, while qualitative judgments were translated into ordinal scores through expert consultation. Weightings were assigned through a participatory Delphi process involving university users, environmental authorities, and technical experts, ensuring that the composite index reflected both scientific evidence and community priorities.
The framework was applied to the 19 buildings of the University of Palermo Campus, each analysed for technical suitability [7], ecological context, economic considerations, and stakeholder perspectives. Data collection involved on-site inspections, microclimatic monitoring, and interviews with campus users. The composite index allowed for ranking the buildings based on overall technical feasibility and identifying the most promising candidates for pilot green wall installations.
To verify the outputs, the results of Palermo were compared with similar cases, to validate the robustness of the framework and to highlight context-dependent adaptations.
The final phase included the development of an operational tool for the selection of buildings best suited to apply new green walls.

Results

The framework applied to the University of Palermo campus confirmed the feasibility of green wall integration on several buildings, mainly due to favourable façade orientation, solar exposure, and accessibility for maintenance. From an environmental perspective, the analysis demonstrated measurable benefits: simulations indicated a reduction of surface and ambient temperatures by 2–3 °C during summer peaks, accompanied by improvements in air quality, rainwater management, and biodiversity activation, particularly for pollinators and small birds.
Economic assessments showed that, although installation costs vary depending on the system, these investments can be partially offset by long-term energy savings—estimated at 10–20% for cooling demand—and by potential increases in real estate value. Finally, the participatory evaluation highlighted strong social acceptance: students valued the educational role of green walls, staff emphasized the importance of maintenance feasibility, and the broader community recognised their contribution to campus identity and liveability.

Conclusion & Future Developments

The framework established through this study proves to be both scalable and adaptable, providing a dynamic tool for planning and decision-making in various urban contexts [9]. Its main contribution lies in connecting design alternatives with measurable performance outcomes: from structural feasibility and cost-effectiveness to microclimatic benefits such as temperature reduction, air quality improvement, and biodiversity enhancement. This multidimensional approach strengthens the replicability and transferability of green wall interventions.
Future developments should focus on the refinement and standardisation of indicator definitions, especially for qualitative metrics such as visual impact and stakeholder participation. Establishing common protocols would improve comparability between projects and facilitate broader benchmarking exercises. At the same time, the integration of recyclable materials, advanced irrigation systems, and sensor-based monitoring will enhance both performance and sustainability. The adoption of IoT technologies can also support real-time maintenance, continuous data collection, and adaptive management strategies [10–11].

Equally important is the reinforcement of participatory planning and co-design processes with local communities, students, and neighbourhood associations. Green walls should not be considered only as technical installations, but as platforms for environmental education, civic pride, and urban regeneration.
Given the climatic similarities and common technological challenges, the methodology and results of this study can be replicated in other Mediterranean university campuses, fostering a regional innovation network for sustainable design. By systematically combining evidence-based evaluation and stakeholder engagement, green walls can evolve from isolated experimental projects into mainstream components of climate-resilient urban strategies.
Ultimately, this research contributes to aligning urban greening initiatives with broader policy frameworks such as the EU Green Deal and the New European Bauhaus, demonstrating how nature-based solutions can act as strategic assets in the transition toward healthier, more sustainable, and inclusive cities.

Acknowledgement

This research was founded by the European Union EU Next Generation Italian PRIN/PNRR 2022 Project titled "Greenwork: an interdisciplinary framework for urban health and urban resilience enhancement based on greening strategies on buildings and open spaces" - Project Code MUR P2022MNKEC 003 - Sector: ERC SH7 - CUP: B53D23029580001 - PRJ-1358.

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Inclusive paths for the experimentation of ecological solutions. Application of participatory strategies at the Unipa Campus

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Highlights

- Student-led workshops tested greening strategies for underused campus spaces
- Context-specific prototypes improved outdoor usability and thermal perception
- Participatory design for replicable, low-impact solutions for environments

Keywords

Architectural Engineering Workshop; Greening Solutions, Design for all, Greening Applications, Participatory Approaches

Workshop on applications of building strategies at Unipa Campus @Author2025

Introduction

The implementation of greening strategies within university environments has gained growing relevance in recent years, as part of a broader reflection on sustainable development, urban resilience, and environmental well-being [1]. Within the consolidated framework of Nature-Based Solutions (NBS), academic campuses are increasingly recognized as living laboratories where ecological interventions can contribute to climate adaptation, social inclusion, and educational innovation [2,3]. In particular, universities in Mediterranean contexts face pressing challenges due to recurrent heatwaves and high solar radiation, which compromise the usability of outdoor spaces and exacerbate thermal discomfort. In such settings, greenery can serve not only an aesthetic function but also act as a climate-responsive infrastructure capable of enhancing microclimatic performance, stimulating sustainable behaviors, and activating underutilized areas [4,5].

Despite this growing awareness, many campuses still present fragmented and inconsistent applications of green infrastructure, often disconnected from spatial functionality and environmental performance [1]. This condition is evident at the University of Palermo (Unipa), where the distribution of green systems is uneven and frequently uncoordinated with the actual use and accessibility of spaces. Several zones remain underused or completely abandoned, especially where vegetation is scarce or inappropriately integrated into the architectural and climatic context [2]. Among these neglected areas, the chapel courtyard emerges as a particularly emblematic case. Despite the architectural and symbolic value of the chapel itself, the surrounding open space is characterized by harsh microclimatic conditions, lack of shading and seating, and an overall absence of spatial quality [2]. These factors have contributed to its progressive abandonment and have prevented the area from serving as a meaningful public space within the campus fabric.

Objectives

This research seeks to explore the potential of greening strategies as a catalyst for reactivating neglected university spaces, focusing on the case of the campus chapel area at Unipa. The project is rooted in the hypothesis that the integration of vegetated systems and environmentally responsive design elements can significantly improve the usability, comfort, and social relevance of outdoor academic environments [3].

The main objectives of the study are to identify spatial and climatic criticalities within the campus, test the applicability of low-impact and reversible green design strategies, and engage students in a hands-on learning process that connects environmental awareness with design practice [4]. A participatory design methodology was adopted, involving a workshop with students from the UNIPA Campus aimed at recognizing the potential of underutilized green areas to be converted into spaces for socialization, collaboration, and the inclusion of vulnerable individuals. Furthermore, the study aims to offer a set of feasible, scalable, and context-sensitive interventions that may serve as a reference for broader applications across similar Mediterranean academic institutions.

Methodology

The methodological framework adopted in this research integrates analytical investigation, educational experimentation, and spatial design. It was developed as part of a workshop that engaged students from architecture and design programs, who acted simultaneously as researchers and designers in the transformation process.

The initial phase of the study was dedicated to identifying priority areas for intervention through a systematic campus survey. The choice of sites was guided by three complementary aspects: the presence of microclimatic discomfort due to excessive solar exposure and lack of vegetation, the recurrent observation of abandonment or limited use during daily student activities, and the reduced accessibility or absence of basic equipment for outdoor permanence. These conditions were verified through quantitative measurements, including surface and air temperature readings, solar exposure analysis, and wind pattern observations, combined with qualitative tools such as user surveys and direct spatial perception assessments [5].

Within this framework, the chapel courtyard was identified as a critical site because of its symbolic value, central position within the campus, and unfavorable environmental conditions. A detailed site analysis recorded surface materials, vegetation, shading potential, and access points, providing the basis for the design brief [6]. Students were then organized into four interdisciplinary teams and invited to develop greening strategies tailored to the courtyard's specific needs [7].

The workshop progressed through successive cycles of analysis, design exploration, and critical review. Rather than focusing on predefined solutions, the process encouraged the open development of low-tech, reversible, and climate-sensitive proposals. Particular attention was given to strategies integrating passive shading devices, vegetated systems, modular seating, and multifunctional furniture designed to support diverse activities throughout the day and across seasons.

To assess feasibility, students developed conceptual models and prototypes using analog and digital tools. The proposals were validated through peer review sessions, tutor evaluations, and comparisons with benchmark studies on small-scale greening interventions in Mediterranean contexts [4,5]. Without full-scale monitoring, expected microclimatic benefits were inferred by aligning the proposed solutions with performance data documented in the literature.

This methodological pathway combined research and design experimentation while establishing a replicable learning model in which students engaged with real-world challenges. By linking quantitative analysis, participatory design, and qualitative validation, the approach showed the potential to generate scalable, low-impact, and context-sensitive greening strategies applicable to other academic environments.

Results

The outcomes of the workshop highlighted both opportunities and challenges in integrating greening strategies in university settings. Each of the four student teams proposed distinct intervention strategies, reflecting different priorities and interpretations of the site's potential. Despite their differences, all proposals shared a commitment to climatic adaptability, spatial inclusivity, and material sustainability [8].

Among the most recurrent design elements were modular seating systems, lightweight shading structures, and vegetated installations based on native or low-maintenance plant species. The prototypes emphasized reversibility and scalability, suggesting that even minimal interventions—when carefully designed—can significantly improve environmental comfort and spatial perception.

To support design proposals with preliminary evidence, microclimatic measurements were carried out in the chapel courtyard using the HD32.3TC data logger. Data collected during summer peak conditions revealed surface temperatures exceeding 46 °C in fully exposed areas, compared to 33 °C in shaded zones, highlighting the critical role of shading in reducing thermal stress. Air temperature measurements confirmed differences of up to 3–4 °C between vegetated and non-vegetated points. Similarly, relative humidity increased slightly (by 5–7%) near vegetation, while globe thermometer readings indicated radiant heat peaks above comfort thresholds during midday hours [5]. These results provided an empirical basis for estimating the potential benefits of the proposed greening interventions, particularly vegetated shading systems, expected to reduce radiant loads and extend courtyard usability.

From an educational perspective, the workshop fostered strong student engagement, enabling participants to experience the full process from analysis and data collection to ideation and prototyping. Their proposals were not only academic exercises but also tangible contributions to the campus transformation debate. The participatory nature of the workshop also prompted discussion on the role of academic communities in shaping their environments and the importance of interdisciplinary collaboration in addressing climate-related challenges.

Despite the richness of the outcomes, some obstacles may hinder real-life implementation, including bureaucratic inertia, limited funding, and the absence of institutional mechanisms for integrating student-driven projects into campus planning. Nevertheless, the results were formally presented to university stakeholders, laying the groundwork for potential adoption and creating a knowledge base for future greening initiatives [9].

Discussion

The experience gained through this research confirms that small-scale, user-centered greening interventions can effectively regenerate neglected academic spaces, particularly in contexts where heat stress and solar exposure reduce outdoor usability. Integrating green strategies improves microclimatic conditions, redefines spatial hierarchies, and fosters community ownership.

The chapel courtyard, once perceived as residual and inhospitable, was reframed as a potential hub of social interaction, environmental regeneration, and symbolic continuity. This transformation was achieved not through costly or complex technologies but through the sensitive application of climate adaptation principles, material compatibility, and spatial empathy. Such an approach is especially relevant in Mediterranean settings, where heritage, climate, and limited resources intersect.

The project also underscores the educational value of embedding real-world challenges into academic curricula. By engaging with concrete environmental problems, students strengthened critical thinking, collaboration, and design skills, while gaining greater awareness of the responsibilities and opportunities inherent in spatial practice.

Conclusion

This study demonstrates that the regeneration of university spaces through greening strategies is both urgent and feasible, provided that interventions are context-sensitive, low-impact, and inclusive. The case of the University of Palermo shows how even marginal areas can become valuable assets through targeted and participatory processes.

The methodological approach outlined here can serve as a replicable model for Mediterranean campuses facing climatic discomfort and spatial degradation. By linking analytical research, design experimentation, and education, the initiative offers a holistic framework for more resilient, livable, and community-driven academic environments.

Nevertheless, several barriers may hinder implementation, including bureaucratic inertia, limited resources, and the lack of governance mechanisms for integrating student-led projects into institutional planning. Addressing these challenges requires stronger institutional commitment and long-term strategies that align ecological objectives with administrative and community priorities.

Although preliminary, the results suggest a clear direction: embedding greening pathways into university development plans, enhancing student participation in spatial governance, and cultivating a long-term vision of environmental and social sustainability [10]. In a time marked by environmental urgency and spatial inequality, such actions contribute to the broader goal of reimagining how we inhabit and care for shared environments.

Acknowledgement

This research was founded by the European Union EU Next Generation Italian PRIN/PNRR 2022 Project titled "Greenwork: an interdisciplinary framework for urban health and urban resilience enhancement based on greening strategies on buildings and open spaces" - Project Code MUR P2022MNKEC 003 - Sector: ERC SH7 - CUP: B53D23029580001 - PRJ-1358.

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Evaluation of a simulation system for ecological strategies for outdoor comfort: a case study on the UNIPA University Campus in Palermo

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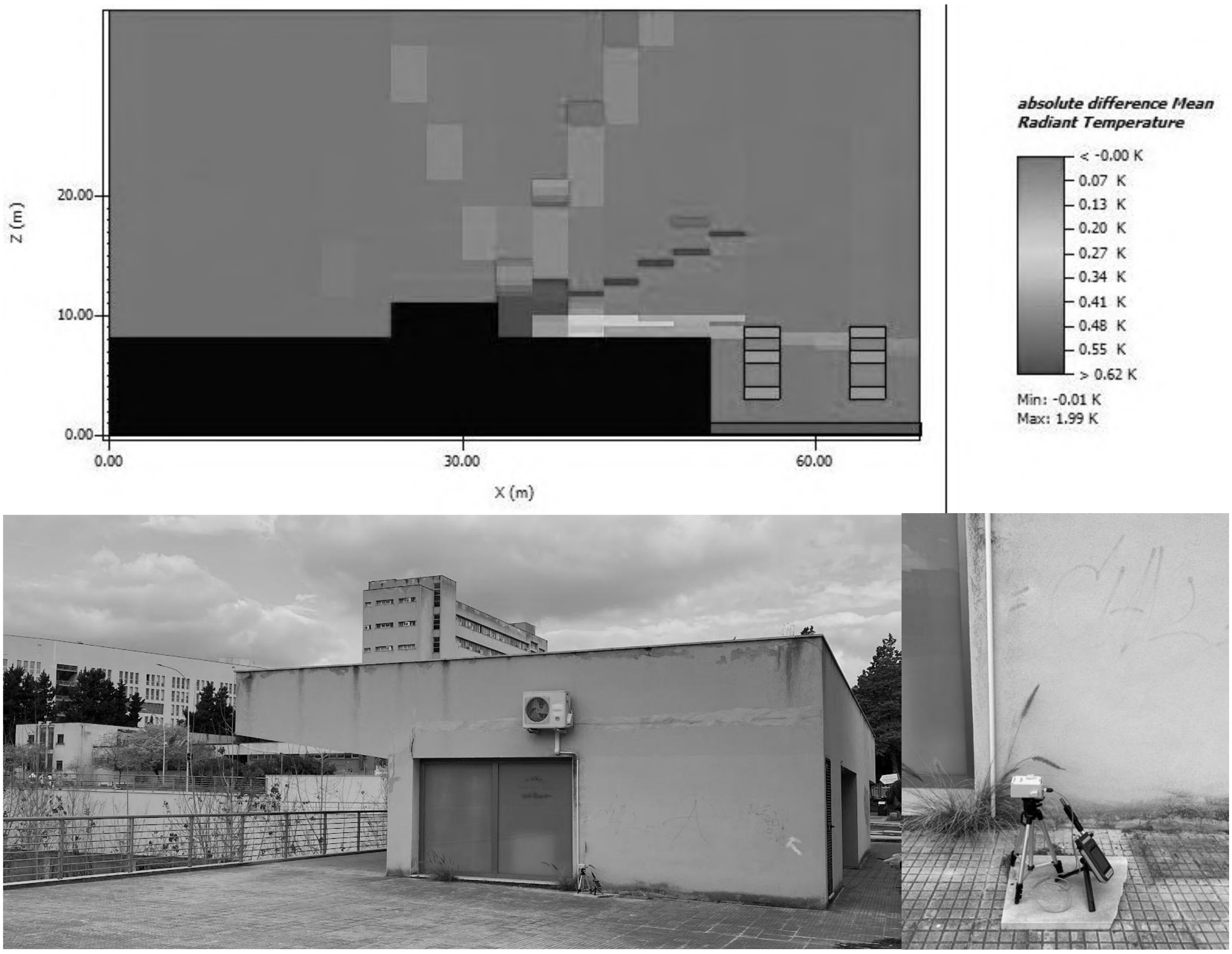
Highlights

- Real microclimate data used to simulate greening impacts
- ENVI-met model tests vegetated wall on university campus
- Improved thermal comfort in semi-open urban spaces

Keywords

Urban Greening, ENVI-met, Outdoor Comfort, Vegetated Wall, Microclimate Simulation



Data collection using a probe to assess outdoor comfort conditions at the Unipa Campus; ©image by author, 2025

Introduction

As global temperatures continue to rise and urban areas experience more frequent and intense heatwaves, cities must adopt innovative strategies to mitigate the Urban Heat Island (UHI) effect and improve environmental comfort. Nature-Based Solutions (NBS), particularly greening interventions such as vegetated facades and walls, are increasingly recognized as effective tools for climate adaptation in dense urban settings [1]. While their potential benefits are widely acknowledged in the literature, the actual design and validation of these systems in real-world scenarios require accurate environmental assessment tools. This study investigates the integration of NBS in a university setting, combining on-site microclimatic measurements with simulation-based analysis to assess their environmental and thermal performance. Focusing on a case study from the University of Palermo (UNIPA), the research explores how microclimate simulation tools can support the design and implementation of green walls to enhance thermal comfort in semi-open urban spaces, while also discussing challenges related to structural integration and plant selection.

Objectives

The primary aim of this study is to test the effectiveness of a vegetated wall system in mitigating thermal discomfort and enhancing the habitability of a specific outdoor campus area. The objectives are threefold: to quantify the baseline microclimatic conditions of the selected site, to simulate the environmental impact of the proposed NBS intervention using ENVI-met software [2], and to evaluate potential improvements in thermal comfort through comparative analysis of key microclimatic indicators [3]. The research also develops a methodology that combines advanced digital modeling (ENVI-met) with on-site measurements from the Building Laboratory of the Department of Architecture at UNIPA. While the study focuses on simulation-based validation, it outlines the potential for future post-intervention monitoring and multi-seasonal assessment, providing a foundation for replicable methodological approaches applicable to other Mediterranean or climatically comparable university settings [4].

Methodology

The research followed a multi-phase methodology combining field data collection, simulation modeling, and post-processing of results. The selected site, a semi-open pedestrian area on the UNIPA campus between buildings 13 and 14 of the Architecture Department, was chosen due to high solar exposure, use of low-albedo materials, and limited ventilation—conditions representative of thermal discomfort during peak hours [5]. On-site environmental monitoring recorded air temperature, surface temperature, mean radiant temperature (MRT), relative humidity, and particulate matter (PM2.5 and PM10) using a handheld climate probe. These data served to calibrate the simulation model and to assess its reliability, highlighting the limitations in spatial and temporal resolution typical of ENVI-met outputs. The simulation environment was developed using ENVI-met, which allows detailed three-dimensional modeling of microclimatic conditions. Geometry and material data for the site were reconstructed, including surface properties and existing vegetation. Two simulation scenarios were modeled: a baseline without intervention and a design scenario featuring a west-facing vegetated wall, with realistic assumptions regarding plant density, irrigation, and surface reflectivity [6]. The simulation was calibrated against field measurements to ensure alignment between modeled and observed parameters. Post-processing focused on thermal comfort indicators—air temperature, MRT, and Predicted Mean Vote (PMV)—at pedestrian level (1.5 meters above ground). Graphical and quantitative analyses evaluated the effectiveness of the intervention, while acknowledging the inherent limitations of simulation-only assessments.

Results

Simulation results indicated significant improvements in microclimatic conditions due to the vegetated wall. Air temperature decreased by an average of 1°C in the immediate surroundings during peak afternoon hours, while surface temperatures showed larger reductions, confirming the heat-mitigation potential of vegetated systems [7]. PMV values shifted from moderate thermal discomfort to near-neutral comfort in shaded areas, particularly in the late afternoon on west-facing surfaces. MRT also decreased, contributing to a more homogeneous and comfortable thermal environment [8]. Beyond thermal improvements, the vegetated wall enhanced spatial perception, walkability, and potential social use, demonstrating the practical benefits of small-scale NBS in semi-public urban spaces. Operational considerations such as plant selection, structural integration, and maintenance planning were identified as crucial for real-world application [9]. While post-intervention validation was not conducted, the study highlights the need for multi-seasonal monitoring and pilot implementation to further assess long-term performance and user experience.

Conclusions

This study demonstrates the relevance of combining simulation tools and on-site measurements for the design and assessment of Nature-Based Solutions in urban environments. The UNIPA campus case study confirms that even small-scale greening interventions, such as vegetated walls, can enhance thermal comfort and spatial quality. By integrating methodological rigor with practical design considerations, the research provides a replicable framework for testing NBS interventions in Mediterranean contexts. Future work should include post-intervention validation, multi-seasonal monitoring, and expanded design integration analyses, addressing structural, botanical, and maintenance challenges [10]. The approach supports evidence-based planning, encourages environmental awareness, and positions academic campuses as both beneficiaries and laboratories for climate adaptation and sustainable urban design.

Acknowledgement
This research was founded by the European Union EU Next Generation Italian PRIN/PNRR 2022 Project titled "Greenwork: an interdisciplinary framework for urban health and urban resilience enhancement based on greening strategies on buildings and open spaces" - Project Code MUR P2022MNKEC 003 - Sector: ERC SH7 - CUP: B53D23029580001 - PRJ-1358.

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Nature-based Solutions for urban resilience: analyzing the role of green facades and green roofs on microclimate at urban, neighborhood, and building scales

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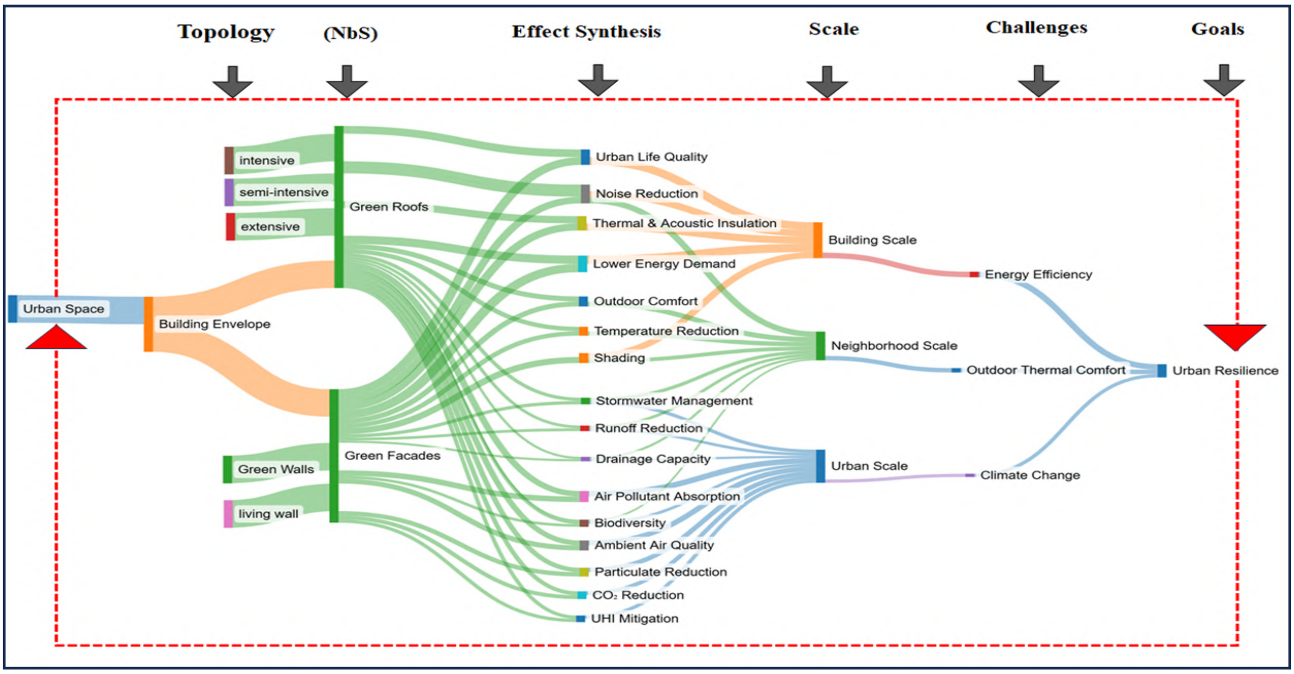
Highlights

- Green roofs and Walls improve urban thermal comfort and energy use
- Multi-scale nature-based solutions enhance urban resilience and biodiversity
- Integrated framework assesses green infrastructure from building to urban scale

Keywords

Urban Resilience; Green Facades; Green Roofs; Urban Heat Island; Nature-Based Solutions;



Framework mapping green infrastructure categories to effects, scaled across building/neighborhood/urban systems, driving resilience

Purpose
This study presents a scalable, integrative framework to evaluate nature-based solutions—specifically green roofs and façades—across building, neighborhood, and urban scales. To ensure academic rigor and transparency, a systematic literature review was conducted following the PRISMA protocol [4]. Using the Scopus database, peer-reviewed publications from 2015 to 2025 were collected with keywords including green roofs, green walls, microclimate, urban resilience, and thermal comfort. The initial search retrieved 1,450 records. After applying inclusion criteria—English language, full-text availability, peer-reviewed status, and relevance to the study focus—687 articles were screened. Ultimately, 118 studies met all eligibility requirements and were included for detailed content analysis. Extracted data on environmental and thermal performance informed the development of a classification framework assessing the effectiveness of nature-based solutions in dense urban contexts. The review addressed three key questions :

- To what extent can these systems enhance resilience and environmental performance at the urban scale under current and future climate scenarios?
- How do they influence microclimate regulation and thermal comfort in dense neighborhoods?
- What configurations best optimize sustainability at the building scale?

Findings: Multi-Scale Performance of Green Walls and Roofs
This study offers an integrative assessment of green roofs and vertical greening systems as nature-based solutions across building, neighborhood, and urban scales. Guided by the conceptual framework in (Figure 1), it highlights hierarchical and lateral links between these strategies and their environmental impacts. The work advances a systems-oriented classification that connects green envelope technologies to broader urban outcomes including climate change adaptation, outdoor thermal comfort, energy efficiency, and urban resilience. The topology of green roofs is classified by substrate depth: extensive (<200 mm), semi-intensive (200–350 mm), and intensive (>350 mm). The topology of green facades, including both green walls and living walls, enhances urban resilience by improving thermal performance and environmental regulation [3].
At the building scale, simulations in Lisbon show uninsulated extensive green roofs reduce cooling energy by 34.9%, while semi-intensive and intensive types lower demand by 60–70% and 45–60%, respectively [5, 6]. Green roofs also reduce noise and enhance shading. Façade greening improves building envelope performance via shading and evapotranspiration. In La Rochelle, modular green walls cut wall temperatures by 15 °C and cooling loads by 64.38% [7]. In Shiraz, living walls reduced ambient temperature by 2.25 °C and saved 15% energy [8].
At the neighborhood scale, green walls and roofs improve outdoor thermal comfort, reduce temperatures, and enhance semi-enclosed urban spaces. In a dense Mediterranean neighborhood, combining green façades and roofs reduced air temperature by 0.7 °C and UTCI by 1.6 °C. In Turin, green walls lowered winter air temperature by 1.6 °C and summer mean radiant temperature by 2.27 °C. They also reduced summer UTCI by 0.55 °C and carbon emissions by 31%, though winter heating emissions rose by 45% [2, 9].
At the urban scale, green walls and green roofs act as complementary nature-based solutions that enhance resilience by mitigating environmental stressors. Green walls reduce bare wall surface temperatures by up to 31 °C, offering localized cooling and alleviating the Urban Heat Island effect, though their vertical orientation limits spatial impact. Green roofs exert broader influence by cooling rooftops and ambient air and regulating urban microclimates. Both systems improve air quality—green walls remove 15–99% of PM2.5, PM10, NO2, and SO2, while green roofs reduce PM2.5 by 7–33% and sequester carbon. Additionally, they enhance acoustic comfort, retain 40–60% of rainfall, support biodiversity, and reduce life cycle emissions by up to 55% [1, 3].
This study presents a systems-based framework that positions urban resilience—the ability of cities to adapt to and recover from climate-related stressors while maintaining essential functions—as the overarching goal resulting from interconnected effects across three spatial scales. At the building scale, green façades and roofs enhance energy efficiency by improving insulation and reducing indoor thermal loads. At the neighborhood scale, these nature-based solutions contribute to outdoor thermal comfort by moderating microclimates and improving local thermal conditions. At the urban scale, green roofs facilitate broader climate change adaptation by managing stormwater, lowering surface temperatures, and mitigating urban heat island effects. Each of these scale-specific contributions reinforces the overall capacity of the system to support resilient urban environments. However, in Mediterranean cities, challenges such as seasonal performance variability, structural limitations in dense or historic areas, and complex maintenance requirements necessitate tailored,

context-sensitive strategies. Future implementation should prioritize water-efficient retrofits for compact urban forms, AI-enabled monitoring systems for adaptive maintenance, and equity-driven policies that transform green envelope systems from isolated architectural features into essential infrastructure for sustainable and climate-resilient urban futures.

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Topic C

Interventions at the building scale

Retrofitting school open spaces for climate resilience: thermal and environmental metrics from a French pilot project

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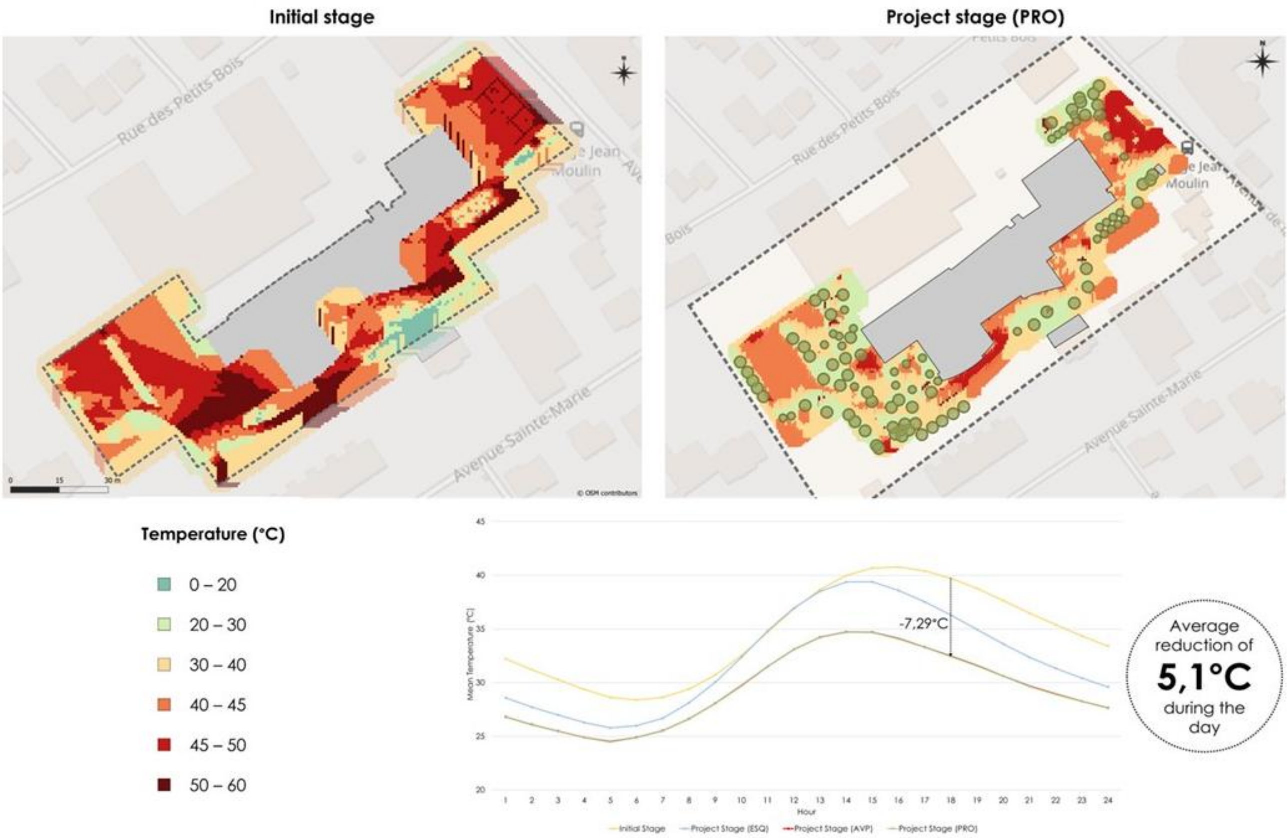
Highlights

- UHI drop: −5°C avg, −7.3°C peak via albedo and permeability upgrade
- Winter sun access: >80% of courtyards get ≥2h/day of direct light
- GHG cut 35% via low carbon cement, reuse, and tree/soil carbon sequestration

Keywords

Outdoor Microclimate; Urban Heat Island Mitigation; Promotion of Greening; Life Cycle Impact Reduction; Sunlight Access



Outdoor microclimate simulation comparing surface temperature profiles before (left) and after (right) the implementation of landscape retrofitting strategies at the Jean Moulin secondary school, Chaville

This study presents a rigorous assessment of an integrated landscape retrofitting intervention conducted at the Jean Moulin secondary school in Chaville (Hauts-de-Seine), France. The objective is to evaluate the microclimatic efficacy of this intervention in mitigating Urban Heat Island (UHI) effects and enhancing outdoor thermal comfort in a dense educational urban context. The methodology is grounded in a comparative pre/post analysis of physical parameters—specifically surface albedo, soil permeability, vegetative cover, and material thermal behaviors supported by simulation-based performance modelling. The study quantifies the impact of strategic material substitution, spatial reconfiguration, and vegetation integration on surface thermal regimes, and assesses their potential for climate-resilient adaptation in urban educational environments.
Urban schools face high-stress environments due to impervious surfaces, minimal vegetation, and intensive use. There is a clear link between surface thermal properties, vegetation, and temperature regulation, especially concerning urban heat islands (UHIs). However, data on schoolyard retrofit performance is limited. This project fills that gap with comprehensive environmental design, including thermophysical simulations and carbon impact assessments. The intervention aligns with the WELL Building Standard v2 Features T09β (Thermal Comfort) and M09 (Biophilia II), emphasizing microclimatic regulation and nature-based designs in learning areas. Evidence shows that nature exposure benefits students' cognitive and emotional well-being, improving attention, reducing stress, and enhancing academic performance. Incorporating vegetation and temperature regulation, this project offers climatic and educational advantages.

The Case study

The Jean Moulin secondary school in Chaville, Île-de-France, sits in a densely urbanized area with limited ecological connectivity and high climate stress. Its 4958 m² open spaces, including circulation corridors, courtyards, and recreational fields, were originally covered with low-reflectivity, impermeable asphalt. This layout led to high runoff and negligible vegetation, causing significant thermal stress in summer.
The transformation began under the Département des Hauts-de-Seine’s climate adaptation program for 26 public schools, aiming to enhance environmental resilience and youth welfare by targeting vulnerable legacy infrastructure. The Jean Moulin schoolyard exemplified functional inadequacy in meeting contemporary climatic demands and offered an opportunity for climate governance-oriented intervention to achieve measurable environmental and social outcomes.

Urban Heat Island mitigation

Before intervention, the Jean Moulin schoolyard had an high surface impermeability index of 83%, which contributed to localized heat accumulation and hindered passive hydrological regulation. The retrofit strategy addressed this by replacing the material most commonly present (asphalt), resulting in a post-intervention impermeability coefficient of 39%. This was achieved through integration of hydraulically active surfaces such as porous concrete, stabilized mulch substrates, and open-graded vegetated soil beds. This transition not only provided hydrological benefits but also improved thermal properties, with the site’s weighted average albedo increasing from below 0.18 to approximately 0.31.
The recalibration of albedo was tailored to specific materials: porous light-colored concrete used in circulation areas achieved an albedo of 0.30; sports tracks made from pigmented polymeric surfaces showed values between 0.355 and 0.415; while vegetated earth zones varied from 0.23 to 0.39 depending on granulometric composition and vegetation density.
Thermal simulations conducted using the ICETool software, configured for mid-summer design days (T_air = 35°C, clear sky), indicated a mean surface temperature reduction of 5.0°C across the site's functional zones throughout the day, with a peak average reduction reaching 7.3°C around 6 pm. Additionally, functional ecological indicators showed significant improvements: the site’s thermal regulation coefficient increased from 37% to 50%, and the biotope coefficient rose from 31% to 45%, indicating enhanced ecological permeability and bioclimatic performance.
These results demonstrate the effectiveness of integrating material and environmental strategies in mitigating UHI effect and position the intervention within best-practice benchmarks for microclimate-responsive educational infrastructure retrofits.

Outdoor comfort

The optimization of outdoor thermal comfort was conducted through a simulation-informed design process integrating seasonal solar access modeling and pedestrian-level wind flow analysis. Early-phase simulations using parametric environmental plug-in suite identified critical solar exposure patterns across seasonal cycles. In the winter scenario, over 80% of the courtyard surface area achieved the threshold of ≥2 hours of direct sunlight per day, confirming adequate passive solar access for thermally beneficial use during colder months. Conversely, initial simulations for the summer condition indicated that only 32–39% of the surface area met the benchmark, which requires outdoor occupied areas to be shaded for more than half of daylight hours (less than 6 hours per day) by tree canopies, awnings, or other structures. This suggests a potential risk of prolonged thermal stress.

Design iterations improved deficiencies by reorganizing vegetation, differentiating surface materials, and adding shading types. This refinement process kept adequate winter sunlight while gradually increasing summer shade, especially in high-density areas.

In parallel, computational fluid dynamics (CFD) analyses were conducted to evaluate and optimize wind comfort conditions. The CFD workflow informed decisions on vegetation placement, edge permeability, and corridor orientation to ensure air movement conducive to thermal dissipation without generating discomforting turbulence. Final simulation outputs confirmed that the principal zones of educational and recreational use (lower courtyard and forecourt) maintained mean wind velocities below 2.0 m/s—optimal for sedentary outdoor activities—while the higher courtyard registered wind peaks up to 4.0 m/s, considered tolerable for dynamic activities such as sports.

Simulation-guided design has improved the site's microclimate by reducing surface temperatures in vegetated and shaded areas during summer. The improvements between the current state and the project state using digital environmental tools in landscape design demonstrate their effectiveness in creating climate-resilient educational spaces.

Promotion of Greening in Urbanized Areas

The greening strategy aimed to enhance microclimatic regulation and biodiversity potential. A total of 934 m^2 of open-soil planting zones were introduced to enable interaction between vegetation and subsoil hydrological systems. The vegetative composition was expanded with 37 deciduous tree specimens, chosen for their high canopy density (up to 60% foliage cover) and tolerance to urban stress conditions, including moderate drought. The main species are Celtis australis, Pyrus calleryana, and Liquidambar styraciflua, selected for their shading capacity, seasonal evapotranspiration profiles, and low maintenance needs.

These interventions were placed in thermally sensitive zones to enhance surface cooling through transpiration and solar blocking. However, without detailed vegetative data—such as Leaf Area Index (LAI)—the integration of volumetric cooling effects into advanced models is limited. While some outcomes are observed, predicting dynamic vegetation-climate interactions remains challenging. Nonetheless, expanding vegetative infrastructure is crucial for thermal mitigation, ecological connectivity, and educational enrichment in urban schools.

Carbon Evaluation of Greening Measures

The Jean Moulin retrofit's environmental performance was evaluated through a life cycle carbon analysis (LCA) as per French regulations (Loi AGEC, Décret 2021-950) using ADEME's QuantiGES methodology. The assessment included GHG emissions from materials, transport, and biogenic sinks (like green areas and trees) over 50 years. Material strategies emphasized the substitution of carbon-intensive components with low-emission alternatives. Most notably, the replacement of conventional Portland cement mixtures with CEM III/A low-carbon cement resulted in an estimated 72% reduction in embodied CO_2 per square meter. This material transition was complemented by dual-stream reuse protocols: in-situ reutilization of hardscape elements (e.g., pavers, site furniture) and ex-situ incorporation of recycled mineral aggregates, achieving net carbon savings of approximately −30.5 $kgCO_2e/m^3$ for granular substrates.

The aggregate GHG emissions for the project lifecycle were calculated at 225.4 tons CO_2e—representing a 35% reduction relative to a business-as-usual (BAU) scenario benchmarked against conventional public schoolyard retrofits. Furthermore, vegetative carbon sequestration was modeled using standardized absorption coefficients: 296 tons CO_2e attributed to green surface treatments and 1885 tons CO_2e projected for the total arboreal biomass (existing and newly planted) over the analysis period.

Transport emissions were determined using mass-distance factors based on transport distances to regional facilities. This approach exemplifies best practices in low-impact urban greening and underscores the importance of early-phase carbon performance criteria for climate adaptation projects.

Workflow Capabilities and limitations

This design-research integration effectively combines drainage improvement, surface material optimization, and greening strategies for better climate performance. Simulation outputs confirm reduced thermal loads and improved ventilation, driven by strategic spatial and material reconfiguration. The workflow is modular and transferable, supporting climate-responsive retrofitting in diverse urban and climatic contexts. It enables early integration of environmental performance criteria into the design process. However, limitations remain due to the absence of post-intervention monitoring, incomplete vegetation parameters, and lack of thermophysiological modelling. Future studies should incorporate empirical validation and dynamic simulation coupling to strengthen the robustness and generalizability of the approach.

Conclusions

The Jean Moulin schoolyard retrofit serves as a model for climate adaptation in urban educational environments. The intervention shows improvements in six environmental areas: hydrological permeability, surface reflectance and temperature, student comfort, vegetative biodiversity, and lifecycle carbon impact, supported by simulations and metrics. The methodology uses an iterative process of environmental modelling, material optimization, and lifecycle analysis to enhance microclimatic efficacy. Reductions in surface temperature (up to −5°C on average over the courtyard area), impermeability (−44%), and embodied carbon (−35% relative to BAU) make this case a reference for European school retrofits.

This approach offers a prototype for authorities and designers to incorporate environmental performance targets early in public realm projects. The Jean Moulin project provides a quantifiable and replicable framework for climate-sensitive design, contributing to urban microclimate governance and regenerative educational landscapes.

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Vertical greenery for sustainable building redevelopment

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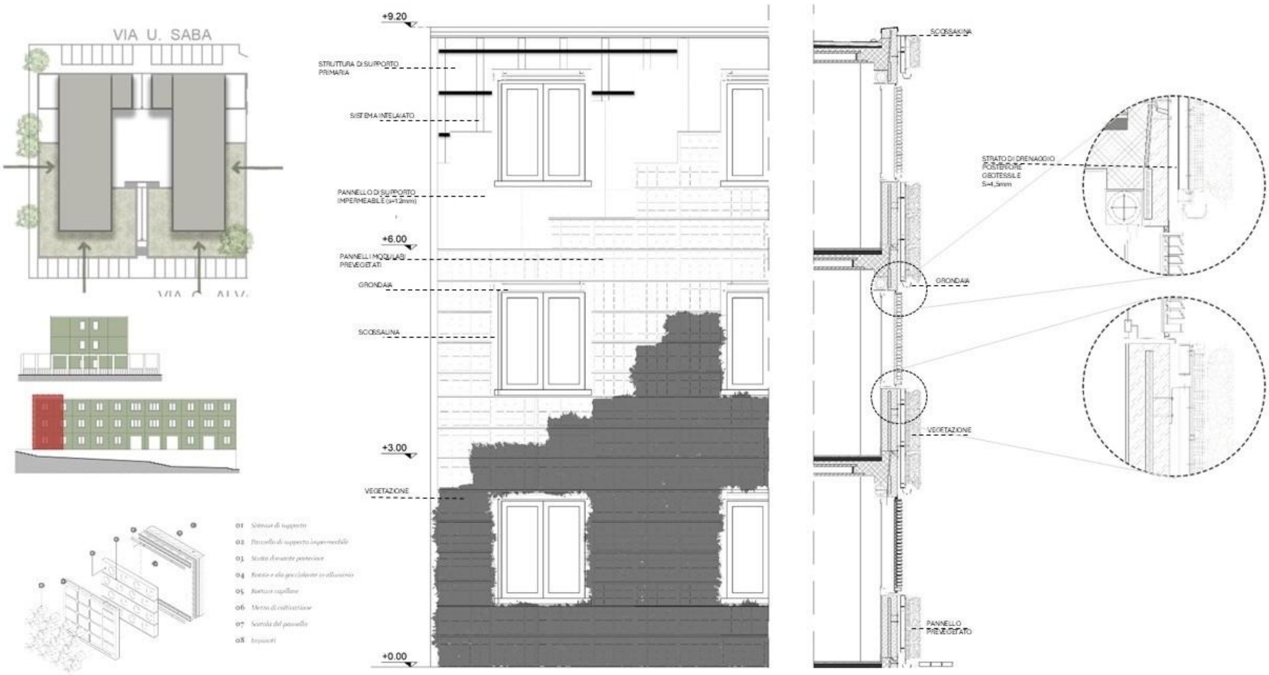
Highlights

- VGS improve urban comfort, reduce CO_2 and the urban heat island effect
- The AHP method selects the green façade best suited to the context
- The Pozzuoli case study highlights environmental and social benefits

Keywords

Vertical Green Systems; Urban Regeneration; Energy Efficiency



Technological detail of the green facade

Growing urbanization and the spread of impermeable surfaces, such as asphalt and concrete, are significantly reducing the availability of green spaces within cities [1]. This trend has clear repercussions on urban health and citizens' well-being, contributing to the intensification of climate change effects. Even at the building scale, these dynamics demand a new capacity for adaptation: buildings are now expected to respond proactively to changing environmental conditions by integrating sustainable solutions that ensure both indoor and outdoor comfort. In this context, Vertical Green Systems (VGS) are emerging as an innovative and effective response to contemporary environmental and urban challenges [1] [2]. Beyond enhancing the aesthetic quality of the built environment and improving energy performance through thermal and acoustic insulation, these systems help reduce air pollution by absorbing CO_2 and fine particulate matter, support urban biodiversity by creating habitats for insects and birds, and mitigate the urban heat island effect, contributing to cooler and more sustainable cities [3] [4] [5].
The present study aims to explore the application of Vertical Green Systems (VGS) on existing buildings, assessing their potential in the sustainable redevelopment of the built environment. Beginning with an in-depth literature review, the most recent green façade systems were classified, combining theoretical analysis with a market survey of leading international green wall manufacturers to compare solutions, technical features, and design configurations. The integration of scientific literature, market research, and the analysis of relevant case studies enabled the identification of fourteen key criteria to be considered in VGS design. These criteria formed the basis for a comparative evaluation framework, conceived as a practical tool to support design decision-making. The parameters analyzed include effectiveness in mitigating the urban heat island effect, management of rainwater and greywater, air pollution control, and enhancement of urban biodiversity, as well as noise reduction, visual impact, microclimatic comfort, and economic sustainability.
The study involved the design application of Vertical Green Systems (VGS) on existing buildings, with the goal of promoting sustainable building redevelopment. The selected pilot site is a residential complex located in the Monterusciello district of Pozzuoli (NA), built in the 1980s following the bradyseism events that affected the Phlegraean area. The district spans approximately 87,000 m² and comprises 30 residential buildings featuring diverse architectural typologies, along with community-oriented spaces and services—many of which, however, were never completed.
Despite the presence of green areas, the overall urban fabric currently exhibits a widespread sense of degradation, mainly due to the use of low-quality materials lacking in aesthetic and identity value, which has contributed to a weakened sense of community among residents. The specific intervention area is located in the northern section of the neighborhood, near major roads (Via Saba, Via Gatto, and Via Alvaro), and is situated within a context rich in public services, including schools, parking facilities, and an archaeological site.
The case study focuses on a complex composed of two identical buildings arranged around a courtyard (measuring 12 x 36 meters), each rising three stories high and divided into four residential units per floor. The selection of this typological block was based on criteria such as accessibility, environmental exposure, and representativeness. Preliminary environmental analysis revealed that the North-West-facing façades are more exposed to CO_2 pollution, while the North-East and South-West façades benefit from the best sunlight and ventilation conditions—thus identifying them as priority areas for targeted VGS application.
Based on the analyses conducted, a multi-criteria evaluation was developed to identify the most suitable type of Vertical Green System (VGS) for the specific context, as well as to define the corresponding construction-technological model and its components. The Analytic Hierarchy Process (AHP) was adopted as the decision support methodology (DSM)—a well-established tool for comparing design alternatives based on weighted performance criteria. The AHP was implemented using the “Spice Logic” software, which enabled the assignment of specific weights to each criterion and the subsequent calculation of overall scores for each solution evaluated.
The comparison of four different VGS typologies identified the “Wall-Based” green façade with modular panels as the optimal solution. This system consists of a metal support structure anchored to the building wall using brackets, vertical uprights, and crossbeams, onto which 600x450 mm steel modules filled with a growing substrate are mounted. The chosen substrate is Grodan horticultural rock wool, a high-performance inert material manufactured according to high environmental and quality standards.
The plants—selected for their climate adaptability, aesthetic qualities, and low maintenance requirements—are pre-cultivated in nurseries within the modules to ensure maturity and integrity at the time of installation.

The irrigation system uses drip lines, with pipes placed on horizontal tracks above each row of panels. This setup ensures a uniform distribution of water and nutrients, thereby optimizing the system’s water efficiency.
The stratigraphy of the assembly, from exterior to interior, includes: vegetation, modular panels, T-shaped tracks made from recycled aluminum, and a support panel equipped with drainage material—all designed to prevent moisture infiltration into the building structure.
Environmental studies and sunlight simulations led to the placement of the system on the South-East façade to maximize bioclimatic efficiency and enhance indoor microclimate conditions. In addition to the intervention on the South-East façade, further strategies have been proposed to improve both energy performance and architectural quality: the application of green panels on the North and West walls, and the installation of prefabricated aluminum balconies designed to support climbing vegetation in communal areas.
Although not explored in detail in this study, these additional interventions aim to enhance the usability of outdoor spaces for residents while strengthening the visual identity and overall sustainability of the built environment.
The study demonstrates that the application of Vertical Green Systems (VGS) extends far beyond a purely aesthetic function, positioning itself as an integrated design strategy capable of generating environmental, social, and economic benefits. The identified advantages include reductions in air and noise pollution, enhancements in urban biodiversity, more efficient rainwater management, energy savings through improved thermal regulation of buildings, and an overall improvement in urban quality of life.
The selection of the wall-based green façade system with modular panels emerged as the most effective solution—not only based on the AHP multi-criteria analysis but also due to its inherent qualities: design flexibility, durability, ease of maintenance, and low water demand. These features make it particularly well-suited for retrofitting existing buildings, which are often subject to structural, regulatory, or historical constraints.
Particular attention was paid to ensuring compatibility between the selected VGS solution and the specific characteristics of the existing building context. The analysis of environmental, morphological, and material conditions of the case study enabled the development of a tailored solution that integrates harmoniously with the surrounding urban fabric. Relevant regulatory, landscape, and archaeological constraints were also taken into account to ensure full technical and administrative feasibility of the intervention.
A key focus of the project was the sustainable management of water resources. The drip irrigation system, combined with a high-performance growing substrate, ensures efficient water use—an essential consideration in Mediterranean climates such as that of Pozzuoli, where rainfall is irregular and often concentrated in short periods.
Ultimately, the proposed case study provides a basis for potential future developments, allowing for scalability and replication in other buildings within the same neighborhood or similar urban contexts. The intervention offers a flexible and adaptable operational model to guide sustainable urban regeneration strategies. The applied methodology—based on multi-criteria analysis and supported by the AHP method—has proven to be an effective, replicable, and robust tool for informing design decisions that promote both environmental resilience and architectural quality.

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A site-specific methodology for the sustainable design of green roofs in urban climates

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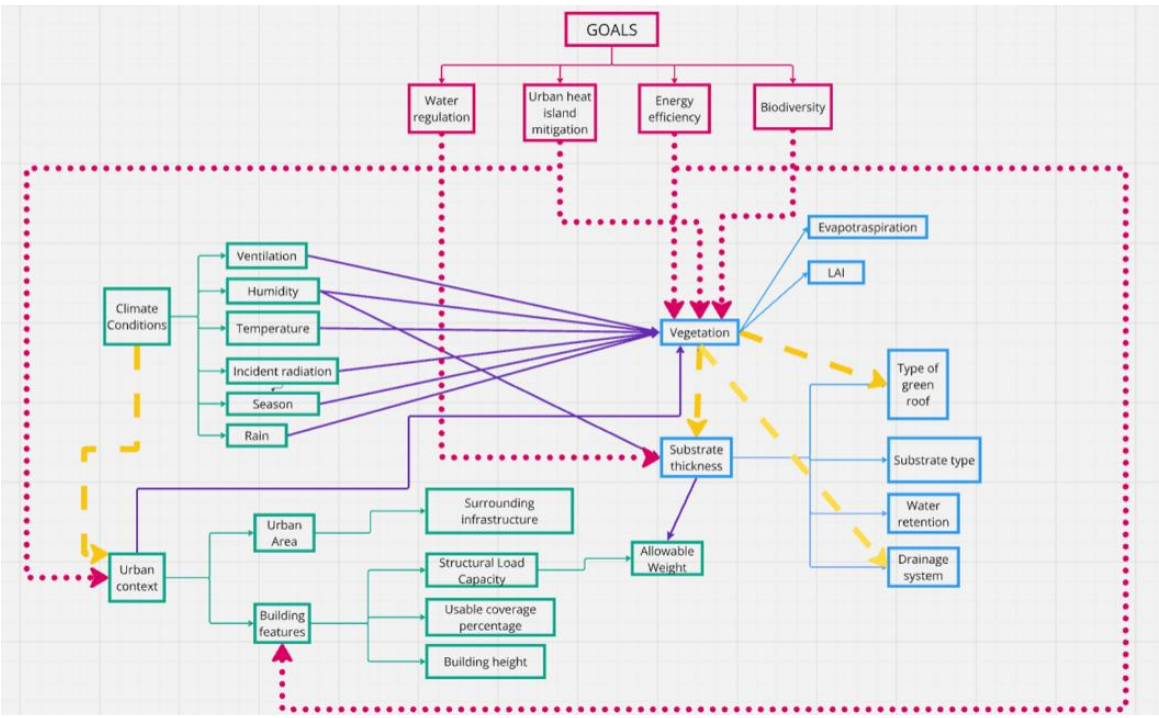
Highlights

- A site-specific, step-by-step framework integrating climatic, ecological, and structural parameters for green roof design.
- Parametric simulations linked to Ellenberg ecological indicators and Köppen climate classification.
- Practical methodology validated through a real case study, adaptable to diverse climates and replicable in professional practice.

Keywords

Green Roofs; Climate-adaptive Green Infrastructure; Framework for Sustainable Design; Urban Heat Island Mitigation; Site-specific Vegetative Systems



Schematic representation of the proposed site-specific framework for green roof design. The diagram illustrates the relationships between climatic parameters, structural constraints, vegetation and substrate selection, and their contribution to urban sustainability goals

The progressive rise in temperatures in urban environments, exacerbated by soil sealing and urban densification, has intensified the urgency for effective and sustainable adaptation strategies. The phenomenon of the Urban Heat Island (UHI) effect, first systematically studied by Oke [1], continues to represent one of the most critical environmental challenges for contemporary cities. Increased surface temperatures not only compromise thermal comfort but also aggravate energy consumption, air pollution, and public health risks [2]. In this context, Nature-Based Solutions (NBS) such as green roofs are increasingly promoted as key interventions to counteract climate change impacts in urban areas [3]. Green roofs have been widely recognized for their multifunctional benefits, including thermo-hydrological regulation, stormwater management, building energy efficiency, biodiversity enhancement, and improved urban livability [4]. Numerous studies have demonstrated their potential in reducing peak stormwater discharge [5], lowering roof surface temperatures [6], and contributing to the cooling of dense urban districts [7]. Moreover, they offer a valuable opportunity for retrofitting existing building stock, which represents a significant portion of European cities' assets. Despite this wide recognition, the design and implementation of green roofs are often still based on generic prescriptions, catalogues, or aesthetic considerations rather than scientifically grounded methodologies tailored to local climatic and structural conditions. This gap limits their long-term effectiveness and risks compromising both ecological and technical performance.

A review of international practices highlights common weaknesses. Many projects do not adequately consider climate-specific vegetation selection, failing to adapt plant species to local temperature, precipitation, or radiation regimes [8]. Substrate characteristics are frequently chosen without regard to climate or plant requirements, resulting in poor water retention or excessive structural loads [9]. Furthermore, the interaction between environmental factors such as wind, solar exposure, and rainfall with vegetation and substrate choices is rarely assessed systematically. The absence of an integrated, site-specific methodology often leads to inefficiencies, reduced biodiversity, and increased maintenance costs.

To address these shortcomings, this paper proposes a holistic and site-specific framework for green roof design. The framework integrates climatic classification, ecological bioindicators, solar radiation analysis, substrate characterization, and structural verification into a progressive decision-making process. The objective is to provide designers with a scientific, replicable, and adaptable method capable of guiding design choices that are coherent with the environmental context, the building's structural characteristics, and long-term sustainability goals.

Methodology

The proposed methodology is structured into successive phases, each addressing a specific dimension of the design process while remaining interconnected with the others (Figure 1).

Step 1. Climatic classification

The first stage involves the collection of climatic and environmental data from the intervention site, including average and extreme temperatures, relative humidity, annual and seasonal precipitation, solar radiation, and wind regimes. These parameters are synthesized through the Köppen-Geiger classification system [5], one of the most widely adopted climatic frameworks worldwide. The classification enables the identification of the climate zone and guides vegetation choices toward species that are naturally adapted to similar environmental conditions. For example, in a Csa Mediterranean climate such as Naples, species must be tolerant to hot, dry summers and moderate rainfall.

Step 2. Ecological bioindication

To refine species selection, the methodology incorporates the Ellenberg indicator values [6], a widely used system of ecological indices that quantify the environmental preferences of plant species for light (L), temperature (T), moisture (U), soil reaction (R), nutrients (N), and salinity (S). By associating Ellenberg values with site conditions, the designer can filter species that are ecologically compatible with the project location. For instance, plants with low Ellenberg U values are selected in arid climates, while species with high L values are suited to sunny roof areas. This phase narrows the initial database into a shortlist of species likely to thrive under the specific microclimatic conditions of the site.

Step 3. Solar radiation analysis
The third phase addresses solar exposure through parametric simulations using Rhino, Grasshopper, and Ladybug Tools. Three-dimensional models of the building and its surroundings are generated, incorporating shading elements such as parapets, adjacent buildings, and vegetation. The simulations provide detailed irradiance maps for daily, seasonal, and annual periods, identifying zones of high and low solar exposure. These maps are then cross-referenced with Ellenberg L values, ensuring that species selected in Step 2 are assigned to roof microzones that correspond to their light requirements. This integration prevents mismatches between ecological needs and actual site conditions, optimizing both vegetation performance and spatial distribution.

Step 4. Substrate selection
Substrate choice is fundamental for the hydrological, thermal, and ecological performance of green roofs. The methodology draws upon technical databases and standards such as FLL (2008), ASTM (2005–2006), and UNI 11235 (2015) [8]–[10], evaluating substrates according to dry and saturated bulk density, water retention capacity, hydraulic conductivity, organic matter content, and particle size distribution. Compatibility is assessed not only with plant root systems but also with the structural load-bearing capacity of the roof. By integrating substrate characteristics with ecological and climatic constraints, the methodology ensures that vegetation is paired with a growing medium capable of sustaining its development without exceeding building limitations.

Step 5. Structural verification
The structural capacity of the existing roof slab is assessed through a dual approach. First, an analytical calculation is performed according to the Italian Technical Standards for Construction (NTC 2018) and the Eurocodes, determining maximum admissible loads based on slab geometry, material properties, and reinforcement details. Second, a computational model developed in Grasshopper allows for real-time simulation of the green roof system's weight under dry and saturated conditions. This parametric tool supports iterative testing of different design configurations, immediately excluding those exceeding structural limits. The combination of analytical rigor and parametric flexibility ensures robust, safe, and feasible design choices.

Step 6. Validation and automation
The methodology is designed to be validated through environmental simulation tools such as ENVI-met, which model the impact of green roofs on microclimatic conditions, including air temperature, humidity, and wind speed. Furthermore, the medium-term goal is the development of an interactive abacus that integrates vegetation, substrate, and structural data, generating validated design solutions automatically.

Case Study

The methodology was tested on a real project: a residential building at 18 Via Dalbono in Portici (Naples), located at 40°49′26″ N, 14°20′21″ E. The building, a reinforced concrete frame structure, is situated in a Csa climate zone according to Köppen-Geiger [5].
In Step 1, climatic data confirmed long, hot summers with average maximum temperatures above 30 °C and moderate annual rainfall concentrated in autumn and winter. Step 2 applied Ellenberg values, filtering an initial database of over 100 herbaceous species and 46 mosses to identify drought-tolerant species with low moisture requirements and tolerance to summer heat. Step 3 used parametric simulations to map irradiance across the roof, revealing sharp contrasts between shaded areas near parapets and highly exposed zones at the center. By cross-referencing solar maps with Ellenberg L values, shade-tolerant species (L=3–5) were positioned in low-irradiance zones, while sun-loving species (L=7–9) were allocated to exposed areas.
In Step 4, substrate types were selected from literature and normative standards, balancing water retention needs with structural constraints. For example, lightweight substrates with high porosity were chosen for sun-exposed zones, while denser, moisture-retentive substrates were used in shaded areas to prevent waterlogging.
Step 5 assessed the structural capacity of the latero-cement slab: analytical calculations confirmed allowable loads of approximately 350 kg/m², while Grasshopper simulations verified that the proposed green roof stratigraphy (including vegetation and saturated substrate) remained within safety margins.

The results confirmed that the methodology allows for the progressive narrowing of vegetation choices from a broad initial database to a final, ecologically and structurally feasible configuration. The approach ensured that selected species were both climatically adapted and structurally compatible, minimizing risks of plant failure or roof overloading.

Discussion and Applicability

The case study demonstrates that this methodology offers significant advantages over traditional design approaches. By integrating climatic classification, ecological bioindicators, and parametric simulations, it provides a scientifically grounded framework that reduces uncertainty and inefficiency in species and substrate selection. From a sustainability perspective, the framework enhances biodiversity by prioritizing species adapted to local climates rather than ornamental or exotic plants. It also reduces maintenance and irrigation requirements by aligning vegetation choices with natural ecological preferences. From a technical perspective, the integration of structural verification ensures that retrofitting interventions remain feasible and safe, a crucial factor for existing buildings.

Conclusion

In conclusion, the proposed methodology contributes an innovative and applicable framework for the sustainable design of green roofs. It is distinguished by its site-specific, multidisciplinary, and interactive nature, integrating engineering standards, ecological science, and parametric modeling. Validated through a real case study in the Mediterranean climate, it demonstrates its potential for replication in diverse geographical contexts. By systematically linking climatic parameters, ecological indicators, solar radiation analysis, substrate selection, and structural verification, the methodology ensures that green roof design is no longer arbitrary but scientifically substantiated. Ultimately, it equips designers with a practical tool to deliver durable, efficient, and climate-responsive green roofs, contributing to UHI mitigation, improved microclimates, biodiversity, and urban resilience. In an era marked by climatic and environmental emergencies, adopting such rigorous and adaptable design approaches is not just desirable but necessary for the sustainable transformation of our cities.

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Investigating the indoor-outdoor cooling potential of Nature-based Solutions from the building to the district scale

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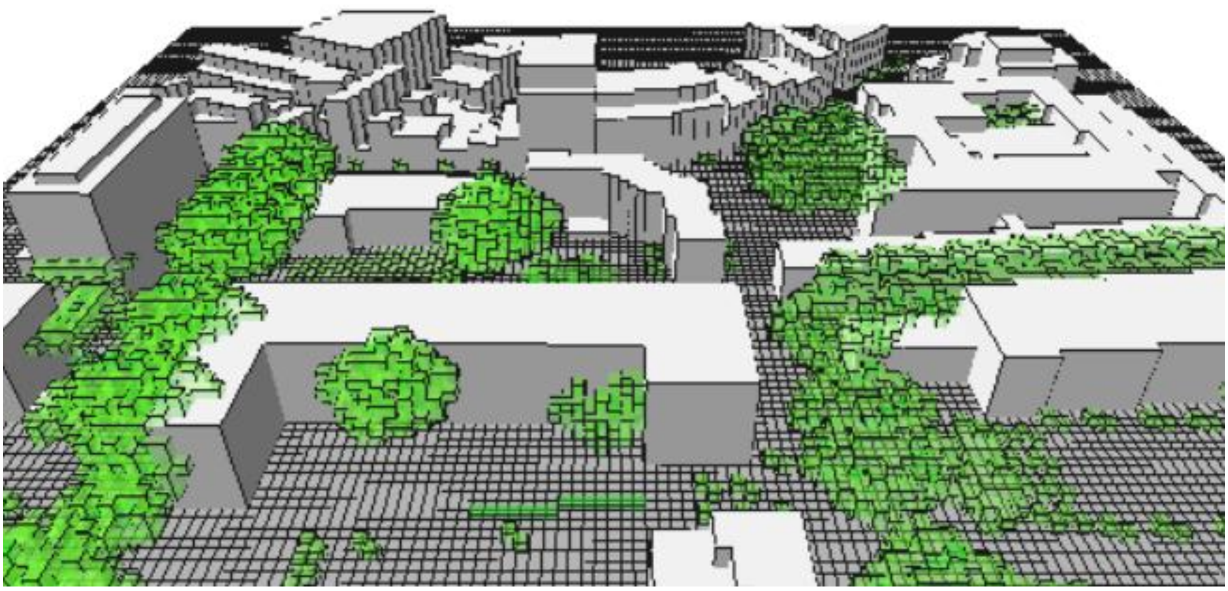
Highlights

- District-scale green facades have a notably impact on outdoor thermal comfort
- District-scale green roof applications have higher impact on air temperature
- Combining green facades and green roofs enhances their positive impact indoors

Keywords

Green Façade; Green Roof; ENVI-met; Nature-Based Solutions; Urban Heat Island



ENVImet 3D model for the ''Base Case'' scenario

The present climate emergency is significantly impacting the quality and liveability of urban ecosystems. Urban areas are particularly vulnerable during the summer months, as increasing numbers of heat waves result in unbearable thermal conditions in both indoor and outdoor spaces. Furthermore, the shift towards a hotter climate is exacerbated by the urban heat island effect, increasing energy consumption and heat-related risks in cities. In this context, urgent action is needed to reduce both urban and building overheating.

The re-naturalisation of urban environments is the best solution to reverse such a vicious heat cycle. Increasing urban green infrastructures can have multiple climate benefits, among which is the reduction of air temperature and mean radiant temperature at the street level. When it comes to the building scale, nature-based solutions (NBS) such as green facades (GF) and green roofs (GR) can be adopted. In summer, GFs and GRs reduce the heat flux to the buildings' interior, while also reducing the external radiant temperatures. Therefore, they can have a positive impact on both the indoor and the outdoor environments.

The positive effect of GF and GR on the indoor thermal conditions and cooling energy demand of buildings has been confirmed by several studies. A comprehensive review on the thermal performance of GFs was carried out by Reza Bakhshoodeh [1]. The results showed a consistent reduction in external wall surface temperature and air temperature gap in summer, across different climate regions. The review examined the impact of various design features, revealing that detached façades have a higher cooling potential than attached ones. It also emphasised the significance of volumetric water content of the substrate as a critical factor in the cooling capacity of green façades through evapotranspiration. Some studies also investigated the positive impact of GF and GR at the urban scale. Peng et al. [2] examined the potential of large-scale GFs application to reduce cooling demand in urban blocks with different layouts and densities. The results showed that the cooling energy saving potential of GFs at the block scale varies with urban form, being lower in high-rise, high-density areas than in mid-rise, mid-density areas. Similarly, Abuseif et al. [3] investigated the cooling potential of various types of green roofs in different urban layouts. Their results suggest significant potential for improving indoor thermal conditions and reducing building cooling energy loads, as well as having a positive impact, albeit reduced, on outdoor air temperature. However, the cooling effect varies significantly depending on the GR system and urban density. Together, these studies emphasise the variability in the cooling potential of NBS when applied to individual buildings versus larger scales. This underlines the importance of conducting district-level analyses to determine their overall cooling potential. This study aims to investigate the indoor and outdoor cooling potential of NBSs applied to buildings and districts. This is based on the hypothesis that GFs and GRs can have a greater positive impact on the urban heat island effect when applied at the district scale, and that this improvement in the urban microclimate would have a positive effect on the cooling demands of urban buildings.

To this end, we propose a simulation approach using the ENVImet software to assess the impact of different deep-retrofit scenarios using GF and GR. As opposite to previous studies, we carried out simulations for a real-world urban area: the UPC University Campus of Terrassa (Catalonia, Spain). The simulations are carried out for different scenarios considering the application of GF to just one individual building – the campus's library – or at the district scale, including all the buildings in the surrounding urban block.

Four scenarios are simulated and compared:

Scenario 1 (Base case) [Figure 1]: Representing the current situation for urban form, vegetation and materials.

Scenario 2 (GF): It involves the application of GFs only to the campus' library building.

Scenario 3 (District GF): It consists of applying the GF also to the district buildings. In this scenario, the GF accounts for 50% of the buildings' envelope, to account for the percentage of wall surface without windows.

Scenario 4 (District GF + District GR): It considers the application of GR to the library and the district. The ratio of GR is 50% of the total roof area in the district. This percentage corresponds to the ratio of flat roofs in the district, which are suitable for the installation of green roofs.

Each scenario includes the measures implemented in the previous one, with the addition of the newly introduced intervention, in order to analyse the combined effects. All the simulations are carried using one typical day of August as input weather data. The simulation period is 48 hours, as the first day serves to let the model warm up properly and obtain more reliable results starting from the second day.

The simulation results showed that all the scenarios have a positive impact at both the district scale and the building scale, but with significant differences among them. At the district scale, we analysed the change in potential air temperature, mean radiant temperature, and relative humidity, all factors involved in the calculation of PET, Physiological Equivalent Temperature. This allows understanding the potential improvement in terms of outdoor thermal comfort (OTC) for pedestrians in each scenario.

The results show that the combination of different strategies produces greater positive effects on outdoor thermal comfort. The best results in air temperature reduction is observed with the application of green roofs, while a notable decrease in mean radiant temperature is achieved through the use of green façades at the district scale. The combination allows a reduction in PET by up to 2 °C in the afternoon.

For the library building, the results are also analysed at the building scale. At this scale, we focus the analysis on the impact of GF and GR on the external surface wall temperatures in the different orientations and the building's indoor air temperature. The greatest impact of GF is found on the external surface temperature of the wall, with a maximum decrease of up to 19°C compared to the brick wall. These results are in line with other studies reporting a maximum surface temperature difference of up to 21.9 K between greened and bare façades [4].

The surface temperature reduction determined by GF is analysed at different points of the four façades oriented south, west, north, and east. The smallest impact of GF on surface temperature reduction is observed on the north façade, as expected. On the south façade, GF has a significant positive impact on brick wall surface temperature. Conversely, where, in the base case, a white solar protection system is present, the application of the GF does not lead to a significant surface temperature reduction. In fact, the wall surface temperature behind the GF becomes even hotter than the white solar protection in the hours of maximum solar irradiation. However, the white solar protection also cools down more slowly, remaining warmer during the night hours compared to the GF.

We also analysed the impact of the different scenarios on the building's indoor temperature. The results show a clear reduction in indoor temperatures starting from noon and increasing in the afternoon and night hours. According to ENVImet simulations, the application of GF allows a maximum reduction in indoor temperatures by 1 °C compared to the baseline model. This result is consistent with a previous study [5] finding a reduction in the indoor surface temperature of a wall with a GF by 0.7 °C compared to a bare wall on sunny days. When both GF and GR are applied, the internal temperature decreases by almost 3 °C compared to the base case, confirming the greater contribution of GR on indoor building thermal conditions as found by [3].

It must be noted that these results are based on ENVImet simulations, which are not very accurate for calculating building indoor thermal conditions compared to detailed models such as EnergyPlus. The building energy model in ENVImet considers the dynamic heat transfer through the building envelope, but does not account for internal gains and ventilation. Despite that, the results are in line with experimental data [5]. Further developments of this work will investigate a more accurate coupling simulation methodology using ENVImet and EnergyPlus.

In conclusion, the study confirmed a significant potential of NBS applied to buildings in both the indoor and outdoor environments. Significant improvement in outdoor thermal comfort is obtained when GF and GR strategies are combined and extended beyond individual buildings. District-scale GR applications have a higher urban heat island mitigation potential. At the building scale, both GF and GR have a positive impact on indoor air temperature, with GR being more relevant. These results confirm the potential for district-scale building retrofits using NBS to improve urban thermal comfort while contributing to the transition towards climate-neutral buildings and cities.

This work has been supported by the EDUPED project (PCI2024-155068-2), funded by the Spanish State Research Agency (AEI) under the 'International Collaboration Projects' initiative. Call: PCI2024-2"

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Biochar-enhanced green roofs for Mediterranean climate

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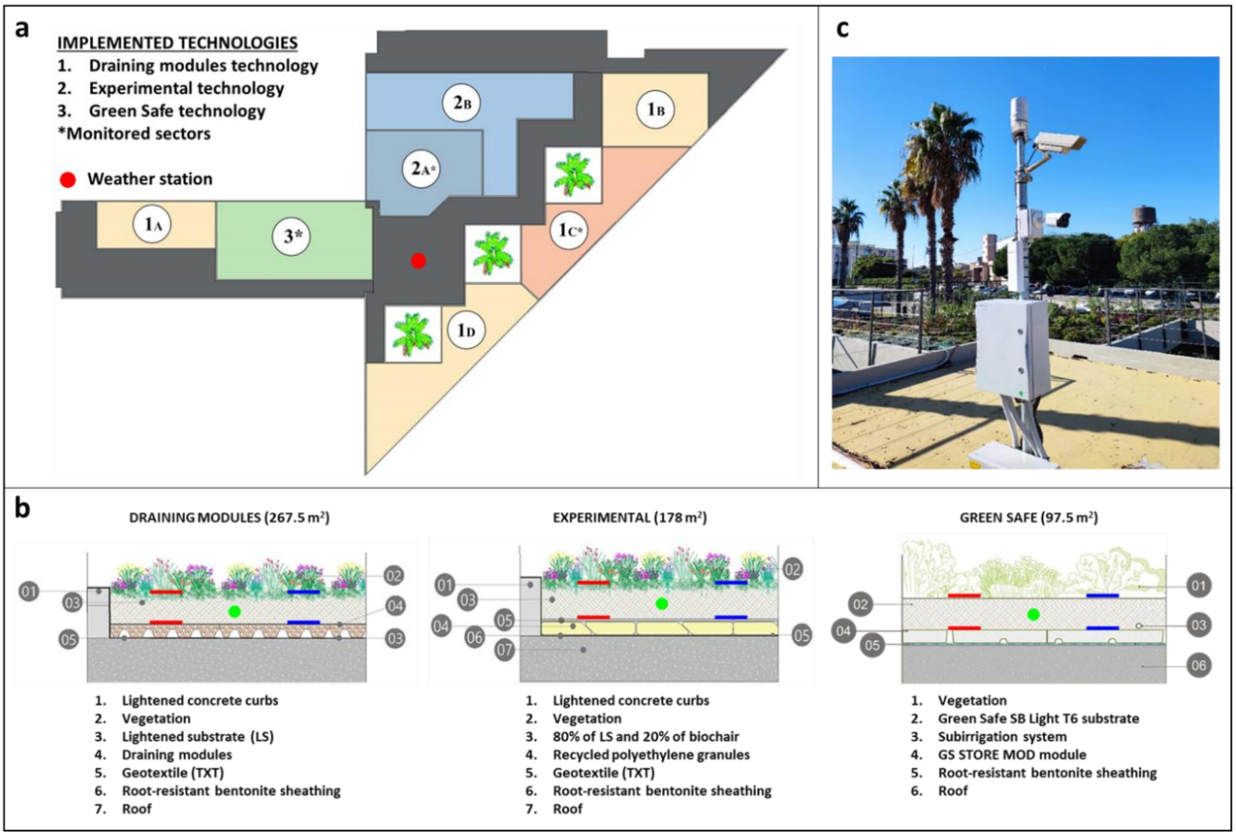
Highlights

- Biochar boosts green roof cooling under hot and dry summer conditions
- Enhanced water retention improves thermal stability and plant health
- Energy simulations show 10% cooling demand reduction in buildings

Keywords

Urban Heat Island Mitigation; Cooling Energy Savings; Water Retention Capacity; Thermal Insulation Performance; Sustainable Building Design



Schematic layout of the green roof installation with monitored sectors (a), installed weather station used for environmental monitoring (b), cross-sectional diagrams of the three implemented technologies (c)

Introduction

Urbanization and climate change are intensifying the environmental and energy challenges facing cities, with Mediterranean urban areas vulnerable due to their climatic profile, characterized by hot and dry summers and mild and wet winters [1]. This combination of meteorological stressors exacerbates urban heat island (UHI) effects, increases energy consumption for cooling and limits the effectiveness of vegetation-based climate adaptation strategies [2]. Among nature-based solutions, green roofs are recognized as multifunctional systems that mitigate urban overheating, regulate stormwater, enhance biodiversity and improve building energy performance [3].

However, most existing research on green roof effectiveness has focused on temperate or tropical climates, with limited empirical data and comparative assessments available for Mediterranean conditions. The region's unique climate demands localized evaluations of green roof technologies regarding substrate composition and long-term performance during extended dry periods [4]. Moreover, innovative materials such as biochar, a carbon-rich product of biomass pyrolysis with excellent hydrological and thermal properties, remain underexplored in green infrastructure applications [5].

This study addresses these research gaps by providing a comparative analysis of three extensive green roof technologies, such as Draining Modules, Green Safe and an Experimental biochar-enhanced system, installed on a public institutional building in Catania, Italy. Through field monitoring and calibrated energy simulations, the research aims to assess their performance in terms of thermal regulation, water retention, energy efficiency and UHI mitigation. The study also examines the potential of biochar as a sustainable substrate component in green roof design.

Methodology

Lorem The study was conducted within the framework of the INTERREG V-A Italy-Malta GIFLUID project and implemented on the 900 m² atrium roof of the Bioscientific Hub at the University of Catania (Figure 1). The roof was divided into sectors, each assigned a different green roof technology:

- Draining Modules: A conventional design using polypropylene drainage panels filled with expanded clay and a mixed lightweight substrate.
- Green Safe: Featuring water-retentive polyester felt and sub-irrigation pipes within a mineral-rich substrate.
- Experimental Technology: Incorporating recycled polyethylene granules for drainage and a substrate composed of 20% biochar and 80% commercial green roof mix.

A reference roof with a standard waterproof membrane and ceramic tiles was used for comparison. The monitoring period spanned the peak summer week of June 22–30, 2024, during which no irrigation was applied to simulate typical drought conditions.

High-precision sensors were deployed to collect thermal and hydrological data at 10-minute intervals. These included Type K thermocouples (for surface and substrate temperatures), heat flux sensors (DPE240), Time Domain Reflectometry (TDR) probes for volumetric water content and a weather station recording ambient conditions. All sensors were calibrated before deployment.

In addition to field monitoring, energy simulations were conducted on a representative six-story residential building model using DesignBuilder interfaced with EnergyPlus. Simulation parameters were validated using the experimental data and evaluated using ASHRAE 14 guidelines. The simulation assessed surface temperature reduction and cooling energy demand.

Statistical analyses included Welch's ANOVA and Tukey's HSD post-hoc test to verify the significance of performance differences across the three technologies.

Results

The Experimental Technology demonstrated superior thermal performance. Average midday surface temperatures were 26.5°C, compared to 30.0°C for Draining Modules and 31.5°C for Green Safe. The biochar-enhanced substrate also exhibited the lowest substrate temperatures and heat flux values, confirming its effectiveness in insulating the building and reducing thermal gain.

Water retention results followed a similar trend. The Experimental system maintained an average volumetric water content of 73.7%, outperforming the Draining Modules (65.2%) and Green Safe (60.3%). The porous

structure of biochar enabled enhanced moisture retention and evaporative cooling, contributing to the system's superior thermal behavior during the dry summer period.
Statistical validation confirmed the observed differences. Welch's ANOVA yielded $F = 149.10$, $p < 0.001$, indicating significant variance across the technologies. Tukey's HSD identified the Experimental roof as cooler than both Draining Modules ($p < 0.001$) and Green Safe ($p = 0.0017$). The Green Safe system, despite its integrated sub-irrigation, underperformed thermally due to limitations in substrate composition and moisture distribution.
In terms of energy performance, simulations revealed that the Experimental system reduced summer cooling demand by 10%, equating to 3.8 kWh/day or 340 kWh over the cooling season. The Draining Modules reduced energy use by 6.5% (2.5 kWh/day), while Green Safe achieved a 5% reduction (1.9 kWh/day). These figures align with the experimental findings on surface temperature and heat flux.
Regarding UHI mitigation, the biochar-based system achieved the largest reduction in ambient rooftop air temperature, 3.8°C on average, compared to 2.7°C for Draining Modules and 2.1°C for Green Safe. These reductions were most pronounced during afternoon peak hours, when solar radiation and heat re-emission are highest. This confirms the potential for biochar-enhanced green roofs to contribute to localized cooling in urban neighborhoods.
To complement the summer campaign, the study included a preliminary seasonal assessment using shorter-term data collected in spring and winter. The Experimental roof continued to exhibit the best performance in terms of thermal stability, with reduced winter heat losses and minimized daily temperature fluctuations. Water retention also remained more consistent year-round, highlighting the resilience of the biochar substrate across seasonal extremes.

Discussion

The results of this study underscore the multifunctional advantages of biochar-enhanced substrates in green roof applications within the hot-dry context of Mediterranean cities. The combination of improved water retention and moderated surface temperatures provides substantial benefits for building energy efficiency and local microclimatic regulation.
The Experimental Technology outperformed both commercial alternatives in all monitored and simulated dimensions, confirming biochar's role as a high-performing and sustainable substrate amendment. These findings are consistent with previous research in agricultural and ecological domains, where biochar has demonstrated notable hydrological and thermal properties. However, this study extends its application into the built environment, demonstrating its relevance for passive design strategies and climate adaptation at the urban scale.
The implications for policy and sustainable design are substantial. The adoption of biochar-enhanced green roofs aligns with the goals of:

- The European Green Deal and the Renovation Wave initiative, which promote large-scale energy efficiency improvements in the building sector;
- Italy's CAM (Minimum Environmental Criteria) for environmentally sustainable construction;
- The United Nations Sustainable Development Goals, particularly SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).

Nevertheless, several limitations should be acknowledged. Although the monitoring period was well-calibrated to capture peak summer conditions, extended multi-seasonal and multi-year observations are required to assess long-term substrate performance, vegetation dynamics, potential biochar degradation and maintenance needs.
In addition, the scalability of biochar use in urban green roof applications warrants further investigation. While biochar presents circular economy benefits when derived from locally sourced organic waste, such as pruning residues or agricultural by-products, challenges related to production capacity, supply chain logistics, standardization and cost competitiveness remain. These factors may limit widespread deployment unless integrated within regional waste valorization strategies or supported by green public procurement policies.
From an environmental standpoint, a preliminary life cycle perspective suggests promising benefits in terms of carbon sequestration and avoided emissions. However, a comprehensive life cycle assessment (LCA) of biochar-based substrates is essential to quantify their environmental footprint and net climate impact. Such an analysis should account for feedstock origin, pyrolysis conditions, transport distances and end-of-life

scenarios. The integration of LCA findings with economic evaluations would also support a holistic cost-benefit comparison with conventional green roof systems.
Finally, future research should explore the potential for integrating biochar-based systems within digital workflows, including BIM (Building Information Modeling) and urban digital twin platforms.

Conclusion

This study presents an evaluation of green roof technologies under the demanding environmental conditions of a Mediterranean climate. The Experimental Technology, incorporating biochar in its substrate, demonstrated improved performance across thermal and energy-saving metrics compared to both commercial alternatives and a traditional reference roof. It also contributed to reductions in rooftop temperatures and localized UHI effects.
These findings affirm the role of biochar-enhanced green roofs as a viable strategy for promoting sustainable urban development and enhancing resilience to climate change. By combining empirical monitoring and simulation the study offers evidence for integrating such systems into climate adaptation policies and building design standards.
Continued research over multiple seasons and at larger urban scales is essential to support the broader adoption of biochar-based systems and unlock their full potential in sustainable infrastructure development.

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Non-invasive energy efficiency techniques applied to an office building in Southern Italy

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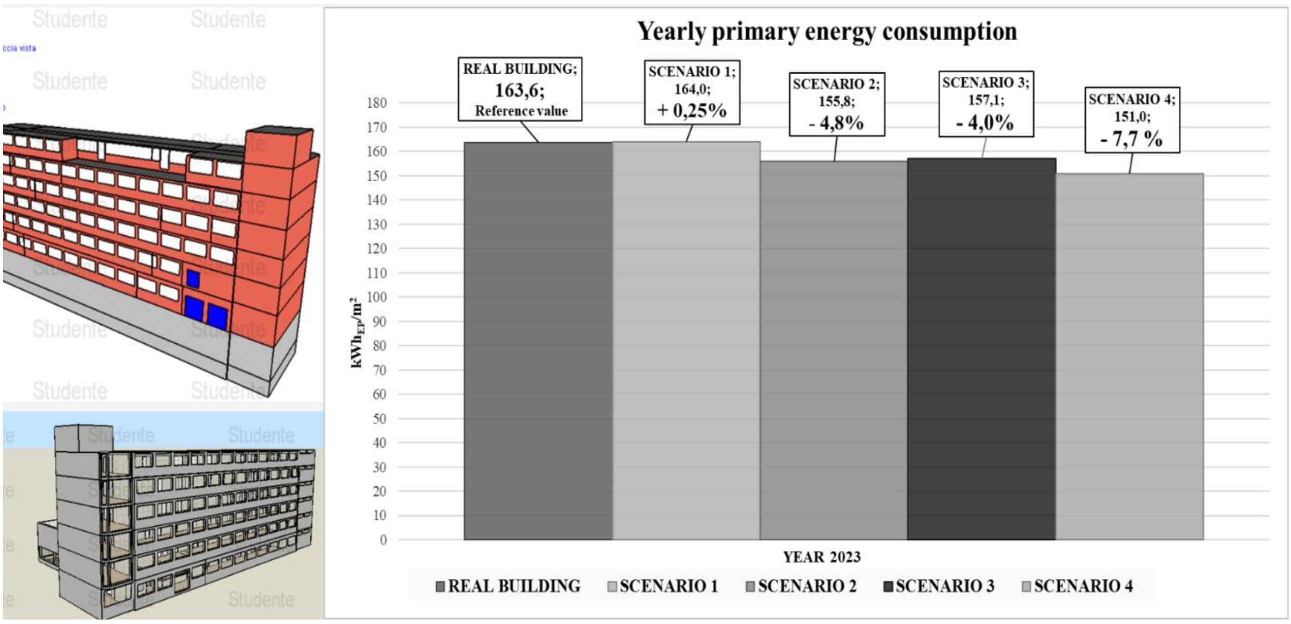
Highlights

- Changing indoor air temperature set point saves 4.8% energy without investments
- Replacement existing generator with a heat pump saves 29% on heating energy
- Combining both methods results in total energy saving of 7.7%

Keywords

Energy Efficiency; Daylight Saving Time; HVAC; Dynamic Simulation; Heat Pump



Office building used as case study and yearly primary energy consumption for the different proposed retrofit scenarios

The recent energy crisis has brought to the forefront issues related to energy security, ecological transition and energy-saving strategies. Energy efficiency measures — such as thermal insulation of building envelopes, replacement of outdated windows and the use of renewable energy sources — are often expensive and time-consuming to implement. For this reason, attention has been given to energy efficiency strategies that can deliver energy savings more quickly and with little or no additional cost. Daylight saving time has been the subject of ongoing debate; several studies have assessed its impact on the construction sector, showing that its adoption can have varying effects on energy consumption, depending on the sector involved (commercial, public or residential) and the time of year during which it is applied [1][2]. The penalization of indoor air temperature setpoints consists of lowering the heating setpoint in winter and raising the cooling setpoint in summer. According to Italian regulation DPR 74/2013 [3], the average indoor temperature must not exceed 20 °C in heated environments and must not fall below 26 °C in cooled ones. Penalization strategies adjust these limits to 19 °C in winter and 27 °C in summer, reducing energy consumption for heating and cooling. Studies, such as that of M. Bagheri et al. [4], confirm that this approach can lower gas demand. One of the main energy efficiency techniques is the replacement of a traditional heat generator, such as a gas boiler, with a more efficient generator, such as an air-to water heat pump. The heat pump is an efficient heating and cooling technology with both economic and environmental benefits, as confirmed by other studies and in particular in the paper by G. Thomaßen et al. [5].

Based on this, the aim of the paper is to investigate these simple energy efficiency techniques that can reduce the final energy consumption of an existing office building. The analysis is performed using DesignBuilder, a dynamic simulation software based on EnergyPlus [6] calculation engine to evaluate heating, cooling, lighting, ventilating and other energy consumption, based on the features and capabilities of BLAST and DOE-2. Before implementing the model in the software, a series of preliminary operations were carried out. Site surveys were conducted to gather information and data on the building and its systems, including the stratigraphy of the building envelope components, technical specifications of the HVAC system components, occupancy data, office equipment in use, installed lighting and more. All the collected data were processed and analyzed to develop a model that accurately reflects the actual building. Modelled the real building in DesignBuilder, dynamic simulation was carried out to define the energy consumption of the case study building. The energy consumption obtained has been converted into primary energy by applying the conversion factors taken from D.M. 26/06/2015 [7], reported in Table 1.

Table 1.*Conversion factors of energy vectors into primary energy from D.M. 26/06/2015 [7]*

Energy vector	$f_{P,nren}$	$f_{P,ren}$	$f_{P,tot}$
Electricity from the grid	1.95	0.47	2.42
Natural gas	1.05	0	1.05

The case study concerns an existing office building located in Naples (Southern Italy), a city characterized by mild winters and hot summers. The building has six above-ground floors and two underground levels. The total net area of the thermal zones is approximately 3,412 m², with a total net volume of 11,092 m³. The thermal zones include offices and corridors, all maintained at the same indoor air set-point temperature — 20°C in winter and 26°C in summer — though they differ in parameters such as occupancy levels and internal heat gains. The occupancy schedules are:

- for the offices: from 07:00 to 17:00, from Monday to Friday;
- for the corridors: from 07:00 to 18:00, from Monday to Friday.

The existing HVAC system uses natural gas and electricity as energy sources. It consists of fan coil units and an Air Handling Unit (AHU) connected to a traditional gas boiler (nominal capacity: 201.0 kW) and a water-cooled chiller (nominal capacity: 405 kW) linked to a cooling tower. The toilets are equipped only with an exhaust ventilation system.
Four different scenarios have been proposed (Fig.1) to analyze simple energy efficiency techniques, with the aim of determining which of them would result in the greatest energy savings for the existing office building.

- Scenario 0: Existing building and related systems.

- Scenario 1: equal to scenario 0, but without the adoption of the daylight-saving time.
- Scenario 2: this scenario considers the existing building and associated systems with the implementation of indoor air temperature penalization in air-conditioned spaces. Specifically, the indoor air temperature setpoint is reduced from 20°C to 19°C in winter, while it is increased from 26°C to 27°C in summer.
- Scenario 3: existing building and related systems, but a new heat generator is considered (an air-to-water heat pump).
- Scenario 4: this scenario combines the two energy efficiency measures previously analyzed in Scenarios 2 and 3: the penalization of indoor air temperatures in air-conditioned environments and the replacement of the traditional heat generator. The indoor air temperature setpoints are adjusted to 19°C in winter and 27°C in summer, while the gas boiler is replaced with an air-to-water heat pump.

The main characteristics of the traditional gas boiler, the water-cooled chiller and the proposed air-to-water heat pump are reported in Table 2, Table 3 and Table 4, respectively.

Table 2. *Thermal and energy parameters of the traditional gas boiler*

Gas boiler	Nominal capacity [kW]	η (efficiency)
Heating	201.00	0.92

Table 3. Thermal and energy parameters of the water-cooled chiller

Water-cooled chiller	Nominal capacity [kW]	EER (Energy Efficiency Ratio)
Cooling	405.00	4.66

Table 4.*Thermal and energy parameters of the proposed heat pump*

Air-to-water heat pump	Nominal capacity [kW]	COP (Coefficient Of Performance)
Heating	202.5	2.98

By comparing the primary energy savings achieved through the application of different energy efficiency techniques across the four scenarios, the following conclusions can be drawn:

- The adoption of daylight-saving time can be considered a complementary technique, resulting in a minimal energy consumption reduction of 0.25%.
- The penalization of indoor air temperature setpoints in air-conditioned environments can be considered as an effective non-invasive energy efficiency strategy, as it reduces energy consumption by 4.8%.
- Replacing the traditional gas boiler with an air-to-water heat pump results in energy savings of 4.0% and is one of the most effective minimally invasive efficiency upgrades.
- The combination of the two strategies — adjusting indoor air temperature setpoints and replacing the heat generator — results in substantial energy savings of 7.7%.

Specifically, when considering energy consumption related to heating and cooling systems:

- Adjusting indoor air temperature setpoints leads to notable savings: primary energy consumption for heating is reduced by 24.1% and by 18.4% for cooling.
- Replacing the traditional gas boiler with an air-to-water heat pump produces 29.0% reduction in primary energy consumption for heating.
- The combination of temperature adjustment and replacement of the gas boiler with an air-to-water heat pump achieves very high energy savings: a 46.1% reduction in primary energy consumption for heating and an 18.4% reduction for cooling.

Another result concerns thermal comfort. This has been evaluated through Fanger's model [8] in DesignBuilder, with comfort indicators PPD (predicted percentage of dissatisfied) and PMV (predicted mean vote). The UNI EN ISO 7730:2005 [9], defines three classes (A, B, C) each corresponding to a certain predicted percentage of dissatisfied PPD and a certain range of PMV. Through these classes, you can define comfort in indoor air-conditioned environment as "optimal", "acceptable" and "limit", as shown in Table 5:

Table 5. *Thermal comfort categories from ISO 7730:2005 [9]*

Class	PMV	PPD (%)	Comfort in indoor air-conditioned environment
A	from -0.20 to +0.20	≤ 6	"Optimal comfort"
B	from -0.50 to +0.50	≤ 10	"Acceptable comfort"
C	from -0.70 to +0.70	≤ 15	"Limit comfort"

During the winter season, the real building does not meet thermal comfort standards, as the comfort indices fall outside the acceptable PMV range (−0.5 to +0.5), with a percentage of dissatisfied occupants exceeding 10%. Lowering the indoor air temperature to 19°C further worsens thermal discomfort, while replacing the heat generator does not affect comfort conditions. In the summer season, the real building achieves thermal comfort corresponding to Class A. Both the non-adoption of daylight-saving time and increasing the setpoint temperature by 1°C led to a higher percentage of dissatisfied occupants; however, comfort conditions remain within acceptable limits, corresponding to Class B. To ensure thermal comfort during the winter season would require the adoption of invasive energy efficiency measures aimed at modifying parameters that directly influence thermal comfort, such as indoor air relative humidity and overall mean radiant temperature
Based on the results obtained, the most significant energy savings were achieved during the winter season, primarily due to the replacement of the traditional heat generator with a more efficient one (heat pump). In contrast, no modifications were required for the cooling system, as the existing chiller already demonstrated a high Energy Efficiency Ratio (EER). Nevertheless, it was observed that increasing the indoor set point temperature in summer by just 1 °C can lead to a substantial reduction in energy consumption. This strategy is particularly relevant in Mediterranean climates, where a significant rise in cooling demand is expected due to climate change. The study focuses on the implementation of energy-saving strategies which, although effective in reducing energy consumption, may also reduce building environmental impacts that require further assessment. Future developments of the analysis will extend beyond the scale of individual buildings to include neighborhood level applications, aiming to evaluate the overall effectiveness and sustainability of these interventions. This broader perspective is crucial for addressing the complex and systemic challenges posed by climate change.

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Thermal benefits evaluation of a construction system for green facades in existing buildings

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Highlights

- Design of a modular vertical greening system for upgrading existing buildings
- Thermal simulations show reduced heat input and improved indoor comfort
- Passive cooling strategies in Mediterranean climate, in line with EPBD 2024

Keywords

Nature Based Solutions; Vertical Greenery System; Green Façade; Energy Efficiency.

Example of VGF4EB application. At blind walls, the system will act as a covering. In this case (detail on the left), the distance from the wall will vary between 0.25 m and 0.3 m, and evergreen plants will be used to provide shade throughout the year. On opaque and glazed surfaces, the system will act as a solar radiation screen. In this case (detail on the right), the distance from the walls will vary depending on the projection of the balconies, and deciduous plants will be used to provide shade during the summer season (top) and maximum natural light in the winter season (bottom)

Maintaining climatic comfort conditions within a building requires significant energy consumption and incurs enormous environmental costs.
The European Energy Performance of Building Directive 2024/1275 (EPBD) aims to improve the energy efficiency of buildings, reduce emissions and achieve the goals of the European Green Deal. It promotes the use of passive technical solutions for buildings, with the aim of achieving, especially in summer, thermal comfort conditions, reducing or avoiding the use of cooling systems. This type of approach may be particularly suitable in Mediterranean climates, such as Italy, where the energy requirements for summer cooling of buildings exceed those for winter heating.
In recent years, urban greening has become a central issue in sustainable city development policies. Among the various greening strategies, Vertical Greenery Systems (VGS) are one of the possible solutions and an effective approach to improve the quality of urban life. VGSs not only contribute to the improvement of the microclimate [1] and thermal performance of buildings [2], reducing energy demand [3] and thus heating and cooling costs (by virtue of the shading produced by vegetation on the exterior surfaces of buildings and the consequent interception of solar radiation [4]), but they also promote mitigation of the urban heat island effect (UHI) [5] achievable through shading and evapotranspiration of vegetation [6], increased biodiversity [7] and reduced noise and air pollution [8].
As part of the PRIN 2022 PNRR Project titled: Greenwork: an interdisciplinary framework for urban health and urban resilience enhancement based on greening strategies on buildings and open spaces, a Vertical Greening Frame for Existing Buildings (VGF4EB) was designed. It is a modular building system, falling under the category of indirect continuous cable systems, made of tubular steel profiles dry-assembled through threaded joints, characterized by high lightness, flexibility of use, ease of assembly, versatility, cost-effectiveness and adaptability [9].
The versatility of the VGF4EB and its ability to adapt to different morphological and geometrical characteristics of various buildings are possible due to two peculiarities of the designed system:
- the parts that make up the elementary module (mullions, transoms and spacers) are all obtainable from the assembly of a small number of elementary tubular profiles, of prefixed dimensions, which can be composed with each other so as to obtain variable overall lengths starting from 50 cm and increasable by 5 or 10 cm at a time;
- elementary tubular profiles are connected to each other by means of joints and threaded sleeves, which allow for adequate tolerance (up to 5 cm for each joint).

The VGF4EB is designed to serve both as a covering for blind walls and as a solar radiation shield for opaque and glazed surfaces [10]. Depending on how it is used, both the distance between the module and the wall and the type of vegetation will vary: evergreen species in the case of cladding, deciduous plants in the case of screening. In the latter case, to ensure good levels of lighting in the rooms even when the plant reaches maximum leaf growth, the application will be carried out in a precise manner on sections of the façade that have no openings or are equipped with openings for service rooms such as bathrooms and laundry rooms.
The devised building system was validated by hypothesizing its application to buildings in the Monte Po economic and social housing district in Catania. And on one of these, of the open courtyard type, the benefits of applying the designed shading, in terms of reducing indoor temperatures and improving the energy efficiency of the buildings, were evaluated using thermal simulation software.
Through simulations using ClimateStudio software, the values of the environmental variables: operating temperature, mean radiant temperature and relative humidity as well as heat fluxes were determined and compared.
ClimateStudio is a plugin for the 3D modeling software Rhinoceros (Rhino) and supports multi-zone thermal simulations using the U.S. Department of Energy's EnergyPlus whole-building simulation program.
To carry out the simulation, a particularly thermally significant apartment within the case study building was chosen, located at the head of one of the two wings that define the building's courtyard, located on the fourth of the building's five total floors and having a triple exposure: northeast, southeast and southwest.
The green façade entirely covers the southeast blind wall, while along the southwest elevation it takes on the function of discontinuous solar shading. It was rendered on the model through a series of rectangular surfaces equal in size to the dimensions of the VGF4EB module. Three levels of surface porosity coinciding with three different values of leaf cover density were evaluated. This parameter, described by the Leaf Area Index (LAI), is different for each plant species and varies throughout the year in deciduous trees. LAI conditions not only the formal results of a green cover also for the bioclimatic functions that can be associated with the vegetation cover: the shading characteristics related to a plant species placed in a covering to an opaque or transparent vertical building closure depend on it.

In the case under consideration, three different LAI values corresponding to 20%, 50% and 70% were evaluated.
The examined dwelling was divided into thermal zones, one for each room. Four models were created that differ only in the porosity of the panel representing the green facade:
1. Current status, taken as the starting data with which to compare the values obtained in the other models;
2. Screening surface simulating the presence of the green façade with LAI 20%;
3. Screening surface simulating the presence of the green facade with LAI 50%;
4. Screening surface simulating the presence of the green facade with LAI 70%.

Simulations were carried out for each of the above listed cases; the results were organized on two levels: whole apartment and single thermal zone.
The results obtained show that, as was to be expected, the summer months represent the most onerous thermal condition.
In particular, comparing the results obtained from the analysis of energy flows of the four simulations carried out for the thermal zone "Kitchen" (southwest exposure) in the hottest week (August 20 to 27), we deduce that:
- the reduction of heat transmitted through the opaque surfaces of the thermal Zone under consideration, resulting from the application of VGF4EB, occurs throughout the year;
- the reduction of transmitted heat varies in different hours maintaining a reduction value between 0.01 kWh and 0.03 kWh.

This reduction although not high, already manifests itself from the lowest value of the degree of coverage of the surface simulating the vegetation layer (LAI equal to 20%); this reduction increases proportionally with increasing leaf density, the values of heat gained and lost are in fact slightly lower when the simulation was performed with the surfaces characterized by a higher porosity index equal to 50% and 70%.
With regard to the average radiant temperature, operating temperature and relative humidity at the center of each Zone, similar considerations to those obtained in terms of energy flows are drawn from the analysis of the results obtained; in particular, the temperature lowering due to solar radiation shielding of the Thermal Zone under consideration, resulting from the application of VGF4EB, is recorded throughout the year, thus also in winter, under the assumption of the use of perennial and non-deciduous plants. The results obtained show that:
- in the absence of VGF4EB, in the week from 20 to 27 August, it reaches a maximum value of 34.0 °C for average radiant temperature, 34.2 °C for operating temperature and an average relative humidity value of 64%.
- in the presence of VGF4EB, in the same week, it reaches a maximum value of 33.7 °C for average radiant temperature, 34.0 °C for operating temperature and an average relative humidity value of 66%.

Although the reduction is not high, it is already evident from the lowest value of the degree of surface coverage simulating the vegetation layer with LAI equal to 20% and increases proportionally when the simulations are performed with LAI equal to 50% and 70%.

Conclusions

The growing need to contain energy consumption for summer cooling of buildings, especially in Mediterranean contexts, makes the use of passive strategies capable of improving the thermohygrometric performance of the building envelope a priority. In this direction, the VGF4EB modular system has proven to be an effective and adaptable solution for vertical greening of existing buildings, due to its light weight, compositional flexibility and ease of installation.
The results obtained from the thermal simulations conducted on the selected case study highlight the effectiveness of the system in mitigating summer heat load, improving indoor comfort and contributing to the energy efficiency of buildings.
Such evidence confirms the potential of vertical greening systems as concrete operational tools for the green transition of the existing building stock, in line with the objectives outlined by the EPBD and the European Green Deal. The use of VGF4EB can be a viable strategy for integrating bioclimatic solutions into redevelopment processes, without compromising building morphology and without further soil consumption.

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Robust design of cost-effective and low emission building-HVAC systems under uncertainties: a new possibilistic approach

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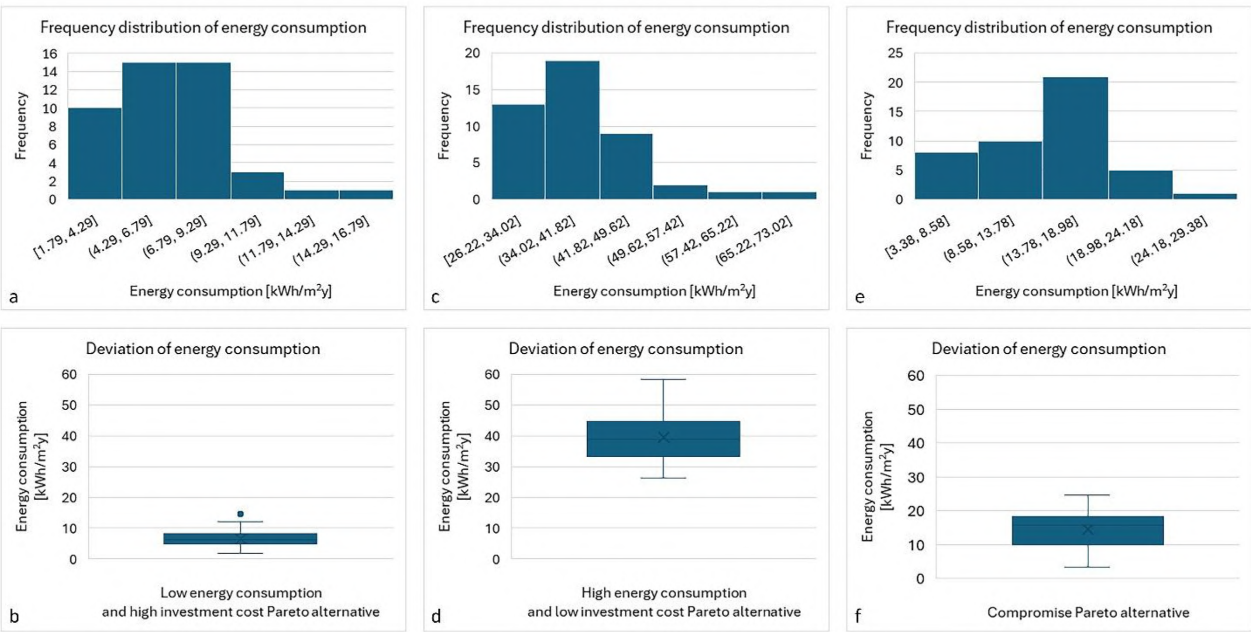
Highlights

- Possibilistic robust optimization for HVAC system design under uncertain scenarios
- Multi-objective trade-offs reveal cost-CO_2 robust balance in HVAC system designs
- Triangular fuzzy numbers map frequency distributions for post Pareto analyses

Keywords

Building Energy Efficiency; HVAC Design; Uncertainty Modeling; Robust Optimization; Possibility Theory



Frequency of occurrence of energy consumption values and related deviations referred to 3 Pareto optimal alternatives: a-b) low energy consumption and high investment cost; c-d) high energy consumption and low investment cost; e-f) compromise

The performance of HVAC (Heating, Ventilation and Air Conditioning) systems, integrated by RES (Renewable Energy Sources), is inherently affected by uncertainties such as weather variability and changing occupancy patterns. Typical uncertainties (future weather, occupancy levels, infiltration and as-built building envelope, HVAC system aging and renewable energy system yield/tariffs) propagate to energy and peak loads, comfort and costs, thereby affecting sizing, life cycle assessment and design choices. These uncertainties can lead to significant deviations from the expected energy performance, undermining both energy efficiency and economic sustainability [1]. Different sources of uncertainty exist in building performance evaluations, including modeling uncertainties arising from simplified representations of complex phenomena, numerical uncertainties linked to the discretization methods used in simulations, and input uncertainties that stem from variability or incomplete knowledge about input parameters [2]. In this study, the focus is on input uncertainties, specifically, the aleatory uncertainties associated with weather variability and occupant behavior. By integrating these diverse uncertainty sources into the performance assessment, the proposed approach aims to develop more robust and resilient design strategies for the building-HVAC-RES systems, under a wide range of future conditions. Traditional design and optimization methods often fail to account for these uncertainties, resulting in systems that may perform well under nominal conditions but poorly when faced with real-world variability [2]. This underscores the critical need for performance robustness in the design of building-HVAC-RES systems. Robust optimization provides a framework for designing systems that maintain optimal performance despite uncertainties and fluctuations in operating conditions [3]. By incorporating robustness into the design process, technicians of the sector can develop systems that not only meet regulatory requirements but also deliver consistent energy savings and comfort levels throughout the building's operational life. Considering the substantial investments involved in implementing these advanced systems, ensuring their reliable performance is essential for achieving long-term sustainability goals and maximizing return on investment.

To design buildings that perform reliably under real-world conditions, it is essential to quantify how uncertainties affect building performance. Indeed, uncertain factors can significantly impact energy consumption, indoor environmental quality and overall sustainability [4]. Different disciplines have developed methodologies to evaluate system performance under uncertainty, employing concepts such as reliability, robustness, resilience, flexibility and adaptability [5]. In the context of building design, robustness assessment is particularly pertinent, also when considering long-term performance over decades. Robustness refers to a building's ability to maintain desired performance levels despite uncertainties in operational and external conditions [6].

Analyzing the propagation of uncertainties and their impact on building performance enables designers to identify strategies that enhance robustness without resorting to oversizing the systems or incurring excessive costs. For instance, multiple design configurations may exhibit similar performance under idealized, deterministic conditions but differ significantly when subjected to real-world uncertainties [7]. Without proper assessment, decision-making processes may inadvertently favor designs that are sensitive to uncertainties, leading to performance deviations during operation. By systematically quantifying the effects of uncertainties, designers can make informed decisions that balance performance, cost and risk. This approach supports the development of buildings that not only meet regulatory requirements but also maintain consistent performance over their lifespan, despite the inherent variability in operating conditions. In practice, designers often have limited information about the probability of various uncertain events, making probabilistic risk assessments difficult. For example, predicting future occupant behavior, climate conditions or policy changes involves significant uncertainty [8]. In such situations, scenario analysis emerges as a valuable tool.

Scenario analysis involves creating a range of plausible future conditions without assigning specific probabilities to them. By evaluating how different design options perform across these scenarios, designers can assess the robustness of each option. This method helps identify designs that consistently deliver acceptable performance under diverse conditions, thereby enhancing resilience to uncertainties [7].

Previous studies have applied scenario-based robustness assessments to specific uncertainties, such as occupant behavior or climate change projections. For instance, evaluating designs under various climate scenarios can reveal potential overheating risks in highly insulated buildings as global temperatures rise [9]. However, assessing each uncertainty separately may not capture the interactions between different factors. An integrated approach that considers multiple uncertainties simultaneously is necessary to provide a comprehensive evaluation of design robustness [10]. Such an integrated scenario-based evaluation enables stakeholders to understand the trade-offs between different design choices and their implications under various future conditions. It supports more resilient design strategies that can adapt to changing circumstances over the building's lifespan.

Building design is inherently a multi-objective problem involving various stakeholders with diverse and sometimes conflicting priorities. Architects, engineers, building owners, occupants and policymakers may each emphasize different performance criteria, such as energy efficiency, cost, environmental impact and occupant comfort [11]. Balancing these objectives requires a comprehensive evaluation of design options against multiple performance objectives, quantified by several key performance indicators (KPIs).

Incorporating uncertainties into this multi-objective assessment adds complexity to the decision-making process. Traditional methods often rely on predefined weighting factors for each performance indicator, which can be subjective and may not accurately reflect stakeholder priorities under uncertain conditions [12]. Assigning appropriate weights becomes even more important when these reflect contrasting interests of different stakeholders, shifting the relative importance of different criteria.

To address these challenges, advanced multi-criteria decision-making (MCDM) methodologies are needed. These methodologies should facilitate the evaluation of design options without relying solely on fixed weighting schemes. Trade-off approaches, such as Pareto optimization, can identify a set of optimal solutions that offer the best possible balance between conflicting objectives. Stakeholders can then select the most suitable design based on their specific preferences. Integrating robust optimization with MCDM allows for the identification of design solutions that perform well across multiple criteria and remain effective under a range of uncertain conditions. This approach supports more informed and balanced decision-making, enabling stakeholders to select designs that align with both their performance goals and their robustness requirements.

To clarify, multi-objective optimization (MOO) refers to the mathematical process of simultaneously optimizing multiple conflicting objectives to generate a set of Pareto-optimal solutions, while multi-criteria decision-making (MCDM) involves the subsequent evaluation and ranking of these solutions by incorporating stakeholder preferences and subjective criteria. In this paper, MOO is used to denote the algorithmic derivation of optimal trade-offs and MCDM to describe the decision analysis framework that facilitates the final selection of the most robust and suitable design option. Each design is simulated across a large Latin-hyper-cube sampling; the resulting empirical distributions of investment cost and $CO_{2\text{-}eq}$ emissions are converted into triangular fuzzy numbers (TFNs) [13] by mapping selected cumulative-probability quantiles to the lower, modal and upper vertices of TFNs. This probability-to-possibility transformation preserves the information content of the data while replacing probabilistic assumptions with a possibilistic description.

The new methodology is demonstrated on a four-story office building whose envelope transmittances, glazing ratio, thermal mass, infiltration rate, photovoltaic system and battery sizes, solar-thermal area, mechanical-ventilation rate and six alternative HVAC/DHW (Domestic Hot Water) system typologies define a thirteen-dimensional design space. Occupancy density, heating- and cooling-season set-points, internal gains, natural-ventilation rates, dynamic solar-shading thresholds and four IPCC SSP (Intergovernmental Panel On Climate Change - Shared Socioeconomic Pathways) climate pathways represent a second set of seventeen scenario variables that capture the main operational and climatic uncertainties.

The first results summarized in **Errore. L'origine riferimento non è stata trovata.** illustrate how the f requency distribution of energy consumption (and consequently related CO_2 emissions) values vary across three distinct Pareto optimal alternatives, each reflecting a different trade-off between energy use and investment cost. The panels can be interpreted as follows:

1. Low energy consumption and high investment cost (panels a–b):
    - Panel (a): The histogram reveals a distribution predominantly concentrated at lower energy consumption levels. This confirms that the design prioritizes energy efficiency.

- Panel (b): The relatively narrow spread of deviations indicates that, although this alternative requires a higher initial investment, its energy performance is consistent and robust across different scenarios of operating conditions.

2. High energy consumption and low investment cost (panels c–d):
   - Panel (c): Here, the frequency distribution shifts towards higher energy consumption values, which is in line with the objective of reducing upfront costs.
   - Panel (d): The larger deviations suggest a higher variability in energy performance. This variability may imply that while the investment cost is lower, the energy consumption outcomes are less predictable, potentially increasing operational risk or uncertainty.
3. Compromise alternative (panels e–f):
   - Panel (e): The frequency distribution in this case falls between the other two alternatives, indicating a moderate energy consumption level. This suggests that the compromise alternative effectively balances the dual objectives.
   - Panel (f): The deviations are also moderate, reflecting a trade-off that neither fully minimizes energy consumption nor investment cost but offers a balanced performance with acceptable consistency.

Overall, these graphs underscore the inherent trade-offs in design choices. The low energy alternative achieves stable and efficient energy performance at the cost of higher capital expenditure, while the high energy alternative reduces initial costs at the expense of increased energy usage and performance variability. Decision making operations using TFNs allowed to find a balanced compromise Pareto alternative. To enhance robustness and limit method-related bias, the fuzzy MULTIMOORA method (combining Ratio System, Reference Point and Full Multiplicative Form into a dominance-based synthesis) is used. Also, equal criterion weights are applied to obtain a balanced compromise solution. The compromise alternative, meanwhile, provides a balanced solution that may be preferable when both energy efficiency and investment constraints are important.

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Cultivating belonging: everyday aesthetics, shared care, and sensory well-being in urban Nature-based Solutions

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Highlights

- From cosmetic greenery to everyday aesthetics in Nature-Based Solutions
- Sensory care practices create urban spaces of meaning and relation
- Aesthetic habits counter eco-anxiety through rhythm and proximity

Keywords

Everyday Aesthetics; Aesthetics of Care; Urban Nature; Participatory Practices; Green Infrastrucure

Dimension	Technocratic NBS	Relational-Aesthetic NBS
Functionality	High technical efficiency, often isolated from social use	Multi-functional – combines ecological, social, and symbolic functions
Sensory Engagement	Low – primarily visual, limited sensory diversity	High – promotes tactile, olfactory, visual and auditory interactions
Community Participation	Low – top-down design with little user interaction	High – co-designed and maintained by local communities
Eco-Anxiety Mitigation	Minimal – lacks emotional and therapeutic engagement	High – supports emotional resilience through care and continuity
Aesthetic Value	Superficial or cosmetic aesthetics	Situated, emergent, and affective aesthetics

From decorative green to Embodied belonging: aesthetic functions of Nature-based Solutions (NbS). This comparative matrix illustrates how relational-aesthetic Nature-based Solutions enhance sensory engagement community belonging, and emotional resilience, shifting the focus from decorative greenery to embodied urban habitability

Introduction

In light of the ecological, health, and social challenges facing contemporary cities, Nature-Based Solutions (NBS) are increasingly recognised as key tools for rethinking the relationship between urban environments, collective well-being, and resilience to climate change. This is evident in numerous European and international policies and frameworks (e.g., the Green Deal, EU Biodiversity Strategy, Urban Agenda for the EU, and UN SDGs).

However, certain implementations risk remaining bound to technocratic, functionalist, or superficially aesthetic logics, reducing urban greenery to mere decorative or environmental technology. This paper proposes a relational approach that highlights the transformative power of shared, slow, and sensory-based practices that nurture a sense of place and foster ecological citizenship. Drawing on the concepts of everyday aesthetics and the aesthetics of care [8,9,5], biophilia [7], and affective ecology [1], it explores how NBS can become not just ecological tools, but lived and performative spaces that enhance inhabitants' well-being and cultivate belonging.

Research Aims and Objectives

This paper aims to reframe Nature-Based Solutions (NBS) through the lens of everyday aesthetics, arguing for a shift from technocratic approaches to more situated, sensory, and participatory practices. The objectives are to:

- theorize the aesthetic dimension of care as a response to eco-anxiety and spatial alienation;
- identify the relational and sensory potentials of everyday green practices;
- demonstrate how small-scale participatory interventions can foster affective ecological citizenship and a sense of belonging.

The study offers a conceptual synthesis that aims to enrich existing literature with a fresh interpretive lens.

Methodology and Theoretical Framework

This study adopts a theoretical and interpretive methodology rooted in environmental humanities, affect theory, and the philosophical tradition of aesthetics. Rather than relying on quantitative data, it develops a conceptual framework grounded in interdisciplinary literature and exemplary urban practices, analysed through the lens of situated aesthetics and affective ecology.

Drawing on key thinkers — from Baumgarten's sensory cognition [2] to Saito's everyday aesthetics [8] — the paper interprets care practices as embodied, sensory knowledge. In this light, care can be understood as both a sensorial experience and a civic act — reconnecting people to space and to one another through embodied, everyday gestures. As participatory ecological art demonstrates, repeated gestures of care can crystallise into aesthetic habits — embodied forms of knowing that foster identity, belonging, and environmental responsibility [4].

Beyond Cosmetic Greenery

In recent years, greenery in urban space has become increasingly visible and technologically advanced (green roofs, vertical gardens, and ornamental planting are widespread). While these interventions have contributed to raising environmental awareness in urban design, they often remain bound to an aestheticising logic focused on external beauty. In some cases, nature is reduced to decorative surface or iconic environmental technology, signalling sustainability without fostering deeper relationships between citizens and their environment.

This phenomenon has been discussed in literature through notions such as "green camouflage," or "eco-gentrification". Projects such as Milan's "Bosco Verticale," while emblematic in terms of architectural innovation and ecological potential, have also prompted critical reflection on accessibility, long-term maintenance, and the relationship between environmental quality and social inclusion. Although they contribute to reimagining urban landscapes, such interventions do not always promote everyday practices of care and spatial appropriation, both essential to genuine eco-social regeneration.

In contrast, participatory and dispersed practices (urban gardens, pocket parks, and co-designed temporary installations) foster a lived aesthetics in which greenery becomes a medium of perception, interaction, and informal learning.

These contexts are characterised by slow, cyclical, embodied time: plant growth, seasonality, and daily care return affective and shared dimensions to the urban landscape. This reflects a situated aesthetic, where beauty does not dominate but co-emerges from interactions between bodies, spaces, and communities, aligned with the vision of an affective ecology.

Moreover, tools such as the Biophilic Quality Matrix [10] show that evaluating green interventions should consider not only the presence of natural elements but their capacity to generate emotional connections, sensory stimulation, and community relations. In this light, greenery becomes a catalyst for embodied and collective experiences, capable of re-signifying urban space and fostering shared ecological citizenship.

Aesthetics of Participation, Care, and Eco-Anxiety Mitigation

The everyday gesture becomes an aesthetic and political act when it transforms space and builds relationships, despite its apparent ordinariness. Simple acts such as planting a flower, watering a garden bed, or constructing shared furniture constitute interventions that affect the urban environment not only functionally, but symbolically, perceptively, and affectively. These gestures generate a quotidian aesthetic that challenges efficiency-driven logics and the demand for immediate impact, instead affirming a diffuse, situated, and emergent beauty.

As Erika Fischer-Lichte [6] notes, performative practices can trigger an “aesthetic contagion” that changes the perception of space and activates belonging. Participatory practices (communal gardening, pocket garden maintenance, or self-building of ecological furnishings) function as collective aesthetic rituals that generate a sense of place.

In this context, Gernot Böhme’s theory of “aesthetics of atmospheres” proves particularly insightful. For Böhme [3], atmosphere is a spatially perceived quality arising from the interaction between environmental elements (light, materials, sound) and bodily perception, irreducible to either subject or object. Urban atmosphere thus becomes an active design dimension, shaping citizens’ experience and fostering shared and affective perceptions of space. Aesthetics of atmosphere (as experience emerging from situated relations among bodies, materials, and context) becomes a lever for affective and symbolic engagement.

Participatory urban greenery can thus become a space that activates resilient communities and fosters social cohesion. In these micro-practices we see the emergence of an aesthetic ecological citizenship that values the interdependence between living beings and their environments.

The growing prevalence of eco-anxiety reflects the emotional difficulty of coping with ongoing environmental transformations. In this context, care can be understood as an everyday aesthetic practice that generates stability, proximity, and orientation. Slow, rhythmic, and situated practices serve as resistance to contemporary instantaneity, helping to decelerate the perception of time and restore depth to urban experience.

Applied Example: Urban Gardening in Palermo

A significant example is the “Orto Capovolto” initiative in Palermo, a grassroots urban gardening project co-managed by residents, artists, and students. Situated in a post-industrial area, the space has been transformed into a community garden hosting activities such as shared cultivation, composting, and seasonal workshops. These slow and cyclical practices engage multiple senses — including sight, touch, and smell — fostering both emotional resilience and ecological sensitivity. The aesthetic experience extends beyond visual enjoyment to include textures, sounds, and practices of care grounded in bodily engagement, encouraging a deeper sense of environmental responsibility. As a micro-laboratory of the principles explored in this paper, Orto Capovolto illustrates how situated practices can reshape urban atmospheres and foster eco-social regeneration. It stands as a compelling instance of the aesthetics of care: through repeated, multisensory acts, it generates atmospheres of belonging and shared ecological consciousness, in line with the perspectives of Böhme and Saito.

Conclusion: Situated Beauty and Shared Habitability

Rethinking urban greenery from an everyday aesthetic perspective means reimagining the city as a lived environment — a place of sensitive coexistence rather than a mere functional infrastructure. In this view, aesthetics is not decoration, but a return to *aisthesis*, the Greek notion of perceptual and embodied world experience. This lineage — from Baumgarten to Böhme and Saito — foregrounds sensory and affective dwelling as foundational to urban design.

Rather than an ornamental addition, aesthetics becomes a structural element that weaves together environmental, sensorial, and social dimensions. Nature-Based Solutions should thus be understood not simply as technical tools, but as affective landscapes that foster well-being, place attachment, and a sense of belonging. Urban policies, in turn, must adopt an interdisciplinary and responsive approach, attentive to the experiential and relational qualities of space, in order to promote environments that are truly livable, inclusive, and enriching. Such an approach invites a renewed aesthetic responsibility in urban planning — one that embraces slowness, care, and co-inhabitation as pillars of ecological resilience.

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Climate change and the building sector: trends in mitigation, adaptation, and green strategies in scientific research

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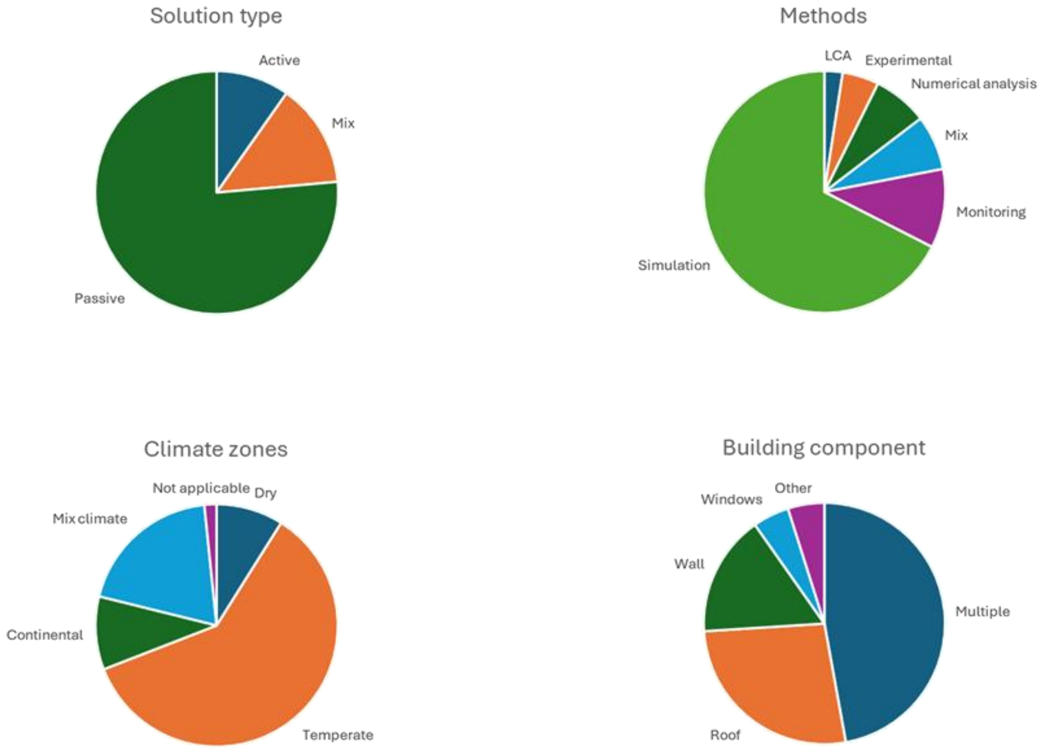
Highlights

- There is an increasing focus on adaptation strategies within the building sector
- Roofs and walls are the most frequently targeted for intervention
- Extreme heat is receiving more attention compared to other climate-related hazards

Keywords

Climate Change, Adaptation, Mitigation, Building Sector Resilience



Distribution of papers according to solution type, research method, climate zone and involved building component

Climate change is a global issue that has caused the temperature in Europe to rise by 2.3 °C (4.14 °F) since pre-industrial times (as of 2022). Buildings contribute to more than 30% of the EU's environmental footprint, making this sector the most significant source of environmental impact [1-3]. Conversely, climate change is increasingly impacting the building sector across Europe, exposing built environments to a growing range of climate-related hazards. Rising temperatures, more frequent and intense heatwaves, flooding, droughts, and extreme winds are already stressing buildings' integrity, energy consumptions, and indoor comfort levels. According to the EU-level technical guidance on adapting buildings to climate change, these hazards threaten not only the longevity and safety of buildings but also the well-being of occupants and the resilience of entire communities [4].
Building on this policy framework, this study presents a descriptive analysis of scientific literature focused on climate change mitigation and adaptation measures in the building sector. The scope of the analysis is to identify prevailing research trends, mitigation and adaptation strategies, and targeted building components.

The dataset for analysis is the result of an extensive, systematised literature review of peer-reviewed papers with a clear quantitative outcome. The authors have screened Scopus documents, published over a decade, from 2014 to 2024. The analysis comprises papers focused on mitigation and adaptation strategies for existing buildings, excluding literature reviews, position papers and any kind of study with no reference to a simulated or tested mitigation or adaptation strategy. Additionally, papers focused on heritage and temporary buildings have been excluded, as well as papers that simulate future weather scenarios with no implications for adaptation and mitigation at the building scale.
The screening process, which initially considered 4,925 articles, resulted in 123 full-texts analysed and categorised according to: type of strategy (adaptation, mitigation, or both); targeted building component or sub-component (e.g., roof, wall, insulation material); type of analysis (e.g., experimental, simulation-based, numerical); building typology (e.g., residential, educational, office); climate-related hazard addressed (e.g., heatwaves, temperature rise, heavy precipitation); and climate zone, based on the Köppen classification system [5].
The analysed papers discuss several mitigation and adaptation strategies, many of which (49;40%) are adaptation measures only, around one third of the papers (38;31%) propose mix strategies and the related implications in terms of both mitigation and adaptation, and the remaining one third (36;29%) propose mitigation strategies only.
Most of the papers involve interventions on multiple building components (58; 47%), especially those related to the envelope. Multiple interventions can also involve heating, cooling, and ventilation systems. Single interventions are mostly reported in reference to the roof (33; 27%), wall (20; 16%), and windows (6; 5%). Around 13% of the analysed papers discuss nature-based solutions, either in terms of green roofs or green facades. Building sub-components are involved too, as around 16% of the analysed dataset is based on this narrow scale analysis.
Benefits and challenges of the explored mitigation and adaptation strategies are quantified via simulations (83;67%), monitoring studies (13;11%) and experimental analysis (6;5%).
The residential sector is the leading sector in terms of climate-proofing scenarios, accounting for almost half of the dataset (50;41%), followed by learning institutions (23;19%) and commercial and business facilities (19;16%).
Both acute and chronic climate-related hazards have been addressed by the current scientific literature, although the results show that many studies concerning the building sector have discussed strategies to deal with rising temperatures and heatwaves mostly. Indeed, acute stresses related to the heat stress, such as extreme temperatures, heatwaves, and urban heat island, are addressed by 54% of the dataset. Moreover, one fourth (24%) of the dataset addresses the rising temperature issue as well as future weather scenarios, providing for long-term analysis and chronic stresses arising from increased temperatures. A very small percentage of the analysed documents present adaptation strategies to heavy precipitation and flooding (5%), and only one paper analyses the issues posed by hurricanes. The remaining papers do not address any specific threat or potentially disruptive scenario.
Heatwaves, intense precipitation events, flooding, and temperature variability represent significant disruptive phenomena that can compromise building functionality, lead to economic losses, pose safety risks, and drive increased energy demand and greenhouse gas emissions. In this sense, the dataset under analysis contains

several mitigation and adaptation measures used to quantify the beneficial effects and trade-offs of the investigated strategies. More specifically, among the measures of mitigation benefits, the reduction of CO2 emissions, reduced energy demand, reduced cooling energy consumption and overall energy savings are reported. Common measures of adaptation benefits include indoor overheating degree or other parameters accounting for the number of hours exceeding a safety temperature threshold, parameters of indoor comfort, outdoor surface or air temperature, heat flux and runoff coefficient.

The climate zones have been categorised referring to the Koppen system which divides climates into five groups based on rainfall and temperature. All European climate zones have been considered for analysis, i.e., temperate, dry and continental climates. Not surprisingly, most of the mitigation and adaptation tested or simulated strategies come from temperate climates (74; 60%), dry climates account for 9% of the dataset and continental climates for 10%. The remaining papers cover more than one climate zone, thus cannot be categorised in one group only.

Finally, 76% of the investigated solutions do not involve mechanical systems nor require energy to be activated (i.e., passive solutions), while the remaining 24% involve active or mixed interventions. Interestingly, adaptation strategies rely more on passive solutions than on active systems, whereas mitigation strategies involve an equal share of active and passive solutions. Figure 1 summarises the results of the conducted descriptive analysis.

The findings of this literature-based analysis highlight the increasing research focus on climate change mitigation and adaptation strategies in the building sector, underscoring the urgent need to address the increasing climate-related stresses on built environments. The predominance of adaptation-focused studies (40%) indicates a growing concern about the immediate and long-term resilience of buildings to acute and chronic climate hazards, especially extreme heat.

The relatively balanced distribution between mitigation-only (29%) and mixed (31%) strategies highlights a promising trend toward integrated approaches, acknowledging the co-benefits and potential trade-offs of strategies that address both mitigation and adaptation objectives. Notably, the prevalence of simulation-based studies suggests a gap in real-world validations that should be addressed in future research. Also, the limited focus on other critical sectors (e.g., healthcare facilities) may indicate knowledge gaps that warrant further exploration.

A notable asymmetry in the attention to climate hazards emerges from the analysis: heat-related stresses dominate the literature, whereas hazards such as heavy precipitation, flooding, and wind are significantly underrepresented. Given the increasing frequency of extreme weather events across Europe, this suggests a research bias or lag in addressing multi-hazard resilience, particularly for regions experiencing compound climate risks.

Finally, the geographical skew toward temperate climate zones reflects both the higher research capacity in these regions and a greater perceived urgency due to rapidly shifting baseline temperatures. The underrepresentation of studies in dry zones, despite their growing vulnerability, calls for greater geographical diversification in future research to ensure that adaptation and mitigation strategies are context-specific and equitable.

To enhance the resilience and sustainability of Europe's building stock, future research must prioritise multi-hazard assessments, empirical studies, and interventions tailored to diverse climate and socio-economic contexts.

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Bioclimatic redevelopment of Villa IX Maggio: an integrated design approach

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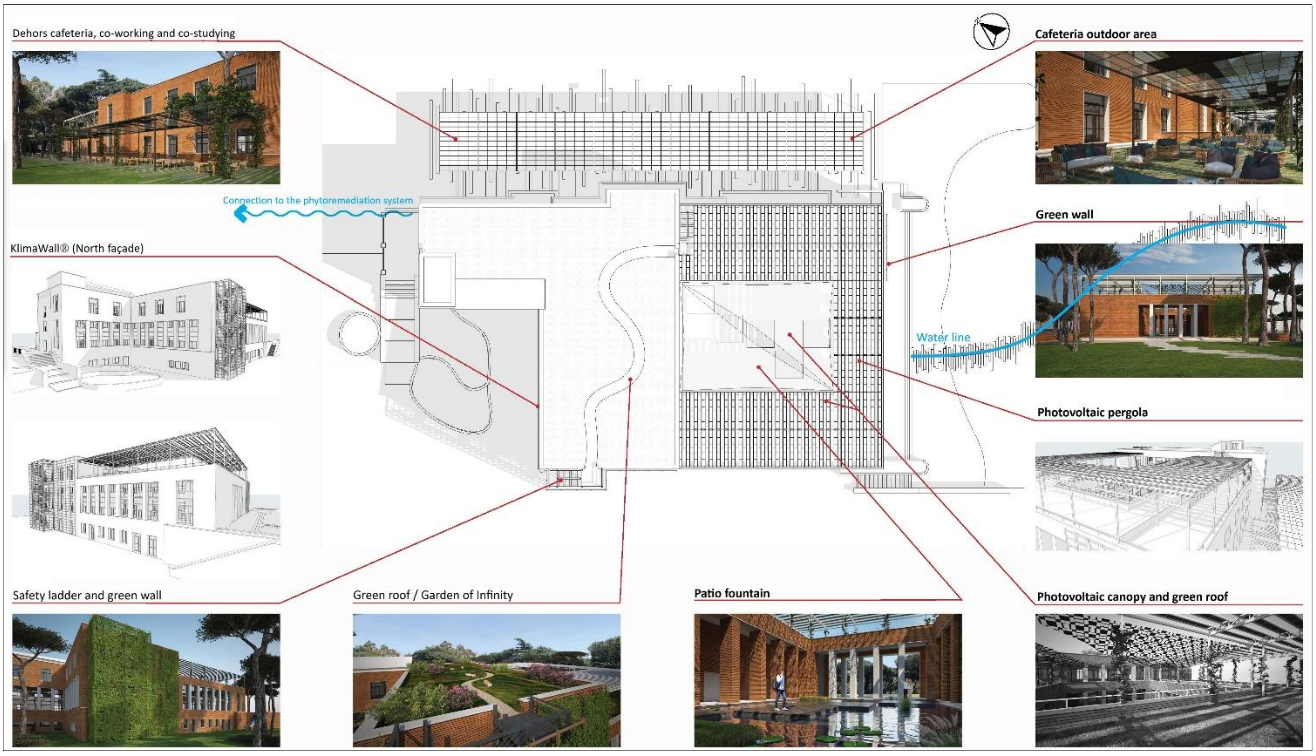
Highlights

- Urban scale: soil re-permeation, pathways & bio-continuity, renewables
- Building scale: low-impact design integrating traditional & advanced technologies
- Social scale: fostering connection, knowledge sharing, and positive exchange

Keywords

Modern Architecture; Bio-Architecture; Green Walls; Green Roofs; Blue–Green Infrastructure.



Overview of the principal bioclimatic interventions on Villa IX Maggio

The final project of the 2nd-level Master's in Bio-architecture, organized by the Fondazione Italiana di Bioarchitettura, provided the opportunity to address the complex challenge of restoring and upgrading a modern building of historical significance through a bioclimatic approach. The design task involved transforming a Rationalist landmark into an innovative, CO_2-positive structure that applies best practices in healthy building, establishing a centre of excellence in bio-architecture and renewable energy technologies while also restoring socio-cultural balance and revitalizing a neglected site.
The case study is Villa IX Maggio, also known as Convitto Locchi, located in Rome's Garbatella district. Designed by Angiolo Mazzoni and inaugurated in 1936 as a girls' boarding school, the villa and its surroundings form the core of the intervention.

Urban Integration and Campus Vision

A primary objective is to establish systemic connections between the villa, the planned Higher Education and Research Campus, the neighbourhood, and the broader urban context of Rome, spanning energy, education, social inclusion, planning, and technology. The project is conceived as a comprehensive redevelopment strategy grounded in integrated design.
The Campus is envisioned as a distributed higher education and research facility. Villa IX Maggio houses classrooms, a conference hall, a multimedia library and exhibition spaces, technical laboratories, offices, co-working and co-studying areas, and a café-garden bar. Practical ecological construction workshops are hosted beneath the *Solar Forest* - an innovative timber structure with a photovoltaic canopy that also accommodates a small arena for performances and seminars.
In the area of the former Roman necropolis, accessible through a timber cycle-pedestrian bridge, *Vertical Gardens* are introduced, including a 56 m long *Green Wall* along Via Cristoforo Colombo. The complex is integrated into a blue-green infrastructure network that recovers and reuses greywater through phytoremediation basins powered by photovoltaic energy. Green infrastructure is diversified to include Mediterranean shrubland, bee gardens, dispersed exhibition areas, and socio-educational, cultural, art installations and sports functions, as well as green roofs and ecological pathways (*Wildlife Crossing*).
The main access to the Campus, shifted to the right of the custodian's house along Via Carlo Spinola, reorients the approach away from the Rationalist monumentality of Villa IX Maggio and towards the identity of the Solar Forest. Overall, the site is re-permeabilized hydrologically, ecologically, and in terms of accessibility networks for pedestrians, cyclists, electric vehicles, and service transport.

Adaptive Reuse of the Villa

The project develops targeted solutions to preserve the historical fabric while reconfiguring the villa as an open-source hub for wellbeing, reduced energy demand, and social interactions.
The ground floor will accommodate the library, exhibition spaces, conference hall, café, co-studying and co-working areas, intended for young professionals, innovators, and start-ups in bio-architecture and renewable energy. Existing windows will be adapted to open outward, integrating with outdoor pergolas, while the central courtyard will host a semi-covered water feature: a fountain recalling the original patio element (later removed) and a photovoltaic canopy providing shade and weather protection.
The first and second floors are dedicated to teaching, faculty, and administrative functions. Flat roofs are converted into green roofs, including the *Giardino dell'Infinito* on the upper level with panoramic views over Rome, inspired by Leopardi's *Colle dell'Infinito*. Photovoltaic pergolas on the second level combine energy generation with summer shading.

Methodology and Bioclimatic Strategies

The design methodology included historical and regulatory analysis, identification of building envelope deficiencies, and assessment of intrinsic resources. Since the façades are protected and could not undergo invasive interventions, some bioclimatic strategies were applied internally. A key example is the use of a *brett-staple* counter-wall to create a ventilated wall system with the external masonry, analogous to the KlimaWall® system. Inspired by the Roman hypocaust, this assembly combines solid wood and brick to form a highly insulating structure with ventilated cavities acting as seasonal thermal reservoirs. Integrated with hybrid solar collectors, heat exchangers, and low-energy heat pumps, the system regulates indoor climate, while the hygroscopic properties of wood provide passive humidity control.

Planned interventions include brett-staple ventilated walls on the north façade; heat exchangers using the volumes of the extended underground war bunker and other volumes, situated below the structure, and the patio fountain to provide seasonal thermal regulation; radiant ceiling systems for classrooms and offices; and air-handling systems for the conference hall. Green walls on the west and south façades improve both environmental and architectural performance. Semi-extensive green roofs on the first level, garden roofs on the second, photovoltaic pergolas, and the photovoltaic canopy over the courtyard further enhance performance (see figure). Windows will be replaced with replicas of the original design but upgraded with triple low-emissivity glazing and argon filling, eliminating thermal bridges. Calcium silicate elements will insulate the ground floor internally. Greywater recovery, phyto-purification, and reuse for flushing, along with draining pavements replacing asphalt, improve water management and permeability.

The Solar Forest

Adjacent to the villa, in an area once used for sports and now abandoned, the *Solar Forest* has been conceived as a multifunctional open structure for teaching, experimental testing, and largescale technological demonstrations. The timber structure with a semi-transparent photovoltaic roof houses modular laboratories (one- or two-story volumes built with exemplary eco-materials), an open-air arena with a straw-and-wood backdrop, and technical rooms for photovoltaic and HVAC systems. Representative construction techniques include Terra Cruda, KlimaWall®, Block-Haus, and straw-wood (Paglia-legno). Sloping timber pillars simulate tree trunks, while the photovoltaic glass of the overhead structure, through its distinctive pattern of alternating translucent and opaque panels, replicates the natural shading of forest canopies. Permeable paving beneath further restores hydrological balance.

The roof integrates multiple functions: sheltering, rainwater collection through a slight slope, photovoltaic energy production, solar gain regulation, operable modules for ventilation, and textile screens for seasonal adaptability.

Vertical Gardens and Ex-Necropolis Area

Beyond Via Padre Semeria, the project introduces a Vertical Garden with a prominent green wall mitigating acoustic and atmospheric pollution. Designed as a prefabricated, fully demountable and reusable system, it represents a reversible, low-impact solution. Gabion walls filled with quarry stone offcuts provide both noise/air screening and support for integrated irrigation planting. The area promotes biodiversity and circular economy through organic horticulture, Mediterranean vegetation, holistic pathways, and a bee garden.

A timber cycle-pedestrian bridge, integrated with vegetation, ensures safe crossing of the road and ecological continuity. The structural system employs Natterer's innovative timber-concrete hybrid: juxtaposed trunks forming the lower extrados with a Roman concrete slab cast above, enabling over 1.6 m of soil depth to support medium-height vegetation.

Vegetation, water and energy

Ecological regeneration requires retaining rainwater on site. This is achieved through green roofs, permeable pavements, phytoremediation basins, rainwater-collecting photovoltaic canopies, and widespread vegetation, all essential for effective water management within the plot. Equally important is the reuse of greywater from the Campus and the synergy with the adjacent primary school, which functions as an integral part of the same compound.

Any new or retrofit intervention must address both energy efficiency and renewable energy supply. Villa IX Maggio, a historic and relatively rigid building, benefits from favourable solar exposure and shading from surrounding trees. In Rome's climate, characterized by mild winters and very hot summers, energy demand is driven primarily by summer cooling needs. While bioclimatic strategies are fundamental, they are not sufficient on their own; solar energy is therefore indispensable, implemented through an Energy Community and the multifunctional Solar Forest roof, which fully satisfies energy needs on sunny days.

Green spaces extend beyond open areas to include green roofs, vegetated walls, gardens, and pergolas, all integral to the overall vegetation system. These diverse spaces serve socio-cultural, artistic, and educational purposes, supporting social, sports, and recreational activities, and are interconnected with one another and with the surrounding urban context to fulfil the project's objectives.

Conclusions

The study demonstrates how bio-architecture principles can be applied to a complex historic structure and its surroundings, creating a benchmark for sustainable redevelopment. By combining ecological regeneration, renewable energy systems, and social inclusivity, the project establishes Villa IX Maggio and its Campus as an innovative model for healthy, low-impact architecture.

Designing interventions within already built and transformed sites - places that have undergone social transformations, where historical pre-existences are significant and where numerous regulatory and contextual constraints apply - actually allows for a more effective implementation of functional, bioclimatic, and interconnection optimizations between the site and its surroundings.

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Vertical greenery systems: critical evaluation of management phase

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Highlights

- VGSs are suitable strategies of greening the existing buildings
- The application of VGSs requires a multi-criteria approach
- The management phase of VGSs represents a critical issue to be thoroughly investigated

Keywords

Nature Based Solutions; Green Façade; Maintenance

On the top: Le Albere district in Trento (IT) with a detail of the irrigation water drainage hole. Pics by A. Lo Faro. On the bottom: a case of lack of maintenance: DSDHA's Paradise Park Children's Centre in Islington, London, Architects' Journal, 25 October 2021, https://www.architectsjournal.co.uk/news/growing-pains-why-some-green-walls-di

The improvement of outdoor comfort conditions in urban areas is a major environmental concern for urban sustainability and resilience. The most recent step in this direction has been the establishment of Sustainable Development Goals (SDGs), which form the 2030 Agenda in conjunction with the Paris Agreement on climate change. The accelerated urbanisation of cities has resulted in the increasing fragmentation of nature in towns and peri-urban areas. The repercussions on the environment have encompassed the Urban Heat Island (UHI) phenomenon and the forfeiture of advantages bestowed by vegetation, such as shade and evapotranspiration [1]. Some nature-based climate change mitigation and adaptation strategies have the potential to improve the regulation of bioclimatic parameters and people's quality of life [2]. Nature can be regarded as a tool that provides ecosystem services, which can be categorised as cultural, regulatory and provisioning. These services can systematically contribute to the reduction of carbon emissions, the resolution of social inequality issues through job creation or food production, and the enhancement of human well-being and health by being incorporated into urban planning at an early stage [3].

According to this assumption, the authors want to examine a particular type of Nature Based Solutions: Vertical Greenery Systems (VGSs). VGSs can be divided into green facades (GF) and living wall (LW) based on the different plants and support structures used [4]. Hypothesising the use of VGS as a greening strategy for the refurbishment of urban building stock in the suburbs, the authors' interest focused on GF [5], as part of the PRIN 2022 PNRR Project titled: Greenwork: an interdisciplinary framework for urban health and urban resilience enhancement based on greening strategies on buildings and open spaces. The extensive utilisation of VGSs in existing buildings requires the preliminary authentication of multiple indicators to ascertain the most sustainable solution. The advantageous outcomes of VGSs may confront various macro criteria such as: Type and classification of GF; Facade design; Cost and Benefit [6]. The macro cost/benefit criterion also concerns the irrigation and maintenance of VGSs, which represent some of the most tenacious barriers to their application. Depending on the type, VGSs have different irrigation and maintenance requirements.

Irrigation

The success of VGSs depends on a permanently operational irrigation system, especially in exposed locations and in containers for planting. The demand of water changes according to weather patterns and over the course of the vegetation year. The VGS is totally dependent on irrigation because it can only intercept a very small fraction of rainwater.

In GF, climbing plants that cover the wall are rooted in the ground or in planter boxes. Therefore, it will only be necessary to provide water manually or via an automated irrigation network at the base. It could also be in each plant box. Therefore, the irrigation network will depend on the location of the plant boxes.

In the LW system, the implementation of an efficient irrigation system is necessary to guarantee optimal water distribution across the entire surface, while concomitantly minimising water loss. The main difficulty in achieving this lies in the role of gravity in water distribution, since the horizontal component of water movement due to diffusion is much less significant than the vertical component. This condition makes the irrigation of vertical surfaces more complex than horizontal surfaces, given that solutions must be found to overcome the negative effects of gravity, such as uneven water distribution and high-water losses. Additionally, there is a difficulty in adapting to species with different water requirements, and establishing hydrozones can also be problematic. For these, it would be necessary to implement a sector-based approach, with particular attention given to runoff from the upper sectors [7].

Due to their lower species diversity, plant density and simpler structure, irrigation design for GF is simpler than compared to living walls [8].

The irrigation requirements of VGSs are highly variable and depend on several factors such as location (in our research always outdoor), light exposure (direct sun light, orientation, presence of shading, etc.), weather conditions (temperature, humidity, etc.), type of employed vegetation and used substrate.

Determining the correct emitter water flow is essential for reducing runoff losses and improving water distribution uniformity. Although high-flow emitters have demonstrated the best water uniformity, runoff losses increase. Some authors recommend to using a recirculating system. In any case, flows of more than 8 L/h should be avoided. When using low flow rates, it must be considered that irrigation times must be increased [9].

If you use water directly from the network supply point, ensure that the pressure and flow values are adequate for the GF irrigation system to operate correctly. An excess of watering can be a problem in VGSs. For this reason, mechanisms to evacuate the excess of water must be provided. When using planters for green facades,

they should have draining holes (Fig. 1). In GF, careful management of water resources involves using the runoff water from the higher planters to irrigate the lower ones.
Especially in summer, due to higher temperatures and related evapotranspiration, more water is needed. To respond to changing water demands in the best possible way, a variety of sensors and control equipment settings are available, including sensors for soil moisture, solar radiation, rainfall, humidity and temperature. Online based control systems are the current state of art and permit remote access as well as remote monitoring.

Maintenance

The maintenance phase is of great importance and it should be a part of the design process and not an afterthought, once the project is completed, as it ensures the durability and the liveability of VGSs (Fig. 1). A valuable maintenance plan should contains a clear description of maintenance objectives, the performance targets, involved skills and available resources [10]. In the early stages following the completion of the VGSs, regular visits (e.g. fortnightly or monthly) from maintenance personnel may be required to ensure the facade is achieving the desired outcome. Once the facade has been established, it may only be necessary to perform tasks such as pruning and fertilising on a semi-annual or annual basis.
In order to ensure the smooth functioning of the VGS, it is imperative to incorporate considerations regarding access in the maintenance plan. Maintenance contractors may, for instance, be required to utilise heavy machinery such as scissor/boom lifts or building maintenance units when undertaking tasks in the context of a tall green facade or wall. The accessibility throughout the year of all areas across the lifecycle of the greening measure, for care and maintenance, needs to be established. If ladders or trestles are insufficient for this purpose, related equipment is required, e.g. anchor points for climbing gear and/or dedicated areas for lifting equipment or scaffolds.
Care and maintenance include irrigation plant, fertilisation, weeding, ground loosening and pruning as well as investigating secondary structures (climbing support, structural greening elements) regarding road traffic safety. Cutting and pruning of plants is undertaken with the aim of protecting the building and preserving plant vitality. For ground-based greening, typically one care run per year is sufficient. For wall-based greening, at least two care runs per year are required [10].

Conclusions

To have a healthy and good looking VGS, irrigation and maintenance operations are crucial. Irrigation of green facades is not always simple: the LW present peculiarities such as mixture of species with different requirements and variable environmental conditions that make an efficient water management challenging.
Proper growth and development of the VGS requires a management plan to be created. This includes maintenance and monitoring, both of which must be planned for during the design phase of the VGS.
The following operations are generally included in the management plan for a VGS: maintenance of vegetation cover; monitoring and modulation of growth factors; management of irrigation systems and fertiliser dosing; maintenance of irrigation water collection and disposal systems. Establishing maintenance plans specific for each installation will ensure a correct performance of the VGSs.
Of particular importance are the settings and checks during the installation phase, which lasts a few weeks, during which the vegetation adapts to the new planting situation.
Monitoring during the start-up phase is equally important. This phase is used to verify changes in seasonal requirements during the first year, as well as to gather information about the conditions throughout the year. During the initial installation phase (the first three or four years), excellent vegetative conditions can easily be maintained through rigorous plant management. Periodic checks of filters and systems help to prevent sudden failures. Moderating humidity and nitrogen fertilisation also helps to prevent parasitic infestations.
Although the greening of buildings has been understood as the application of a special material for several years (some authors talk about “technological green”), the vegetation has its own specific requirements that must be considered to achieve an adequate level of green cover.
All these reasons motivated the choice of GFs as the most sustainable greening solutions and therefore the authors' focus was on them.

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Assessing green walls as a Nature-based strategy to improve urban microclimate and reduce energy demand under current and future climate conditions

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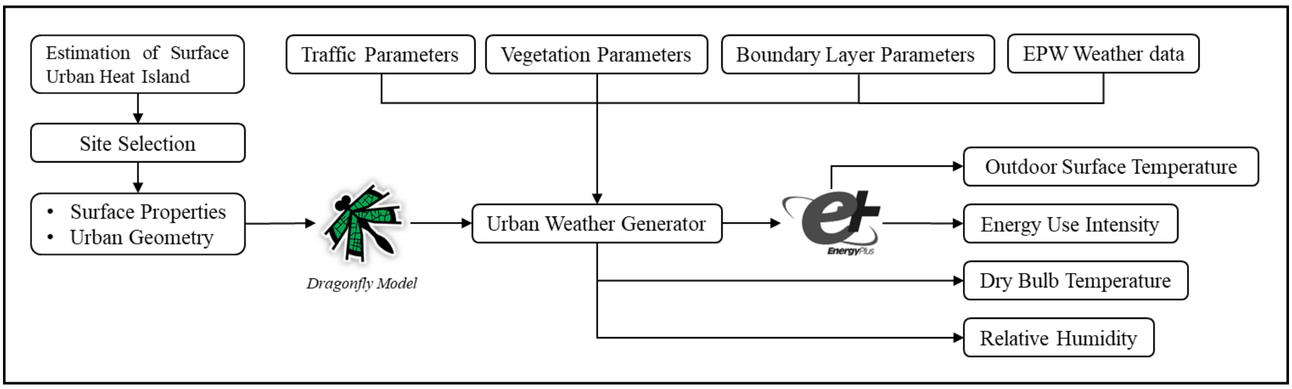
Highlights

- The urgency of urban adaptation under rising temperatures projected for 2050
- The limited consideration of Vertical Greenery Systems (VGS) energy impact in typical urban planning
- The untapped potential for district-scale green infrastructure to enhance building energy performance

Keywords

Energy Use Intensity; Vertical Greenery; Urban Resilience; Cooling Demand; Climate Adaptation



Analysis flowchart of the green wall's cooling impact on energy efficiency

Introduction

Rapid industrialization and urbanization have caused various ecological and environmental issues, raising the risk of climate change in urban areas, and the increasing prospect of escalating climate hazards is threatening cities and citizens worldwide, indicating the unprecedented importance of building urban climate resilience. Buildings as the producers of greenhouse gases (GHGs), consuming 34% of the world's total energy and contributing 37% of global CO_2 emissions. The significant energy demand and carbon emission of buildings create a critical feedback loop in urban areas, where energy consumption is intensified by the Urban Heat Island (UHI) effect, buildings contribute to climate change, while they are becoming increasingly vulnerable to the urban climate shift [1].

Studies report that UHI contributes to cooling load increases ranging from 4% to 65% and heating load reductions of up to 100% [2]. Building passive energy-saving strategies usually refer to improvement in building energy performance regarding envelope elements and architectural design, such as building orientation, material, natural ventilation, shading, and greenery [1]. Looking ahead, the role of technology in urban greenery is poised to expand significantly. VGSs are more straightforward in structure, more uncomplicated to construct, have lower economic costs, and are less burdensome to the environment. [3], [4]. Green façades can provide shading for the building, which reduces the heat flux and ultimately the heat load of the building. At the same time, the evapotranspiration of plants increases the relative humidity around the building, providing a good cooling effect on the air. The shading effect of an indirect green façade with an air gap brought a temperature drop of 23.1 °C was observed on the surface of the external walls, and the average temperature in several experimental rooms decreased by 1–5 °C. In the cooling experiments, the room with indirect green façades has the highest energy-saving rate of 45.75 %. However, the room with direct green façades covered only has an energy saving rate of 6.43 %.[5]

VGSs such as Green Walls (GWs) are known to improve outdoor thermal comfort as they have the best cooling potential. However, their full impact on energy efficiency on the urban scale, especially during future climate scenarios, remains understudied. This research addresses this gap by evaluating the influence of GWs on Energy Use Intensity (EUI) and cooling demand in a dense district of Turin, Italy, using both current and future (2050-RCP8.5) climate scenarios.

Methodology

This study adopts a novel and scalable workflow, as illustrated in Figure 1, building on previous research [6], utilized satellite imagery to detect Surface Urban Heat Island (SUHI) hotspots, identifying high-temperature zones across the urban area without the need for extensive on-site sensor measurements. These hotspot areas served as spatial inputs for subsequent simulation steps. Using this spatially informed basis, local microclimate conditions were modeled with Ladybug Tools, and dynamic building energy simulations were conducted using EnergyPlus, while the Mean Radiant Temperature (MRT) was validated against in-situ measurements according to ASHRAE Guideline 14 [7] in Eqs. (1)–(3), which specifies acceptable limits for calibration of: ±10% MBE and ≤30% CVRMSE.

$$\mathrm{MBE} = \frac{\sum_{i-1}^{N_p}(M_i - S_i)}{\sum_{i=1}^{N_p} M_i} = 6.08\% \tag{1}$$

$$\mathrm{CVRMSE} = \frac{\sqrt{\sum_{i=1}^{N_p}(M_i - S_i)^2 / N_p}}{M_p} = 16.06\% \tag{2}$$

$$(\overline{M_p} = \frac{\sum_{i=1}^{N_p} M_i}{N_p}) \tag{3}$$

Both current and projected 2050 high-resolution climate datasets from the *Turin-Caselle Airport* weather station [8], [9] were incorporated to assess the combined effects of thermal insulation, shading, and evaporative cooling from green walls on urban energy demand. Using the Urban Weather Generator (UWG) component,

microclimate conditions and weather parameters such as air temperature, relative humidity, and wind speed were modeled and used as background inputs for energy consumption analysis on 29th July, representing the hottest day of the year, from 8:00 to 18:00, when most activities occur [10].
The green walls, with a plant height of 0.1 (m) and a substrate thickness of 0.05 (m), were assumed to cover all outdoor vertical building surfaces exposed to canyons and streets. During the simulation, green wall was represented as a separate and ventilated thermal zone, with a flow per exchange area of 0.0006 (m^3/s per m^2) of façade and an air change rate (ACH) of 3.

Results

The results of comparing the EUI of TMY from the Turin-Caselle Airport weather station and morphed TMY data of UWG during the current weather condition, showed an increase of 15% in EUI from 0.33 (kWh/m^2) to 0.38 (kWh/m^2), because of urbanization, which causes the UHI effect. The Implementation of GWs showed modest changes in average air temperature with a maximum reduction of 0.1 (◦C) under future projection climate conditions and an increase in average relative humidity by 1%; however, for the current condition, these remain unchanged. However, the shading effect of GWs showed the significant reductions in outdoor surface temperatures by 24 (◦C) with the average reduction of 1.8 (◦C) during current conditions and reduction by 34 (◦C) and average reduction of 2.15(◦C) under future climate projection.

Results also indicate substantial energy savings due to GWs implementation:

Current scenario: EUI decreased by 35.3%, from 0.38 (kWh/m^2) to 0.2 (kWh/m^2), driven by a 44.5% reduction in cooling demand from 0.3 (kWh/m^2) to 0.14 (kWh/m^2).

2050 scenario: EUI dropped by 35%, from 0.56 kWh/m^2 to 0.36 (kWh/m^2), with cooling demand reduced by 41% from 0.48 (kWh/m^2) to 0.28 (kWh/m^2).

Conclusion

The integration of green walls in dense urban districts demonstrates substantial potential for reducing cooling demand and overall energy use intensity under both current and future climate scenarios. Although modest reduction in air temperatures was observed, the green wall shading effect leads to significant decreases in surface temperatures and cooling loads. Notably, during future climate projection of 2050, simulations show that the implementation of green walls can reduce EUI to levels comparable with today’s conditions, effectively counteracting the additional energy burden expected from climate change and urbanization. This highlights green walls as a practical and widely applicable nature-based solution that can be scaled from single buildings to district-wide interventions, offering policymakers and planners a viable pathway to strengthen urban climate resilience and energy efficiency.

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This volume collect the proceedings of the ENC Enhancing Nature in Cities conference, organized within the framework of the PRIN PNRR GREENWORK research project "An interdisciplinary framework for urban health and urban resilience enhancement based on greening strategies on buildings and open spaces". The collected contributions are structured around three main thematic areas: resilience to urban risks, urban microclimate and open spaces, and interventions at the building scale, offering an interdisciplinary and integrated perspective on the challenges and opportunities of the ecological transition in urban contexts.